The Articulatory Basis of Positional Asymmetries in Phonological Acquisition

by

Tara K. McAllister

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Signature of Author: _____
Department of Linguistics and Philosophy
May 29, 2009

Certified by: _____
Adam Albright
Associate Professor of Linguistics
Thesis Supervisor

Accepted by: _____
Irene Heim
Professor of Linguistics
Department Head

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ABSTRACT

Child phonological processes that lack counterparts in adult phonological typology have long posed a problem for formal modeling of phonological acquisition. This dissertation investigates child-specific processes with a focus on the phenomenon of *neutralization in strong position*, whereby children preferentially neutralize phonemic contrast in precisely those contexts seen to support maximal contrast in adult systems. These processes are difficult to model without making incorrect predictions for adult typology. Here, it is argued that all genuinely child-specific processes are driven by constraints rooted in child-specific phonetic factors. In a phonetically-based approach to phonology, if there are areas of divergence in phonetic pressures across immature and mature systems, differences across child and adult phonologies are predicted rather than problematic. The phonetically-based approach also explains the developmental elimination of child-specific processes, since in the course of typical maturation, the phonetic pressures driving these effects will cease to apply. Because children's speech-motor control capabilities are known to diverge from those of the skilled adult speaker, it is posited that articulatory factors play the dominant role in shaping child-specific phonological processes.

Here it is argued that children have difficulty executing discrete movements of individual articulators, notably the tongue. By moving the tongue-jaw complex as a single unit, the child speaker can reduce the number of degrees of movement freedom and also rely on the action of the motorically simpler mandible to achieve articulatory targets. The effects of mandibular dominance have previously been argued to play a role in shaping sound patterns in babbling and early words (MacNeilage & Davis, 1990). The preference for jaw-dominated movement can be seen to recede over time as the child establishes more reliable articulatory control. However, here evidence from the productions of older children is presented indicating that these effects continue to have an influence in later stages of development than has been previously documented. The pressure to use simultaneous movements of the tongue-jaw complex, formalized in a constraint MOVE-AS-UNIT, is argued to play a role in shaping child-specific processes including positional velar fronting, prevocalic fricative gliding, and consonant harmony. In the present approach, children's tendency to neutralize contrast in strong positions arises as MOVE-AS-UNIT interacts with asymmetries in the force and duration of articulatory gestures across different prosodic contexts. The incorporation of child-specific phonetic factors makes it possible to account for complex patterns of conditioning in child speech processes that would under other assumptions be extremely challenging to model.

Thesis Supervisor: Adam Albright
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Chapter 1. The problem of child-specific phonological processes

1. Positional neutralization in child and adult phonological processes

Efforts to model phonological acquisition have long faced a challenge stemming from the existence of phonological processes that are specific to child speakers. These processes may be quite commonly observed in the speech of both typically developing and phonologically disordered children, but corresponding processes appear to be entirely absent from adult phonological typology. This has led some researchers to characterize child-specific processes as "'invented', 'unnatural', or 'crazy' rules" (Inkelas & Rose, 2008). In English, which will provide nearly all of data for the analyses pursued here, familiar child-specific phonological processes include velar fronting, fricative stopping or gliding, and consonant harmony. These processes are represented in (1)-(3) below. The examples in (1)-(3) highlight an especially problematic property that unifies a number of child speech phenomena: they tend to neutralize phonemic contrast in word-initial contexts while preserving a distinction word-finally. This dissertation will address the problem posed by child processes of *neutralization in strong position*, which preferentially neutralize contrast in precisely those contexts that typically support the greatest range of contrasts in adult languages.

(1) Positional velar fronting affects word-initial but not word-final velars.
   a. [tʌ p] 'cup'
   b. [dʌ k] 'duck'

(2) Positional fricative gliding affects word-initial but not word-final fricatives.
   a. [jak] 'sock'
   b. [maʊ s] 'mouse'

(3) Consonant harmony preferentially involves assimilation of an initial consonant to a word-final consonant.
   a. [gɪ g] 'pig'
   b. [mæ p] 'nap'

These processes stand in direct contrast with neutralizing phenomena in adult phonologies, which tend to affect final rather than initial positions. For instance, children who neutralize stop and fricative manner in word-initial contexts while preserving the manner contrast word-finally present precisely the opposite of the preference expressed by languages like Korean, where the stop-fricative-affricate distinction is merged in coda position (Ahn, 1998). Similarly, children are reported to acquire contrastive voicing in word-final before word-initial contexts; this runs counter to the well-attested voicing asymmetry in adult phonologies, whereby languages like German, Dutch, and Catalan can be seen to maintain a word-initial voicing contrast that is neutralized word-finally (Dinnsen & Eckman, 1975). Efforts to model these anomalous processes in child speech pose a problem if we wish to maintain basic continuity between child and adult grammars. This section will demonstrate that none of the approaches that have been used to model adult processes of positional neutralization (positional faithfulness,

positional markedness, and faithfulness to perceptually prominent contexts) can account for the child pattern without making poor predictions for the range of variation permitted by adult grammars.

These results suggest that it is problematic to adopt the continuity hypothesis, which holds that child grammar must at all stages of development fall within the set of possible adult grammars, in its strongest version (Macnamara, 1982; Pinker, 1984). A weaker version of the continuity hypothesis leaves room for constraints specific to child phonology. However, it is clear that a satisfying model of child phonology will not be derived by positing child-specific constraints at will to accommodate any apparent sound substitution. Here, it is proposed that the only true child-specific constraints are grounded in functional limitations imposed by the properties of immature articulation, perception, or cognitive processing. Because the pressures underlying these constraints will be withdrawn over the course of typical maturation, their absence from adult grammars is predicted rather than problematic. Each analysis to be presented in the chapters that follow is the product of a search for child-specific phonetic factors that can be understood to motivate problematic processes in child phonology. In short, in the spirit of phonetically-based models of adult phonology (cf. Hayes, Kirchner, & Steriade, 2004), this work pursued a program of phonetically-based child phonology. This is not the first such effort, with notable analyses along these lines offered by Pater (1997), Inkelas & Rose (2003, 2008), and Dinnsen & Farris-Trimble (2008), among others. Here it will be proposed that child-specific phonological processes are driven primarily by limitations on the articulatory control of immature speakers, but perceptual factors will also be taken into consideration.

1.1 Strong and weak contexts in adult phonological processes

To understand the anomalous nature of child processes of neutralization in strong positions, first it will be necessary to review the typical pattern of positional neutralization that has cross-linguistic attestation in adult phonologies. Barnes (2002) defines positional neutralization as "any instance of an asymmetrical capacity of two positions (or sets of positions) in the representation to license phonological contrasts, such that one set of positions licenses a larger array of contrasts than another" (p. 1). An early analysis of this phenomenon was offered by Trubetzkoy (1939), who identified structurally conditioned neutralizations that tend to affect the right edge of a word while sparing the left edge. In its modern guise, positional neutralization differentiates between strong and weak positions, where the set of contrasts licensed by weak contexts is a proper subset of the contrasts permitted by strong environments. While loss of contrast can be either assimilatory (e.g. C_1C_2 becomes C_2C_2) or non-assimilatory (e.g. VC_1# becomes VC_2#), the primary focus here is on non-assimilatory loss of contrast.

To a considerable extent, there is cross-linguistic convergence regarding what constitutes a strong position and what can be considered a weak position. Canonically, strong positions include word- and foot-initial segments and syllables, while non-initial segments and syllables typically constitute weak contexts. Strong and weak positions can also be defined in terms of their phonetic properties, where the perceptual cues to phonemic contrasts are more powerful in strong relative to weak positions. The phonetic-perceptual definition of positional strength can give rise to occasional inversions of the traditional distinction between strong and weak contexts: for instance, the phonetic cues to apical contrasts are enhanced in postvocalic contexts, and the non-initial environment thus represents the strong position for these distinctions (Steriade, 2001). However, for the featural contrasts to be examined here, the traditional distinction between strong prevocalic and weak postvocalic contexts will be largely sufficient.

Beckman (1997) has offered an extensive but by no means exhaustive listing of adult languages known to permit contrast in strong contexts (initial syllables) but not in medial or final environments. While her discussion emphasizes neutralizations affecting vowel contrasts, for present purposes the realization of consonant contrasts will be of greater relevance. Thus, Beckman's examples specifically related to consonant contrasts are reproduced in Table 1.

Table 1. Examples of strong-weak contrasts in consonant realization (from Beckman, 1997)

Language	Word-Initial Position	Non-Initial Position	Source
!Xóõ	Click and non-click consonants.	Non-click consonants only.	Traill, 1985
Shilluk	Plain, palatalized, and labialized consonants.	Plain consonants only.	Gilley, 1992
Malayalam	Labial, dorsal, and coronal consonants.	Coda place depends on place of articulation of following onset.	Wiltshire, 1992
Damin (Lardil secret language)	Lardil segments, nasalized clicks, bilabial & velar ejectives, ingressive lateral fricative.	Lardil segments only.	Hale, 1973

1.2 Positional processes in child phonology

The previous section showed that in adult phonological typology, processes of phonological neutralization asymmetrically affect weak, typically postvocalic contexts. However, a number of common processes in child phonology run counter to this generalization, neutralizing contrasts in strong positions while preferentially preserving them in weak positions. According to Dinnsen & Farris-Trimble (2008), this type of process is sufficiently widespread to indicate that a preference to preserve contrast in weak contexts is a general property of child grammar. This dissertation will focus on three such processes of neutralization in strong position: positional velar fronting, positional fricative gliding, and major place harmony in a regressive direction. Additional instances of strong neutralization, described by Dinnsen and Farris-Trimble (2008) and Kirk & Demuth (2003), are also noted below.

Velar fronting is one of the best-known examples of neutralization in strong position in child phonology. It is well-established that this process, which involves fronting of velar target consonants to a coronal place of articulation, preferentially targets velars in word-initial and pretonic positions while sparing final and posttonic velars (Ingram, 1974; Chiat, 1983; Stoel-Gamon, 1996; Bernhardt & Stemberger, 1998; Bills & Golston, 2002; Morisette, Dinnsen, & Gierut, 2003; Inkelas & Rose, 2003, 2008). Inkelas & Rose proposed an analysis of velar fronting that incorporates child-specific articulatory factors. Their hypothesis will be extended with new data and detailed phonological formalism in Chapter 4.

Comparable processes can also be seen to neutralize manner contrasts preferentially in strong positions. The literature contains numerous instances of children who were seen to acquire fricative manner in postvocalic before prevocalic positions; these children typically substitute either stops or glides for fricatives in strong positions (Ferguson, 1978; Dinnsen, 1996; Edwards, 1996; Marshall & Chiat, 2003). Dinnsen & Farris-Trimble (2008) noted that other manner

contrasts have been reported to have their first attestation in word-final position, including the liquid-glide contrast (Smit, 1993) and the stop-affricate contrast (Dinnsen, 1998). Chapter 5 will present a case study of a child who replaced fricatives with glides in word-initial contexts while producing faithful fricatives in other contexts. This process will be argued to have its origins in constraints on the expenditure of articulatory effort.

The third process to be investigated in detail in this dissertation, consonant harmony, has points of both commonality and divergence relative to the preceding two cases. Like velar fronting or fricative gliding, consonant harmony can involve neutralization of place or manner features. It also is well-known that child harmony processes operate preferentially in a regressive direction (Smith, 1973; Stoel-Gammon & Stemberger, 1994; Goad, 1997; Pater & Werle, 2001, 2003). This has the effect of preserving the place or manner feature of a consonant in weak position while neutralizing contrast in the strong word-initial position. However, consonant harmony stands apart from velar fronting and fricative gliding as an assimilatory process of neutralization. It also has a counterpart in processes of long-distance consonant assimilation in adult languages, although the child and adult processes differ in qualitative ways that demand explanation. Chapter 6 will characterize child consonant harmony as the product of constraints rooted in psycholinguistic processing as well as articulation.

While it will not be investigated in detail as part of the present dissertation, the asymmetric development of the voiced-voiceless contrast is cited by Dinnsen & Farris-Trimble as another instance of neutralization in strong contexts in child speakers. The acquisition of voicing has been studied extensively through both transcription and instrumental analyses, but many of these studies have investigated voicing contrasts in only one position. Dinnsen & Farris-Trimble note a small number of studies in which voicing acquisition has been tracked across positions (Smith, 1973; Dinnsen, 1996; Kager, Van der Feest, Fikkert, Kerkhoff, & Zamuner, 2003). They maintain that the consensus emerging from this literature is that the voiced-voiceless contrast emerges in word-final position prior to word-initial position.

A last instance of a child phonological process that disproportionately affects contrasts in strong positions is the simplification of consonant sequences. A few studies of languages other than English have suggested that coda clusters emerge earlier and with greater accuracy than onset clusters (Lléo and Prinz, 1996; Levelt, Schiller & Levelt, 2000). Kirk & Demuth (2003) investigated the development of onset and coda clusters in nine typically developing monolingual English speakers around two years of age. They found that coda clusters were produced with significantly higher accuracy than onset clusters. However, they posited that this onset-coda asymmetry could be reflective of differences in the relative frequency of complex onsets and complex codas in the input to language learners. In a corpus of child-directed speech, Kirk & Demuth found that 74% of biconsonantal clusters at word edges appeared in coda position. While considerations of frequency will be for the most part omitted from the analyses to follow, this is an area of significant interest for future research.

2. Phonological models of positional neutralization

This section will review several approaches that have been used to model positional neutralization processes in adult phonology, with a view to the potential application of these models in accounting for the child-specific positional neutralizations reported above. One possibility is that positional restrictions on the realization of phonemic contrast are encoded

through grammatical principles that make direct reference to weak and strong positions. In this "Pure Prominence" approach, strong versus weak status is an intrinsic property of a position, specified by Universal Grammar (Barnes, 2002). Both positional faithfulness (e.g. Beckman, 1997) and positional markedness (e.g. Zoll, 1998; Smith, 2002) approaches to phonological modeling of positional neutralization are discussed below. Section 2.3 will review a different approach in which phonemic contrast is realized preferentially in contexts where the phonetic cues to the contrast can most readily be perceived (Steriade, 1995, 1999, 2001). In connection with this model, evidence regarding the relative strength of perceptual cues in syllable-initial versus syllable-final contexts will be presented. Each of the abovementioned approaches to the modeling of positional asymmetries in adult phonology will be compared against the data from child patterns of neutralization in strong contexts. It will be demonstrated that positional faithfulness, positional markedness, and perceptually motivated accounts of positional neutralization all fail to capture the properties of the child pattern.

2.1 Positional faithfulness

Beckman (1997) proposed that positional faithfulness constraints can account for the greater range of contrast that is available in strong positions in adult phonology. Her analysis draws on the properties of positional neutralization of vowel contrasts in Shona vowel harmony. Shona contrasts high, low, and mid vowel height in initial syllables, but mid vowels do not have contrastive status in non-initial syllables. Beckman suggests that this system can best be modeled using positional faithfulness constraints that refer specifically to root-initial syllables. Mid vowels are posited to be dispreferred under a general constraint *MID. In the schematic tableaux that follow, the positional constraint IDENT-σ_1(hi) is ranked above *MID, which in turn outranks the general constraint IDENT-σ(hi). Table 2 illustrates that under this constraint ordering, mid vowels will emerge faithfully in a root-initial syllable, which is protected by the high-ranked positional faithfulness constraint. As Table 3 shows, however, neutralization will occur when a mid vowel appears in a non-initial syllable. Beckman's positional faithfulness constraints are also successful in modeling the progressive direction of assimilation in Shona vowel harmony.

Table 2. Positional faithfulness protects mid vowel height in a root-initial syllable

Input: CeCi	IDENT-σ_1(hi)	*MID	IDENT-σ(hi)
a. CiCi	*!		*
b. ☞ CeCi		*	
c. CeCe		**!	*

Table 3. General faithfulness does not protect mid vowel height in a non-initial syllable

Input: CiCe	IDENT-σ_1(hi)	*MID	IDENT-σ(hi)
a. ☞ CiCi			*
b. CiCe		*	
c. CeCe	*!	**	*

It is clear that child processes of positional neutralization cannot be modeled using positional faithfulness constraints as described by Beckman, since adult constraints are all of the type IDENT-STRONG[feature], offering enhanced protection for the feature specifications of

segments in strong positions. To model child processes that preferentially preserve contrast in weak positions, it would be necessary to posit positional faithfulness constraints of the type IDENT-WEAK[feature]. Thus, to encompass child processes of neutralization, it would be necessary to adopt a symmetrical system of positional faithfulness constraints in which either strong or weak positions could be singled out for special preservation. However, if IDENT-WEAK[feature] constraints are possible, we would expect them to emerge in some capacity in adult phonological typology. In actuality, as it has already been discussed, such processes are unattested in mature phonologies. Thus, we cannot use positional faithfulness to model the child processes discussed here without substantial overgeneration of possible adult grammars.

2.2 Positional markedness

Zoll (1998) has asserted that the positional faithfulness model faces a challenge from the phenomenon of augmentation in strong positions, in which a set of prominence-enhancing features (including high tone, long duration, and epenthetic onsets) attach selectively to syllables in prominent positions. While these features further increase the salience of strong syllables, they come at the cost of violations of faithfulness. Zoll proposes that positional markedness constraints are needed to provide an account for processes of strong augmentation. She illustrates her proposal with an example from the distribution of vowel length in Guugu Yimidhirr, originally described by Kager (1995). Certain affixes in this language trigger vowel lengthening in a strong context (notably the first two syllables of the word, which Kager labels a Head Prosodic Word), but not elsewhere. Affix-induced derived lengthening that is specific to strong positions is not amenable to analysis in a positional faithfulness framework. To achieve lengthening in strong positions, the constraint responsible for affix-triggered lengthening must outrank the positional faithfulness constraint, by which token it will also outrank general faithfulness. Thus, there is no way in a positional faithfulness framework to model conditioned lengthening in strong positions without predicting lengthening in weak positions as well. Zoll proposes that this situation should be handled with a positional markedness constraint such as COINCIDE(Heavy syllable, Head PWd): "A heavy syllable belongs to the Head PWd." Note that Zoll does not propose that positional markedness should take over for all of the functions of positional faithfulness; rather, she suggests that the two can coexist, but she maintains that her examples illustrate the necessity of including a component of positional markedness.

Smith (2000, 2002) has offered a functionally motivated version of positional markedness. She suggests that the cross-linguistic tendency of prominence-enhancing properties to migrate to stressed or heavy syllables can be modeled with markedness constraints that refer specifically to strong positions, such as HAVETONE/σ′ or ONSET/σ′. However, Smith makes the observation that it would be problematic to allow any markedness constraint at all to single out strong positions, since processes of featural neutralization, as discussed elsewhere, preferentially target weak rather than strong positions. Thus, a constraint such as *LAB/σ′ would ban labials in stressed syllables but not other positions, a distribution that is not attested in the adult languages of the world. To constrain the application of markedness constraints referencing strong positions, Smith offers the Prominence Condition: "A markedness constraint can be relativized to a strong position only if it acts to enhance the prominence of that position" (2000, p. 2). In Smith's model, prominence is defined as any property, such as high tone, stress, or long duration, that has the effect of enhancing perceptual salience. Since featural markedness constraints (*LABIAL,

etc.) do not enhance prominence, the problematic constraint *LAB/σ′ is ruled out by the Prominence Condition.

De Lacy (2001) has offered a similar analysis of neutralizing processes that preferentially affect prominent positions, which he terms Π-neutralization. Like Smith, de Lacy argues that there is a need for markedness constraints that refer specifically to prominent positions, but the set of contexts in which positional markedness can be invoked must be constrained. He proposes that processes of Π-neutralization can only affect segment classes that are defined by sonority, never by subsegmental features such as [labial]. If the latter type of constraint did exist, we could expect to find some language in which a feature such as [labial] would be neutralized in prominent positions only, yet there is a complete absence of cross-linguistic evidence for such a system among adult phonologies.

The restrictions that Smith (2000, 2002) and de Lacy (2001) impose on the space of possible positional markedness constraints prevents us from adopting this type of constraint to model child processes of neutralization in strong positions. The child-specific processes laid out in Section 1 call for positional markedness constraints limiting featural contrasts in strong positions. For instance, the child process of velar fronting in onsets of stressed syllables would require a markedness constraint such as *σ′/Ons/Velar. This is precisely the type of constraint that Smith and de Lacy argue must be expressly banned, since fully developed languages with this type of neutralization remain unattested in spite of extensive cross-linguistic investigation. Thus, positional markedness constraints cannot be invoked to explain child-specific processes of positional neutralization without making incorrect predictions for adult phonological typology.

2.3 Positional neutralization and perceptual prominence

2.3.1 Modeling faithfulness to perceptually prominent contexts

Steriade (1995, 1999, 2001) has argued against the idea of a fixed, prosodically-determined division between strong and weak contexts for the realization of phonemic contrast. Instead, she maintains that a strong position with respect to the realization of a given contrast is the environment in which that contrast can most readily be perceived. To incorporate this perceptual information into the grammar, Steriade posits a new grammatical module termed the P-map, which can be understood as a store of knowledge about the perceptibility of sound contrasts. The content of the P-map includes information about the relative perceptibility of contrasts across different phonetic and prosodic contexts, as well as any absolute differences in the perceptibility of featural contrasts. Steriade proposes that the information contained in the P-map is expressed in the grammar through correspondence constraints of the form "underlying X must not surface as Y." These constraints can be ranked according to the perceptual dissimilarity between X and Y, where a constraint that militates against correspondence between an input and an output that is highly perceptually dissimilar is ranked higher than a constraint governing the correspondence between more perceptually similar forms. Correspondence constraints referring to perceptually prominent positions, where deviations from the input form are most readily detected, will penalize unfaithfulness more heavily than correspondence constraints referring to perceptually weak positions.

The following will review experimental results that provide a phonetic basis for differentiating between perceptually strong and perceptually weak positions. One well-documented finding indicates that the perceptual cues to featural contrasts have greater salience in the context of consonant-vowel relative to vowel-consonant transitions. With a perceptual

asymmetry thus motivating a preference for contrast in CV relative to VC contexts, the P-map recreates the traditional claim that onsets have greater licensing power than codas. Steriade's model has an added advantage in that it can explain not only cross-linguistic generalizations over neutralizing processes, but also the exceptions to those generalizations. For example, it has been demonstrated that apical featural contrasts are realized preferentially in postvocalic positions, posing a problem for models in which prominence appears as a fixed property of syllable position. The anomalous behavior of apical contrasts can be understood to reflect the dynamic nature of retroflex consonant articulation, which involves movement from a retroflex point of closure to a more anterior point of release. The closure phase is thus posited to carry stronger cues to apical contrasts than the release phase, and the P-map accordingly predicts that these contrasts should be realized preferentially in postvocalic environments. In sum, the P-map hypothesis unifies different types of neutralizing processes under the generalization that neutralization tends to occur in contexts where the contrast in question is least salient. However, in Section 2.3.3 it will be demonstrated that child patterns of positional neutralization do not correspond with experimentally determined distinctions between strong and weak positions.

2.3.2 Defining perceptually prominent contexts

Multiple experimental investigations have indicated that prevocalic consonants have greater perceptual salience than postvocalic consonants. Dorman, Raphael, Liberman, & Repp (1975) demonstrated that in synthesized stimuli containing conflicting cues to the place of articulation of an intervocalic consonant, the cues from the consonant-to-vowel (CV) transition tended to predominate over the vowel-to-consonant (VC) portion. Fujimura, Macchi & Streeter (1978) extended this finding using VCCV disyllables created by splicing together VC and CV transition portions from naturally produced Japanese pseudowords, with consonant bursts excluded. With VC cues from one place of articulation and CV cues from another, these stimuli offered conflicting information regarding the identity of the medial consonant. The spliced stimuli were presented to both native Japanese speakers and speakers of American English, and subjects were asked to identify the nonword they heard given a forced choice among labial, coronal, and velar places of articulation. For both speaker groups, the identified place of articulation was consistent with cues from the CV transition in more than 85% of cases. This indicates a perceptual bias favoring CV transitions that is independent of the properties of the consonant burst, since bursts were excised. Fujimura et al. additionally observed the same bias when they played their recorded stimuli in the reverse direction. This suggests that the preference for CV transitions reflects a perceptual bias rather than an articulatory asymmetry that might be inherent in the stimuli. Lastly, the fact that similar results were obtained from speakers of English and Japanese, two languages with very different phonotactics, strongly suggests that the observed effect reflects universal perceptual tendencies rather than an effect of language-specific bias.

Ohala (1990) investigated positional asymmetries in perception in an effort to explain the cross-linguistic preference for assimilation in a regressive direction in consonant clusters. Ohala spliced together VC and CV tokens to create both homorganic and heterorganic medial consonant clusters (e.g. *atta, akka; apta, apka*). Consistent with previous results, the second consonant was found to predominate over the first in listeners' perception of heterorganic clusters. More recently, Redford & Diehl (1999) investigated the relative discriminability of phonemic contrasts in initial and final positions in naturally produced CVC syllables. They examined a total of seven consonant targets in three vowel environments, using different carrier

phrases such that word-final consonants occurred in both preconsonantal and prevocalic contexts. Redford & Diehl recorded the percentage of perceptual errors occurring for each target in each position, using an open response design. An analysis of variance over these values revealed that word-initial consonants were perceived with significantly greater accuracy than word-final consonants. Contrasts in word-final preconsonantal contexts were the most difficult to discriminate, returning significantly lower accuracy than either of the two prevocalic contexts. Redford & Diehl maintained that the perceptual advantage of prevocalic position obtained for both place and manner contrasts, although this claim was not substantiated by separate analysis of the two categories. Overall, these studies supported Fujimura et al.'s finding of a perceptual advantage for CV over VC transitions. However, experiments that use natural speech stimuli played exclusively in a forward direction do not permit a strong conclusion that perception itself is asymmetric; differences in response accuracy could reflect an asymmetry inherent in the speech signal, articulatory rather than perceptual in origin.

In total, the experimental results reviewed in this section have converged on the conclusion that for most consonantal contrasts, prevocalic contexts can be considered strong in that they carry more salient perceptual cues than postvocalic positions. The following section shows that this will present a problem for efforts to model child patterns of positional neutralization using the framework of enhanced faithfulness to perceptually prominent positions.

2.3.3 Perceptual asymmetries and child processes of positional neutralization

Children's patterns of positional neutralization appear anomalous from the point of view of a model like the P-map hypothesis, which predicts enhanced faithfulness to perceptually prominent contexts. If the relative perceptual salience of CV versus VC contexts described in the previous section holds for child speakers, children appear to neutralize contrasts in precisely those contexts where they are most perceptually salient, simultaneously preserving distinctions in perceptually weaker contexts. On the other hand, a perceptually motivated model of positional neutralization could still be available for the child pattern if there are substantial differences in the nature of perceptual preferences across child and adult speakers. This possibility was explored by Dinnsen & Farris-Trimble (2008), who argued that child processes of neutralization in strong position could be unified as the consequence of a child-specific perceptual bias favoring word-final over word-initial contexts. This proposal will be discussed in detail in Chapter 3. However, in that chapter experimental results will be presented showing that a child with multiple processes of neutralization in strong position in production exhibited an adultlike perceptual advantage for word-initial over word-final contrasts. In place of a perceptual difference between child and adult speakers, here it will be argued that the child-specific pattern of neutralization in strong position has its roots in articulatory factors specific to unskilled speech-motor control. An overview of this approach is briefly laid out in the following section.

3. Child-specific processes as a reflection of articulatory differences

The preceding sections discussed the challenges faced by efforts to model child-specific processes of neutralization in strong position using constraints borrowed directly from models of adult phonologies. It is particularly puzzling that children's preferential neutralization of contrast in prevocalic contexts contravenes expectations based on the relative perceptual salience of

contrasts across CV and VC environments. Here, it will be argued that child-specific processes can be understood as the natural consequence of articulatory phonetic pressures that are experienced by speakers with limited speech-motor control but not by skilled speakers. In the chapters that follow, it will be shown that articulatory factors play a key role in shaping the three processes of strong neutralization highlighted above, namely positional velar fronting, prevocalic fricative gliding, and regressive consonant harmony. Part of this account of the contrast between child and adult phonologies will rest on the claim that constraints militating for minimization of articulatory effort, which are demonstrably active in adult phonologies, play an especially important role in the phonology of the unskilled speaker. However, the bulk of the difference between child and adult patterns will be attributed to a child-specific pressure to replace discrete articulatory movements, such as an isolated tongue-tip raising gesture, with unitary movements of the entire tongue-jaw complex. This preference to move the articulators as a single unit facilitates motor control by reducing the number of degrees of movement freedom. It also allows the speaker to achieve articulatory targets using motorically simple jaw gestures, minimizing the role of the more complex lingual articulator. However, the use of these simplified articulatory patterns can cause divergence from the adult target form; for example, the child process of positional velar fronting can be analyzed as the consequence of an undifferentiated pattern of linguopalatal contact resulting from unitary gestures of the tongue-jaw complex. These articulatory limitations become inactive over the course of typical motor maturation, predicting the absence of the associated processes from adult phonologies. The articulatory factors posited to play a role in child-specific speech processes are laid out in detail in Chapter 2.

While there is ample evidence of non-equivalent articulatory pressures across child and adult speakers, it is not yet obvious why these differences should give rise to the child bias for neutralization in strong position. In the analyses to follow, it will be shown that asymmetries in child speech can be attributed to phonetic differences in the realization of phonemic targets across initial and final positions. There is considerable evidence that a single phoneme will take on different articulatory properties across different positions in the word or syllable. Early studies by Lehiste (1960, 1961, 1964) demonstrated that word-initial consonants are longer in duration than medial or final allophones. She also demonstrated that properties such as aspiration and flapping differentiate consonant production in initial versus non-initial positions. Subsequent studies have supplemented acoustic results with direct investigation of articulation via electromagnetic articulography, electropalatography, and x-ray microbeam methodologies. These investigations have converged on the finding that word-initial position is "generally associated with tighter articulatory constrictions and with greater stability" relative to non-initial contexts (Krakow, 1999, p. 25). A summary of articulatory asymmetries across initial and final positions is repeated below (Fougeron, 1996, p. 26; cited in Keating, Wright, & Zhang, 2001):

> In initial position, the glottal opening gesture for consonants is longer and greater. Vowels are glottalized or preceded by a glottal stop. Labial muscular activity in initial consonants and vowels is greater. The velum is higher in initial oral and nasal consonants. The tongue is higher and linguopalatal pressure greater in consonants.

The analyses to follow will also draw on asymmetries in timing across initial and final contexts. Evidence from the framework of Articulatory Phonology will be adduced in support of the notion that consonant-vowel transitions are subject to a more stringent timing requirement than their counterparts in the vowel-consonant context (Byrd, 1995, 1996). This asymmetry can

be observed in adult speakers in the properties of domain-final lengthening (Beckman, Edwards, & Fletcher, 1991). Finally, although the analyses of child phonological phenomena pursued below are primarily articulatory in nature, some role will also be granted to asymmetries in perception, notably the greater salience of phonetic cues in CV relative to VC contexts.

It is worth noting that, although these asymmetries are present in the speech of adults as well as children, in adult phonologies they do not give rise to a tendency for neutralization in strong positions. Instead, the enhanced articulatory status of consonants in word-initial position has been invoked to explain their greater ability to resist processes of assimilation and lenition (Ohala & Kawasaki, 1984; Fougeron, 1998, 1999; Lavoie, 2000). Here it will be argued that these same factors can lead to different outcomes in connection with child-specific articulatory pressures. Chapter 4 will pursue an analysis of velar fronting inspired by the phonetically-motivated account put forward by Inkelas & Rose (2003, 2008). Inkelas & Rose suggested that the greater force of articulatory gestures in prosodically strong positions can induce velar fronting in some child speakers, while less forceful gestures in weak positions can more readily be produced faithfully. Here, it will be proposed that velar fronting reflects the child-specific preference for unitary movement of the tongue-jaw complex, which is sensitive to the force of an articulatory gesture. In Chapter 5, the child preference for postvocalic over prevocalic fricative production will be demonstrated to follow from differences in the timing of CV versus VC transitions. It will be seen that an elongated transition is permitted in the latter context, which allows the speaker to produce a slower and therefore less effortful movement of the jaw. This, in turn, permits the child speaker to avoid faithfulness violations that are induced by the need to minimize articulatory effort in the context of the more rapid CV transition. Finally, the discussion of consonant harmony in Chapter 6 deviates from the preceding analyses, invoking motor planning rather that motor execution as the primary force driving phonological neutralization. The regressive bias in child consonant harmony will be demonstrated to follow from general processing principles in an activation/competition model of phonological planning. However, the phenomenon of major place harmony, which is well-attested in child phonology but absent from adult typology, will be analyzed as another consequence of the child preference for jaw-dominated gestures rather than discrete movements of individual articulators. In summary, note that the present account does not make the claim that child grammars literally reverse the definition of weak and strong contexts relative to their status in adult grammars. Instead, child processes of neutralization in strong position emerge when asymmetries that are present in adult as well as child speech (including articulatory enhancement in strong positions and the asymmetrical timing of CV versus VC transitions) interact with child-specific articulatory limitations, most notably the pressure to move the tongue-jaw complex as a single unit.

4. On the incorporation of phonetic factors into phonology

The previous section indicated that child speakers are subject to articulatory pressures distinct from those experienced by adults. One possible interpretation would hold that these child-specific limitations are manifested as performance limitations at the level of motor execution of phonemic targets (cf. Hale & Reiss, 1998). However, it will be argued that the systematic, prosodically conditioned character of child speech processes requires an account invoking phonological grammar rather than accidental deviations in speech-motor control. Here

it will be maintained that child speech processes are the consequence of child-specific phonetic factors expressed through phonological constraints. This is an entirely conventional claim from the standpoint of phonetically-influenced models of phonology, which have argued that models of phonological patterns both within and across languages can be made more satisfactory through the incorporation of phonetic information. If we take the view that phonetic factors are expressed in the phonology, and children are subject to phonetic pressures distinct from those experienced by adults, differences between child and adult phonologies are only to be expected.

Within the framework of phonetically-based phonology, however, there are several distinct perspectives on how phonetic principles can best be incorporated into the grammar. These include models in which the influence of phonetics is exerted only through diachronic changes, models in which the set of possible phonological constraints is limited based on phonetic principles, and models where the phonetic properties of an utterance participate directly in the evaluation of phonological well-formedness. While it will be argued that child-specific processes are most readily modeled using directly phonetic constraints, it is worthwhile for our purposes to compare among these approaches, with special consideration for the choice between phonetically-grounded and direct phonetic approaches to child phonology.

4.1 Phonetic influence through diachronic changes

One perspective on phonetics in phonology holds that the phonetic component exerts its influence only through a diachronic process of phonologization, in which "naturally arising language-specific phonetic patterns are divorced from their phonetic origins and made phonological" (Keating, 1996, cited in Barnes, 2002). This approach is closely associated with works by Ohala (1981, 1990, 1993, *inter alia*) as well as Hyman (1977, 2001), Hale & Reiss (2000), Barnes (2002), Blevins (2004), and Bermúdez-Otero (2007). While Ohala has argued strongly for the incorporation of phonetic insights into phonology, he espouses the claim that the influence of phonetics is indirect, operating exclusively through diachronic changes. He suggests that if two sounds are highly confusable in a particular context, the contrast is likely to become unstable and may be eliminated over time. In Ohala's view, neutralization is the consequence of accidental misperceptions and thus is non-teleological in nature: "variation occurs due to 'innocent' misapprehensions about the interpretation of the speech signal…It does not occur to 'optimize' speech in any way: it does not make it easier to pronounce, easier to detect, or easier to learn" (1990, p. 266). Blevins (2004) has argued in support of Ohala's notion of sound change as the diachronic consequence of innocent perceptual misinterpretations. She contends that the role of phonetic factors must be indirect based on the existence of certain phonetically unnatural sound alternations. These "crazy rules" (Bach & Harms, 1972), which include instances of morphological analogy, rule inversion and rule telescoping, are not predicted in a model where phonetic factors are directly involved in the evaluation of well-formedness.

Despite persuasive evidence that phonetic influences can manifest themselves in phonology through diachronic patterns of sound change, the focus of the present study—the search for child-specific phonetic factors to account for problematic processes in phonological acquisition—would not appear to be compatible with the hypothesis that diachronic change serves as the only interface between phonetics and phonology. This dissertation joins previous analyses (e.g. Pater, 1997; Inkelas & Rose, 2008; Dinnsen & Farris-Trimble, 2008) in arguing that certain child speech processes resistant to conventional phonological modeling can best be understood as the consequence of child-specific phonetic factors. If child phonology does reflect properties of articulation and perception that are unique to young speakers, it will be necessary to

posit a more direct interface between phonetics and phonology in the process of phonological learning. Accordingly, the hypothesis that phonetic factors wield their influence exclusively through the diachronic transmission of language will not be given further consideration in the present investigation.

4.2 Phonetically governed constraint selection

Another means by which phonetic influences could come to be represented in the grammar is through the action of a filtering procedure that limits the set of constraints to be considered for inclusion in the grammar. While this notion is shared with the strictly diachronic analyses discussed above—Hale (2003) described the phonetic component as a "diachronic filter" on phonology—in this case the winnowing of constraints takes place within a single speaker and can thus respond to the immediate phonetic pressures experienced by that individual. Barnes (2002), labeling this approach "Neo-Grounded Phonology," notes that it "holds some of the specter of phonetic detail in phonology at bay while incorporating some of the restrictiveness of the Licensing-by-Cue model into the theory" (p. 8).

Hayes (1999) offers an insightful discussion of the challenges that arise in the effort to create phonetically-based phonological theories. He points out that "A research result in phonetics is not same thing as a phonological constraint…In many cases, the phonetic research that explains the phonological pattern has been done very well and is quite convincing; it is only the question of how to incorporate it into a formal phonology that is difficult" (p. 5). That is, having uncovered a phonetic factor that plausibly motivates some phonological process, we may still be quite far removed from the formal phonological constraint that governs the process. Hayes offers several examples supporting his claim that phonological constraints cannot be conceived of as emerging directly from phonetic patterns.

First, Hayes highlights the contrast between the gradient, variable nature of phonetic processes and the categorical, more constrained character of phonology. He illustrates this claim with the example of processes of postnasal voicing. Voicing neutralization following a nasal consonant is a categorical process in some languages, e.g. Ecuadorian Quechua. Hayes & Stivers (1996) posited that this process has its roots in intrinsic aerodynamic properties of the production of voicing, and they demonstrated that a measurable degree of postnasal voicing can also be observed in a language like English, where it is not regarded as an active phonological process. Hayes emphasizes that the phonetic process in English, which is strictly quantitative, non-neutralizing, and highly variable, contrasts with the categorical phonological process in Quechua. He thus argues that a phonological process like postnasal voicing, while reflecting a phonetic bias, cannot be regarded as emerging trivially from the phonetic component.

Secondly, Hayes makes the point that phonology has a symmetrical nature that is absent from raw phonetic data. He cites the example of aerodynamic factors that influence stop voicing, where the interaction of subglottal and supraglottal pressures favors (a) voicing in the case of more anterior points of constriction (e.g. labials) and voiceless production in the context of more posterior points of constriction (e.g. velars); (b) voiceless production in the context of a closure of longer duration, (c) voiced production in postnasal position, and (d) voiceless production in prosodic positions associated with higher subglottal pressure. These phonetic factors do manifest themselves in phonological systems, as in the case of phonemic inventories with gaps at positions that are disfavored by aerodynamic considerations, notably /p/ and /g/ (Ferguson, 1975; Locke, 1983). It is logically possible that a language might set an absolute cutoff value for the level of aerodynamic difficulty that will be tolerated in the production of voiced stops; this cutoff

value could be superimposed on a contour map encoding the relative difficulty of producing each featural target across a variety of contexts. However, adult phonologies can rarely or never be seen to use an absolute phonetic cutoff of this type. Instead, constraints do reflect phonetic preferences, but they do so only within limits imposed by the need to use simple constraints, which generally operate over symmetrical sections of phonological space. Hayes thus concludes that "the influence of phonetics in phonology is not direct, but is mediated by structural constraints that are under some pressure toward formal symmetry" (p. 11).

Hayes then proposes an algorithm by which phonetic factors can be systematically taken into account in the generation of constraints by children acquiring phonology. He rejects the idea that a full set of constraints is part of the human language endowment, instead taking up Kiparsky & Menn's (1977) suggestion that grammar is constructed anew by each individual learner, with non-pathological individuals converging on the roughly the same approximation of the grammar of the environment. Hayes suggests that speakers draw on their direct experience of phonetic factors, including articulatory difficulty and perceptual confusability. Using this knowledge, speakers can construct phonetically natural constraints through a process of inductive grounding. Hayes's grounding algorithm favors constraints that satisfy the phonetic pressure to minimize articulatory effort. To capture the fact that phonologies appear willing to sacrifice some degree of phonetic effectiveness for formal simplicity, Hayes suggests that constraints emerge as local maxima of effectiveness in a constraint space, where constraints are compared only against their neighbors of equal or lesser complexity. This allows some simple constraints to emerge as optimal even when they do not constitute a perfect match for the contours of phonetic difficulty.

4.3 Direct incorporation of phonetic factors

A final possibility is that phonetics wields a direct influence on phonology, with phonetic values entering into on-line computations of constraint violations. The P-map hypothesis (Steriade, 1999, 2001), discussed in Section 3, is one example of a model in which phonetic detail is incorporated directly into the phonology. This section will focus on phonetic models that address articulatory rather than perceptual factors.

Kirchner (1998) has proposed to account for cross-linguistic generalizations over processes of lenition using a constraint directly reflecting phonetic considerations of articulatory effort. Leniting processes cause a reduction in the degree or duration of constriction for a consonant. Because a large number of processes (degemination, flapping, spirantization, gliding, debuccalization, and elision) fall under this heading, it has been difficult to offer a unified formalism to account for the entirety of the phenomenon. Kirchner argues that all lenition processes can be unified under the effect of a single constraint militating for minimization of articulatory effort, LAZY. Effort can be treated as equivalent to biomechanical energy (Lindblom, 1983; Boersma, 1998); Kirchner posits that the speaker has access to some internal measure of the articulatory effort incurred by a variety of gestures. This may lead the speaker to prefer a smaller gesture over a larger one, such as a non-strident fricative instead of a stop. A stop target between two open vowel configurations, requiring sizable excursions of the articulators, is especially strongly dispreferred by LAZY; this accounts for the greater frequency of lenition in intervocalic consonants. Finally, the elevated incidence of leniting processes in rapid speech can be understood on the hypothesis that LAZY is also sensitive to speech rate, since greater effort is required to produce more rapid movements of the articulators.

Flemming (2001, 2008) has argued that phonological and phonetic representations should be unified in a single level of the grammar. Phonological representations contain very little in the way of phonetic detail, such as the duration of aspiration or the degree of coarticulation between segments. While it was previously assumed that these specifics could be filled in by universal properties of articulation, substantial evidence has since accumulated that phonetic-level effects, including coarticulation, are subject to language-specific variation (Keating, 1985). In response to this finding, we may opt to enrich phonological representations with greater phonetic detail, or we may posit an additional component of the grammar—a phonetic module—that specifies the relevant language-specific processes. It has been typical to assume that the phonetic component is separate from the phonology. However, Flemming argues that since the basic elements of phonological representation are generally phonetic in character, maintaining separate phonetic and phonological levels gives rise to the "peculiar consequence that sound is represented twice in grammar, once at a coarse level of detail in the phonology and then again at a finer grain in the phonetics" (pp. 9-10). Flemming proposes that both phonetic and phonological effects can be modeled with a single set of constraints, with phonological categories derived from scalar phonetic information. He argues that the distinction between category-neutralizing and non-neutralizing phenomena (as discussed by Hayes, 1999, cited above) is determined by the relative balance between effort-avoiding constraints and faithfulness constraints militating for distinct realization of segments. Flemming's unified model of phonetics and phonology makes use of constraints operating over scalar phonetic detail, seen also in Byrd (1996) and Kirchner (1997). Given the incorporation of scalar quantities, the resolution of constraint conflict necessarily takes place in terms of relative weights rather than strict dominance.

Of particular relevance for the discussion to follow is Flemming's (2008) application of direct phonetic modeling in an analysis of coarticulatory fronting of back vowels following a coronal consonant. This process reflects a more anterior placement of the tongue body to facilitate contact with dental or alveolar regions. While some degree of F2 raising is present cross-linguistically for back vowels in this context, languages vary in the extent of coarticulation that takes place. Flemming posits that the universal phenomenon of post-coronal fronting is a reflection of limitations on the speed of articulatory transitions, where the sizable transition from a back vowel to an anterior consonant requires a rapid movement that is difficult for the articulatory apparatus to attain. He suggests that rapid articulatory movements are disfavored by an effort-avoidance constraint, *EFFORT ("Minimize articulator velocity"). He formulates the constraint to respond directly to phonetic values, proposing that the cost of violating *EFFORT be assessed as the square of the magnitude of the transition between two targets, multiplied by a positive constraint weight. Offsetting this markedness constraint are the faithfulness constraints IDENT-V and IDENT -C, whose violations are proportional to the square of the degree of deviation from the target position. Flemming suggests that cross-linguistic differences in the degree of consonant-vowel coarticulation reflect language-specific resolutions to the competing pressures of articulatory effort constraints and perceptually weighted faithfulness constraints. Thus, one phonetic system might place greater emphasis on minimization of articulatory effort, while another might favor faithfulness to the target vowel specification.

It is this approach to phonetically-based phonological modeling that will be pursued in the analyses of child phonological processes in subsequent chapters. The following section offers a brief overview of factors in the child phonological data under consideration that are suggestive of the need for a model sensitive to scalar-level articulatory differences.

4.4 Modeling child-specific processes with directly phonetic constraints

While Hayes argued that languages prefer constraints that are both phonetically sensible and formally simple over complex constraints that maximize phonetic efficiency, in the chapters that follow it will be seen that child speakers can exhibit the opposite preference. In Chapter 4, a case study of one child's acquisition of velar place in word-initial contexts will show that the accuracy of velar production was conditioned simultaneously by a variety of factors, including prosodic context, voiced versus voiceless status of the velar target, other laryngeal activity including pre- and postglottalization, and the presence of another velar target elsewhere in the word. This complex pattern suggests that, at least in this child, phonetic efficiency trumps formal simplicity. It would be highly cumbersome to model the full complement of predictive factors with a set of categorical constraints. By contrast, it will be shown that all of these effects can be modeled as consequences of a single constraint that responds to scalar differences in articulatory force, MOVE-AS-UNIT.

A similar phenomenon will be observed in an investigation of positional asymmetry in the acquisition of fricative manner, discussed in Chapter 5. A single case study will demonstrate that accuracy in fricative production can be conditioned not only by position in the syllable, but also by the height of the following vowel. This pattern with be interpreted as the consequence of an effort-minimization constraint (*EFFORT) modeled on the directly phonetic constraint posited by Flemming (2001, 2008). The sensitivity of this constraint to scalar-level articulatory differences will be reinforced with the finding that gradient differences in F1 height made a near-significant contribution ($p = .07$) to the prediction of fricative accuracy in a logistic regression model. In total, the multiplicity of factors that will be seen to condition child phonological processes, together with the gradient nature of certain effects, favors the direct integration of phonetic pressures into the assessment of constraint violations.

5. Conclusion

Child speech processes that lack counterparts in adult typology pose a challenge for efforts to model phonological acquisition. It was noted that numerous child-specific processes neutralize contrast in prevocalic positions while preserving contrast postvocalically. This is a surprising reversal of adult phonologies' preference to neutralize in weak contexts, and it was demonstrated that efforts to extend the constraints that have been used to model adult processes of positional neutralization lead to incorrect predictions for the typology of mature grammars. The child pattern of neutralization is doubly puzzling in that it appears to contravene the universal preference for enhanced realization of contrast in contexts that carry the most salient phonetic cues.

Here it was argued that child-specific processes are a reflection of differences in the phonetic pressures experienced by child and adult speakers. In a phonetically-based model of phonology, if child and adult speakers are subject to distinct low-level pressures, we can expect differences to manifest themselves in different phonological processes. As the child-specific pressures are eliminated over the course of maturation, the anomalous phonological processes will also be eliminated. The most natural place to look for child-specific phonetic factors is in the articulatory domain, since children's capacity for speech-motor control diverges from that of the

skilled adult speaker in well-known and significant ways. Here it will be argued that the child preference to produce unitary, ballistic movements of the entire articulatory complex lies at the root of multiple child-specific speech processes. In the chapters to follow, this pressure will be invoked as part of the explanation for child processes of velar fronting, fricative gliding, and major place harmony. In this approach, the child tendency to neutralize contrast in strong positions is a natural consequence of asymmetries in the force and duration of articulatory gestures across positions in the syllable. Finally, a comparison was made across approaches to the incorporation of phonetic factors into phonology, and it was argued that the child-specific processes to be described here favor an account sensitive to scalar-level differences in articulation.

Chapter 2. Articulatory maturation and implications for child phonology

1. Child phonological processes as child-specific articulatory limitations

Chapter 1 reviewed a number of child-specific phonological processes that have resisted analysis using constraints drawn directly from models of adult phonologies. This dissertation argues that problematic processes such as velar fronting and fricative gliding can be understood as the consequence of articulatory limitations specific to children, who exhibit a substantially reduced degree of control over speech-motor function relative to adult speakers. If these processes are rooted in motor factors that are eliminated over the course of typical maturation, the lack of comparable patterns in adult phonology is an expected consequence rather than a puzzling discrepancy. The previous chapter also reviewed recent decades of phonological research revealing that our ability to model patterns both within and across languages can be expanded by the incorporation of phonetically motivated phonological principles, such as constraints militating for the minimization of articulatory effort. It is only reasonable to assume that a speaker's response to an effort-minimization constraint is dictated by his own experience of articulatory difficulty, rather than the difficulty experienced by an idealized adult speaker. As a consequence, phonetically sensitive constraints should give rise to different outcomes across child and adult speakers, who face distinct phonetic pressures stemming from anatomical and motor-control differences.

The present chapter will review evidence that child articulation differs from adult speech in qualitative ways that can be understood to contribute to child-specific phonological patterns. Particular emphasis will be placed on findings that child speakers exhibit a diminished capacity for individualized control over discrete articulators. Instead, they tend to move the biomechanically coupled tongue-jaw-labial complex as a single unit, relying heavily on the motorically simple act of mandibular raising and lowering. It will be argued that this preference to move the articulators as an undifferentiated unit is best expressed in the form of a violable phonological constraint whose weight diminishes to near-zero over the course of motor maturation. A role for the principle of mandibular dominance will be identified in each of the three child speech processes that will be investigated over the course of this dissertation. Finally, it will be argued that children's nonstandard patterns of articulation are not reflected in a consistent pattern in adult perception, rendering impressionistic transcription an inconsistent indicator of child phonological processes.

This chapter will conclude with a discussion of childhood apraxia of speech, the diagnostic category applied to the single speech-delayed subject whose phonological processes are investigated in three chapters of this dissertation. It will be argued that children with deficits in speech-motor planning offer an interesting window into the interface between speech-motor control and phonology, with implications for typical as well as disordered development.

2. General principles of speech-motor maturation

This section offers a brief overview of several basic features of immature articulatory control that tend to set child speech apart from adult patterns of production. While not all of these factors will play an active role in the analyses of child-specific phonological processes to follow, a general review of the points of contrast between child and adult speech serves as a

useful starting point. The differences to be discussed fall under four main categories: (1) consistency versus variability in speech production; (2) coordination among articulators and systems; (3) speech rate and duration of speech gestures; and (4) rhythm of speech production. An additional difference, a stability-flexibility tradeoff that governs the capacity for independent control of discrete articulators, will be argued to introduce a qualitative divergence between child and adult phonologies; it will thus be presented separately in Section 3. While all of these factors are presented in separate categories, their interrelation as manifestations of speech-motor skill necessarily results in some degree of cross-category overlap.

2.1 Consistency versus variability in speech production

One of the most robustly replicated findings in the speech acquisition literature indicates that children's productions are more variable than adults'. An often-cited example of children's inconsistent output was offered by Ferguson & Farwell (1975). They described a fifteen-month-old child whose efforts to produce the word "pen" suggested general knowledge of the gestural targets involved but had an extremely variable quality, with ten outputs ranging from [dɛ ^{dn}] to [^{m}bõ]. While some variability is viewed as emerging from the phonological grammar, inconsistent output of the type described by Ferguson & Farwell is most typically attributed to limitations at the level of speech-motor performance. Kent (1992) has argued that the extent of variability in child speech can be treated as an index of motor-control maturity or immaturity. The case study data to be reported in following chapters present no exception to the inconsistent nature of child speech; statistical analysis of developmental trends will thus be used to draw inferences regarding phonological development in children with highly variable outputs.

2.2 Inter-articulator and inter-system coordination

An aspect of articulatory maturation that is closely related to consistency in production is the control of coordination between different articulators and functional systems. Kent (1997) asserts that much of the variability in young children's outputs can be attributed to fluctuations in the relative timing of gestural targets from utterance to utterance. Studdert-Kennedy & Goodell (1992) characterized this type of error as "the tendency for gestures to 'slide' along the time line…into misalignment with other gestures, often giving rise to apparent segments not present in the target word" (p. 9, cited in Kent, 1997). Most of the errors cited by Ferguson & Farwell (1975) reflect this type of difficulty in relative timing. For example, voicing and nasalization errors reflect errors in the coordinated timing of oral articulatory gestures with laryngeal and velar gestures, respectively. In the discussion to follow, voicing and other timing errors will be observed in the output of a case study subject (B, described below) whose laryngeal control appears to have matured in advance of his control of the oral articulators.

2.3 Rate of speech and gestural duration

Another hallmark of immature speech-motor control is slow rate of speech, with increased durations of individual articulatory gestures. Slowed speech rate in children's productions has been consistently documented across numerous studies (Kent & Forner, 1980; Sharkey & Folkins, 1985; Smith & Goffman, 1998; and Goffman, 2004). Smith (1977) demonstrated that both words and individual segments produced by typically developing children between 2;6 and 4;6 had a significantly longer duration than their counterparts produced

by a group of adult speakers. In phonetically motivated models of adult phonology, the velocity of articulatory transitions can be used as an index of articulatory effort. For instance, the effort-minimization constraint *EFFORT is expressed as an injunction to "Minimize articulator velocity" (Flemming, 2001, 2008). In the analyses pursued here, the extended duration of children's speech gestures will be taken as an indication that rapid transitions are penalized more heavily in the phonology of speakers with immature speech-motor control. In Chapter 5, limitations on rapid transitions in child speech will be invoked to account for a child-specific asymmetry in which coda fricatives are favored over onset fricatives. It will be shown that the transition in the coda context is extended in the temporal domain, allowing the child speaker to produce a slower, less effortful movement of the mandible.

2.4 Rhythm of speech production

Related to issues of rate and timing is the rhythm of speech production. While mature speech has an underlying rhythmic organization, there is variation within this rhythm, with alternations between differing numbers of stressed and unstressed syllables. In the earliest stages of speech-motor development, namely babbling, speech has a more strictly rhythmic, repetitive quality. The transition from a simple, fixed rhythm to more flexible control of rhythm mirrors developments in other areas of motor control: children's early limb movements take the form of stereotypic kicking and banging activities, which gradually give way to more refined, directed movements. Children with incomplete or deficient speech-motor control tend to overuse these rigidly rhythmic patterns. Thus, atypical prosody, often with what is described as "excessive-equal stress," is considered a hallmark of immature speech-motor ability. Excessive stress will play a role in our analysis of the phonology of case study subject B, who will be shown to have applied the equivalent of adult speakers' phrase-final lengthening pattern at the level of individual words or syllables.

While each of these articulatory factors will make an appearance in the analyses to follow, it will be argued that a single qualitative difference in speech-motor control makes the greatest contribution to the problematic child-specific processes discussed here. This difference, reflecting the emergence of the capacity for control of individual articulators as distinct from gross movements of the jaw, is reviewed in detail in the following section.

3. Skilled versus unskilled motor action

3.1 The stability-efficiency tradeoff in early motor development

The motor development literature recognizes a qualitative difference between skilled and unskilled control of motor function. In has been demonstrated that in the early stages of development, stabilization of the motor system takes precedence over efficiency of movement. Fletcher (1992) suggests that this transition can best be understood through the example of early locomotion. When children first learn to walk, their legs are stiffly extended, with a high degree of activation of both agonist and antagonist muscles. This rigid posture serves to stabilize the system by eliminating a number of degrees of movement freedom (Turvey, Fitch, & Tuller, 1982). However, postural rigidity comes with a cost: movements are imprecise and have a stereotyped quality, contrasting with the adult's flexible and precisely targeted motor control (Fletcher, 1992). Extensive activation across all of the muscles that act on a particular structure also tends to give rise to extraneous movements in the early stages of motor maturation. Fletcher

illustrates this notion with the example of muscle activity during an infant's crying vocalizations: the cry of the newborn is accompanied by full-body movements such as leg kicking and arching of the spine, while later in development the movements associated with crying are concentrated in the face and neck region.

With a high degree of rigidity and superfluous movement, the child's motor system is less energy-efficient than the adult's. However, this additional expenditure of biomechanical energy is obligatory until the child develops more stable, refined control over the course of motor maturation and practice. Further detail regarding changes that take place in the evolution from unskilled to skilled motor control will be presented in Section 5.

3.2 Mandibular dominance in early speech-motor control

In the context of speech, the problem of too many degrees of movement freedom is particularly acute due to the large number of independent structures (jaw, tongue, lips, velum, glottis), each with its own musculature, involved in the act of articulation. One means of reducing the number of degrees of freedom in the act of speech is to move multiple articulators as a single unit. While this configuration limits the flexibility and precision of a child's speech gestures, it simplifies the motor control problem to the point where the child can execute his first directed articulatory movements. It will be argued that children's limited capacity for discrete control of independent articulators lies at the root of a variety of child-specific phonological processes.

Different articulators challenge children's motor-control capacity to differing degrees. Control of the jaw is motorically quite simple. The mandible is stabilized by a bilaterally hinged joint, which limits the degrees of movement freedom; its relatively large mass also exerts a stabilizing influence (Moore, 2001). By contrast, control of the lingual articulator has been argued to present a particular challenge for the developing motor system (Kent, 1992). The tongue is a muscular hydrostat: lacking an internal skeletal support, it achieves rigidity by contracting around its incompressible core. Kent points out that "gaining motor control over a hydrostat presents some special problems to the young child," who must "learn to control the tongue to meet skeletal, movement, and shaping requirements, often simultaneously" (p. 72). Due to these challenges, the tongue appears as a relatively passive participant in early lingual articulations, with mandible taking the active role in creating linguopalatal contact (Kent, 1992). More generally, children are thought to exploit the biomechanical coupling of tongue, lips, and mandible, controlling the entire system through the action of its most stable component, the jaw. This child-specific preference will be referred to as the *principle of mandibular dominance*. Although mandibular dominance has implications both labial and lingual gestures, for present purposes our attention will be confined to the properties of tongue-jaw coordination in young children's speech. The evolution of discrete control of labial gestures is left as a topic for future research.

Claims of mandibular dominance in the speech of young children have been supported with acoustic studies by Hodge (1989) and Nittrouer (1993), and with articulatory evidence from Green, Moore, & Reilly (2002). Hodge (1989) analyzed spontaneous verbalizations of infants and elicited CV syllable imitations in groups of children aged three, five, and nine years, as well as an adult comparison group. She observed less extensive movement in F2 trajectories relative to F1 trajectories in the youngest subject groups, an asymmetry that was not present in the older child and adult groups. This finding suggests that up-and-down jaw gestures predominate at an early stage of development, with movement in the anterior-posterior dimension emerging at a

later stage. Nittrouer (1993) examined formant transitions in groups of children at three, five, and seven years of age relative to an adult comparison group. While F1 patterns, corresponding with jaw gestures, conformed to an adult standard in the three-year-old subject group, the acoustic correlates of lingual gestures diverged significantly from the adult model in all but the seven-year-old group. Finally, Green, Moore, & Reilly (2002) investigated lip and jaw movements in a study with subject groups representing school-aged children, toddlers, and infants as young as one year of age. Infrared light was shined onto reflective markers placed on subjects' upper and lower lips and chin, and movements were recorded during imitation of the disyllables "papa," "mama," and "baba." Traces of displacement for each articulator across the duration of each word were compared against averaged movement paths for adult speakers. Green et al. reported that even in the youngest group, patterns of jaw movement conformed closely to the adult standard, while upper and lower lip movements showed greater variability and diverged considerably from adult patterns. Green et al. concluded that their results support the hypothesis that "the mandible provides the fundamental patterns of early articulation that form the foundation for the learning of other, more specialized articulations" (p. 67).[1]

3.3 The ballistic-controlled distinction

Closely related to the principle of mandibular dominance is the often-cited distinction between imprecise, holistic speech gestures (*ballistic* gestures) and more precisely targeted articulatory movements (*controlled* gestures). Kent (1992) defines ballistic gestures as "movements of short duration, high velocity, and rapid acceleration and deceleration" (p. 85). Controlled gestures tend to be slower and require adjustments to the articulatory trajectory in what Kent terms the *homing phase*.[2] He notes that the duration of the homing phase varies with the size of the target, such that a smaller target requires a longer homing period (MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987). This criterion places fricatives, which require a precise degree of aperture, in the controlled category; liquids are also classified as controlled gestures. The ballistic-controlled distinction thus offers a speech-motor explanation for the observation that children's phonemic inventories are dominated by stops, with fricatives and liquids emerging later in the course of maturation (Kent, 1992; Hall, Jordan, & Robin, 1993).

Although plosives provide the canonical example of ballistic articulation, it is important to note that there is a spectrum of ballistic and controlled production even within the stop consonant category. For example, Kent (1992) points out that adult speakers produce alveolar stops with a relatively controlled manner of articulation. The articulatory target, an isolated point of contact between the tongue tip and alveolar ridge, is small, and the tongue is bent in a manner that Kent characterizes as requiring a refined level of control over the lingual hydrostat. Kent thus argues that children's early alveolar stops are produced in a different, more ballistic manner:

[1] Elsewhere, it has been argued that the dominant role of the mandible in early speech-motor activity can be understood as an extension of jaw movements associated with primitive motor functions such as chewing, sucking, and swallowing (Fletcher, 1992; MacNeilage & Davis, 2000). However, Moore (2001) argued that this claim does not withstand detailed instrumental investigation, with electromyographic studies revealing that speech and nonspeech mandibular movements, such as chewing, are characterized by rather different patterns of muscular activation.

[2] The ballistic-controlled distinction has its origin in studies of limb and digital movements, with Schellekens, Kalverboer, & Scholten (1984) identifying distinct distance-covering and homing components in finger-tapping gestures.

instead of raising the tongue tip, child speakers bring the tongue into contact with the palate by means of mandibular elevation.

The relation between mandibular dominance and the ballistic/controlled distinction is made more transparent in a study by Edwards, Fourakis, Beckman, & Fox (1999), who collected formant transition data from labial, coronal, and velar consonants produced by typically developing children, children with phonological disorders, and adults. Edwards et al. proposed that steeply sloped F2 transitions correspond with a more ballistic manner of articulation. Children's transition slopes were steeper than adults', and the effect was especially pronounced in the child group with disordered phonology. Particular dissociation between child and adult speakers was noted in the case of lingual consonants. Consistent with Kent's (1992) characterization, the adults' production of alveolar and velar consonants appeared to be relatively controlled, while children's steep transition slopes were indicative of a ballistic manner of production. Edwards et al. proposed that the emergence of controlled lingual gestures depends on the speaker's capacity for independent tongue and jaw movement. While a skilled speaker with discrete control of tongue and jaw gestures can position the tongue slowly and precisely, a speaker with limited articulatory control can only produce rapid, ballistic movements affecting the entire tongue-jaw complex. Following Edwards et al., throughout the following discussion it will be assumed that references to a ballistic manner of articulation can be taken to indicate a diminished capacity for independent control of discrete articulators.

3.4 Undifferentiated lingual gestures

While our discussion thus far has focused on differences in movement patterns across child and adult speakers, this section will reflect on the implications of a ballistic, jaw-controlled manner of articulation for patterns of linguopalatal contact in child speech. It will be shown that a highly ballistic manner of articulation can give rise to the phenomenon of the *undifferentiated lingual gesture,* which has been documented in detail through electropalatographic studies of children with articulatory-phonological disorders. Electropalatography (EPG) has significant potential to expand our understanding of articulatory factors in the speech of young or phonologically disordered children, which poses well-known challenges for acoustic analysis as well as for studies based on impressionistic transcription (Buder, 1996; Amorosa, von Benda, Wagner, & Keck, 1985). In an EPG study of children six to fourteen years of age, Fletcher (1989) demonstrated that the area of linguopalatal contact in consonant articulation declined as a function of increasing age, which he interpreted as an indication that speakers were refining the precision of articulatory placement over the course of development. The "undifferentiated" label refers to gestures that span more than one region conventionally associated with a particular place of articulation, such as palatal/velar as well as alveolar regions of the palate (Gibbon, 1999).

Gibbon (1999) has offered an extensive overview of the phenomenon of undifferentiated gesture production in child speech development. Reviewing several EPG studies of children with articulatory-phonological disorders, Gibbon reported that 71% of children across these samples produced at least some gestures that could be characterized as undifferentiated, and a majority among these children actually used this type of articulation for most consonants. She focuses in particular on the neutralization of coronal and velar place contrasts. In typically developing children, coronal consonants are produced with a "horseshoe-shaped" pattern of closure, with contact in the region of the alveolar ridge and extending down the lateral margins of the palate. On the other hand, some children who neutralize the coronal-velar contrast use a gesture with

midsagittal contact extending from alveolar into palatal and sometimes velar regions, indicating simultaneous elevation of tongue tip/blade and body regions. Characterizing one child's undifferentiated lingual gestures, Gibbon described "almost complete contact between the tongue and the hard palate" with "not only an abnormally high tongue body position but also an abnormally convex tongue body surface shape for an alveolar target" (p. 389).

Gibbon also offers a review of proposed causes of children's undifferentiated patterns of lingual contact, noting that most analyses have attributed the pattern to "current or past motor control difficulties involving the tongue-jaw complex" (p. 392). The most typical approach, which will be adopted here, holds that a diminished capacity for independent control of tongue and jaw movements gives rise to undifferentiated gestures. Howard (1998) put forward a slightly different analysis in which excessive tongue-palate contact was described as the consequence of a habitually high position of the jaw and tongue in child speech. Other analyses of the undifferentiated gesture phenomenon, while not directly invoking the notion of mandibular dominance, also fall under the general heading of diminished control of discrete articulators. Specifically, it has been suggested that undifferentiated lingual gestures reflect a decreased capacity for independent control of different functional portions of the tongue. While mature speakers are capable of independent movement of the tongue tip/blade and tongue body articulators, children with limited articulatory control are reported to have difficulty raising the tongue tip without simultaneously elevating the tongue body (Hardcastle, Morgan Barry, & Clark, 1987; Gibbon, Hardcastle, & Dent, 1995). A related possibility is that children who produce undifferentiated lingual gestures have a specific difficulty affecting the capacity for lateral bracing of the tongue against the margins of the palate, which has been argued to play a crucial role in lingual stabilization (Fletcher, 1992; Stone, Faber, Raphael, & Shawker, 1992). The development of discrete control of tongue tip and tongue body articulators will also be invoked in the analyses of child phonological patterns to follow.

Finally, it has been demonstrated that adult listeners show inconsistent perception of child speech sounds produced with undifferentiated linguopalatal contact (Gibbon, Hardcastle, & Dent, 1995). This finding will be discussed in Section 6 as part of a general reflection on dissociations between the articulatory reality of child speech and the perceptually encoded form reported by adult listeners.

4. Phonological consequences of mandibular dominance

While maturational changes in patterns of articulatory activation and motor control are of interest in their own right, our present focus concerns how these forms might interface with the grammar to give rise to child-specific phonological processes. Section 4.1 reviews reasons to believe that children's speech-motor difficulties play a role in the phonology instead of appearing as purely external performance limitations, while Section 4.2 introduces the constraint that will encode the principle of mandibular dominance, MOVE-AS-UNIT. A subsequent section offers a preliminary overview of MOVE-AS-UNIT effects in child speech. Finally, Section 4.4 discusses the motoric and phonological factors that account for the elimination of MOVE-AS-UNIT effects in the transition to mature speech.

4.1 On the phonological status of mandibular dominance effects

In the analyses to be proposed in Chapters 4, 5, and 6, the immature motor preference for articulatory activation at the level of the tongue-jaw complex will be encoded in a violable constraint termed MOVE-AS-UNIT. However, it has not yet been clearly established that children's avoidance of discrete gestures must be encoded in a phonological constraint. Instead, it could appear as a performance restriction applying over the output of the phonology. This section will review reasons to believe that the child-specific limitation on the control of individual articulators is best expressed through a violable constraint.

First, it should be borne in mind that tongue-jaw dependency in child speech appears as a gradient preference, not a fixed condition on movement. That is, when we speak here of a child whose speech conforms to the principle of mandibular dominance, it is presumed not to be the case that this child has no capacity to move the tongue apart from the action of the jaw. Rather, his speech will reflect a preference for jaw-controlled articulation, with most gestures falling on the ballistic end of the continuum from highly imprecise to highly controlled movements. Even studies of early babbling (MacNeilage & Davis, 1990, *inter alia*) do not indicate that mandibular oscillation predominates to the point where tongue movements play no role whatsoever. As it will be reviewed below, MacNeilage & Davis found that infants were strongly biased to produce consonant-vowel pairs that agree for the major locus of lingual constriction. However, no child produced *exclusively* this type of syllable, indicating that some jaw-independent movements of the tongue were occurring even at this early stage. Furthermore, the preference to move the tongue-jaw complex as a unit can still be discerned in children who regularly exercise independent control of the tongue and the jaw, as evidenced by their largely unrestricted production of consonant-vowel strings with separately specified places of articulation. For instance, both typically developing and phonologically delayed four-year-old children studied by Edwards, Fourakis, Beckman, & Fox (1999) were found to produce lingual stops with a steeper formant transition slope than an adult comparison group. As it will be discussed in more detail below, Edwards et al. interpreted these rapid transitions as indicative of a more ballistic gesture recruiting the entire tongue-jaw complex. To account for these findings, it is essential to acknowledge gradient degrees of tongue-jaw dependency in the course of speech development, a progression that might be expressed using a violable constraint whose rank or weighting can be adjusted over the course of maturation.

However, it is also conceivable that a gradient preference to move the articulators as a unit could emerge from performance limitations external to the phonology. For instance, a purely physical limitation such as lingual weakness could give rise to differing degrees of mandibular dominance across affected speakers. It is often argued that a speech-motor pressure such as mandibular dominance must be incorporated into a phonological constraint in order to capture the systematic character of child speech processes. On the other hand, Hale & Reiss (1998) made the claim that child phonological processes can be understood as the consequence of extragrammatical performance considerations in spite of their non-random nature. They invoked the example of intoxicated speech, which is reported to include processes such as word-final devoicing and deaffrication (Johnson, Pisoni, & Bernacki, 1990). These have the character of phonological substitutions, yet limitations on motor function and processing rate would seem more plausible consequences of alcohol consumption than reranking of grammatical constraints. However, Hale & Reiss's argument has been criticized on the grounds that the systematicity of child speech processes is qualitatively different from the trends that emerge from the speech of

intoxicated persons. Inkelas & Rose (2008) argued that "despite obvious physiological disadvantages," young children exhibit "extremely systematic and well-controlled articulations reflecting their grammatical organization, rather than unwittingly failing through physical disability to articulate the target segments" (pp. 729-730). The present account will adopt the same perspective on the fundamentally grammatical nature of child speech processes, although here the emphasis will be reversed in order to focus on the means by which child grammar accommodates the child's awareness of his own articulatory limitations.

This last consideration leads us to one further reason to believe that children's articulatory limitations are integrated into the phonology rather than remaining as external physical limitations. The phonetically-based model of phonology adopted here includes effort-minimization constraints that favor articulatory actions associated with the smallest possible expenditure of biomechanical energy. For such constraints to be implemented, a speaker must have some internal representation of what is relatively easy versus hard for him to produce. Assuming that speakers already possess some map of articulatory effort, there is no reason to exclude the difficulty associated with producing discrete as opposed to unit-level gestures. In fact, to claim that the difficulty associated with discrete gestures should alone be excluded suggests that children are aware which aspects of articulatory difficulty are permanent and which will be eliminated over the course of maturation. It is doubtful that they would have access to such knowledge. In total, it is desirable to encode children's decreased capacity to produce discrete articulatory gestures in the form of a violable constraint, both to capture the systematicity of child productions and to conform to general assumptions regarding the representation of articulatory difficulty in the grammar.

4.2 Assessing violations of MOVE-AS-UNIT

The following constraint is proposed as the phonological reflex of the child-specific property of mandibular dominance:

(1) MOVE-AS-UNIT: Lingual targets are produced with movements of the tongue-jaw complex.

This constraint's reference to the *tongue-jaw complex* reflects the fact that the tongue is not a completely passive participant even in jaw-dominated gestures. It is assumed that the tongue is stiff rather than flaccid in early lingual articulations. When the child raises the jaw and the tensed oral tongue as a single unit to produce a lingual consonant target, an undifferentiated pattern of linguopalatal contact (cf. Gibbon, 1999) is the predicted consequence. This broad region of closure will play a crucial role in accounting for children's perceptually anomalous lingual stops, most notably in the phenomenon of velar fronting. Thus, in this analysis, high-weighted MOVE-AS-UNIT gives rise to undifferentiated gestures and thus to perceptually deviant productions. However, the reader might ask whether there is not a way for children to move the tongue-jaw complex in synchrony without producing undifferentiated contact. This could be achieved, for instance, by moving the entire tongue-jaw complex while the tongue is held in a fixed posture such that only the tongue tip or the tongue body is raised. However, such a posture would require differentiated activation of distinct functional regions of the tongue, which was noted previously to pose particular difficulty for speakers with immature speech-motor control (Hardcastle, Morgan Barry, & Clark, 1987; Gibbon, Hardcastle, & Dent, 1995). The relation between MOVE-AS-UNIT and undifferentiated gesture production will be explored in greater

detail in Chapter 4, where it will be argued that the rotational component of jaw movement gives rise to a characteristic phasing of closure and release gestures as the tongue makes contact with multiple regions of the palate.

Having already noted that children with an active MOVE-AS-UNIT constraint are not completely deprived of the capacity for lingual movement, it will be important to establish what kind of lingual movements are most likely to remain available in a child whose articulatory gestures are mostly jaw-dominated. It is a general principle of motor control that postural stability must be established before directed movements can be carried out (Duffy, 2005). In the case of the tongue, which lacks internal skeletal support, it is particularly challenging to establish a stable base from which controlled gestures can be executed. However, if the tongue remains close to the supportive structure of the mandible, with the possibility of bracing the lateral margins of the tongue against the lower teeth, it can borrow stability from the jaw. As the lingual hydrostat is moved further away from the mandible, on the other hand, it becomes increasingly challenging to control. Accordingly, it is predicted that discrete lingual gestures with a low articulatory target should be produced earlier and with greater accuracy than gestures with a higher target. This claim will be substantiated with evidence from one child's acquisition of velar place in Chapter 4, where velar gestures associated with a low articulatory target were consistently produced with greater accuracy than more forceful velar gestures. Here we encounter one final question regarding a possible means of satisfying MOVE-AS-UNIT without producing undifferentiated linguopalatal contact. Specifically, if MOVE-AS-UNIT does allow for discrete lingual gestures on a small scale, we might expect that children could raise the jaw partway to the palate and then execute an independent lingual gesture of the acceptable magnitude. In fact, such a mechanism is not predicted to be available to a child speaker with limited speech-motor control. This proposed movement pattern would call for the child to integrate separate distance-crossing and homing phases into a single gesture, yet this is precisely Kent's (1992) definition of the class of controlled gestures, which are hypothesized not to emerge until relatively late in the course of development.

4.3 Phonological manifestations of MOVE-AS-UNIT

This section provides a preliminary overview of MOVE-AS-UNIT effects in child phonology. The role of mandibular dominance in determining the shape of children's babbling and early word productions has been extensively investigated by Davis, MacNeilage and colleagues, whose findings are reviewed in Section 4.3.1. Section 4.3.2 briefly describes the role that will be posited for mandibular dominance in the analyses of three child-specific phonological processes to be discussed in detail in Chapters 4-6 of the present work.

4.3.1 The frame-dominance hypothesis

Davis & MacNeilage have extensively detailed a "frames, then content" (or "frame dominance") theory to account for regularities in the sound patterning of babbling and early speech.[3] They propose that children acquire the *frame* of the syllable, namely a regular open-close oscillation of the mandible, before they acquire specific *content*, which involves mandible-

[3] Davis & MacNeilage stress the value offered by studies of infants' babbling as a source of insight into the capacities and limitations of the speech-motor system at an early stage of development. Information from babbling is particularly relevant in light of the demonstrated continuity between late babbling and early words with respect to multiple properties, including phoneme preferences and timing (Vihman, Macken, Miller, & Simmons, 1985).

independent articulatory configurations that correspond with different consonants and vowels (MacNeilage & Davis, 1990). Thus, children's earliest productions are posited to reflect the action of a passive tongue riding on a rhythmically oscillating mandible, consistent with characterizations by Kent (1992) and Moore (2001) reported above. Independent activation of the tongue is posited to emerge at a later stage, when the infant has acquired some degree of differentiated control over the lingual articulator. The frame-dominance hypothesis predicts that consonant-vowel sequences should be characterized by the cooccurrence of certain properties. Specifically, on the hypothesis that the tongue does not move independently during the oscillatory cycle, the identity of the consonant is highly constrained by the vocalic context. MacNeilage & Davis posited that coronal consonants would tend to co-occur with front vowels in the "fronted frame," and dorsals with back vowels in the "backed frame." Labial consonants, which place no constraint on the tongue, were predicted to co-occur with central or neutral vowels in the "pure frame." MacNeilage & Davis proposed that anterior versus posterior placement of the tongue is determined at the onset of a sequence of oscillations and changes minimally over the course of an utterance.

To test their hypotheses, MacNeilage & Davis (1990) transcribed the productions of one child between 14 and 20 months of age. Their predictions were borne out in this child's utterances, which were characterized by above-chance correspondences between coronal consonant place and front vowels, labial place and central vowels, and velar place and back vowels. (Here, "above-chance correspondence" reflects comparison of the observed frequency against the frequency of cooccurrence that would be expected if vowels and consonants were randomly distributed, scaled by their relative frequencies in the overall corpus.) Davis & MacNeilage (1994) reported similar correspondences between anterior consonants and front vowels and between labial consonants and central vowels in the transcribed babbling of one infant between seven and twelve months of age. Velar consonants were very sparsely attested in this child's output, precluding an adequate assessment of the predicted correspondence between velar consonant place and back vowels. Finally, Davis & MacNeilage (1995) aimed to substantiate the claims of the frame-dominance hypothesis through investigation of a large corpus of babbled speech collected longitudinally from six typically developing infants. Once again, above-chance cooccurrences between coronal consonants and front vowels and labial consonants and mid vowels were observed across all subjects. The predicted correspondence between velar consonants and back vowels was observed in four out of six subjects.[4] Overall, while there is a lack of clarity regarding the proposed correspondence between velars and back vowels, the claims of the frame-dominance hypothesis regarding preferred consonant-vowel cooccurrences have generally been upheld.

A second prediction of the frame-content theory relates to the nature of feature alternations that are expected to occur in children's "variegated" stage of babbling. On the hypothesis that mandibular control precedes lingual control, MacNeilage & Davis suggested that early-emerging variability in babbled strings should stem from adjustments in the height of the mandibular oscillation. Such adjustments can be expected to bring about changes in vowel height and consonant manner. Changes in vowel backness and consonant place, controlled by the lingual articulator, are posited to represent a later-emerging source of variability in babbled

[4] MacNeilage & Davis suggested that the rather weaker association between velar consonants and back vowels could reflect a relatively palatal placement of the tongue in consonants transcribed as velar in some infants. This is consistent with the analysis to be adopted in Chapter 4, where velar fronting will be analyzed as the consequence of undifferentiated linguopalatal contact in connection with jaw-dominated gestures.

strings. In the corpus examined in Davis & MacNeilage (1995), 84% of all differentiated vowel pairs in variegated babbling were distinguished by vowel height rather than backness, significantly more than the proportion that would be predicted if vowels were randomly distributed in accordance with their overall frequency in the corpus. Likewise, the proportion of instances of consonant-consonant variegation that were characterized by a difference in manner substantially exceeded the percentage predicted by chance. Overall, the patterns of variegation reported by MacNeilage & Davis conformed to their predictions based on the frame dominance hypothesis. Their analyses provide evidence that a thorough understanding of child-specific aspects of articulation can extend our understanding of phonological patterning, at least through the stages of babbling and early word production. Below, it will be argued that these factors continue to play an active role in shaping phonological processes through a later stage of development than has previously been demonstrated.

4.3.2 Other phonological reflexes of mandibular dominance

In the literature so far, discussions of the role that mandibular dominance plays in determining children's speech patterns has been limited largely to the context of babbling and early word productions. In the chapters that follow, it will be argued that ballistic movements and undifferentiated patterns of lingual contact can illuminate our understanding of later stages of phonological development.

In Chapter 4, it will be argued that the child-specific process of positional velar fronting can be analyzed in terms of children's limitations on discrete articulatory control. Edwards, Fourakis, Beckman, & Fox (1999) have already speculated that velar fronting is related to the ballistic manner of production in child speech. Analyzing formant transitions in CV contexts in both child and adult speech, they found that children's transitions had a steeper slope than those of skilled speakers; they interpreted this to indicate that children produced more ballistic gestures of the tongue-jaw complex. Interestingly, Edwards et al. found that the most consistently ballistic productions in their data set were elicited from two children who exhibited a pattern of velar fronting. However, they did not elaborate on the nature of the relationship between ballistic gestures and fronted velar production. Inkelas & Rose (2008) argued that the positional nature of velar fronting reflects the fact that gestures are produced with greater articulatory force in prosodically strong positions. They posited that, in the context of their immature articulatory apparatus and limited speech-motor control, children's efforts at prosodically conditioned strengthening cause the region of linguopalatal contact to extend anteriorly into the coronal region. The analysis to be pursued here incorporates elements of both of these accounts. Consistent with Edwards' observation that young or disordered children tend to produce highly ballistic lingual gestures, it will be maintained that velar fronting is a property of children who preferentially use movements of the tongue-jaw complex rather than discrete lingual gestures. These unitary movements of the tongue and mandible will be argued to give rise to an undifferentiated pattern of linguopalatal contact extending from velar into coronal regions, in keeping with the findings reported by Inkelas & Rose. Crucially, it will be demonstrated that the likelihood of undifferentiated production is correlated with the force of the gesture, i.e. the height of the articulatory target.

Chapter 5 will identify a role for mandibular dominance in shaping patterns of fricative production in child phonology. Although sibilant fricatives are typically characterized as belonging to the class of controlled gestures, the preference to use a ballistic manner of articulation can nevertheless be found to influence patterns of production in children who have

already added fricatives to their phonemic inventory. In particular, some children who have acquired postvocalic fricatives appear to experience continuing difficulty with the transition from a fricative to a following vowel. It will be demonstrated that the typical pattern of fricative-vowel coarticulation used by adult speakers requires dissociated action of tongue and jaw, with the jaw lowering to anticipate the position of the vowel while the tongue remains high to maintain frication. This pattern of coarticulation is presumed to be disfavored by child speakers in whom lingual control remains heavily dependent on the action of the jaw. In combination with the effort-minimization constraints discussed in Section 2 above, the pressure to move the articulators in a single unit will be shown to account for an otherwise perplexing child-specific pattern of positional fricative gliding.

Finally, in Chapter 6 it will be argued that mandibular dominance plays a role in creating the child-specific pattern of consonant harmony affecting major place of articulation. While consonant harmony is attested in adult phonologies, it typically operates only between highly similar segments, such as two sibilant fricatives which might be induced to agree for anteriority (e.g. [saʃa] → [ʃaʃa]). Here it will be argued that the adult ban on major place harmony reflects a general dispreference for sequences of identical consonant place; this bias is evident in that sequences of consonants with identical major place occur with lower than chance frequency across lexicons of the world's languages. Repetition avoidance has been argued to have roots in articulatory effort (Rochet-Capellan & Schwartz, 2005; Walter, 2007). When there is alternation between different place gestures, articulation can be made more efficient by anticipating the placement of the next consonant during execution of the present one, but this effort-minimizing coarticulation is blocked when current and upcoming gestures are identical. With effort considerations thus ganging up with faithfulness to block major place harmony, in adult phonology harmony is limited to sequences that were already specified to involve repeated activations of a single major articulator. Crucially, it will be argued that the effort advantage for alternating over reduplicated sequences is not active in the context of young children's articulation. This is because the relevant type of anticipatory coarticulation is largely unavailable in child speakers with an active MOVE-AS-UNIT constraint banning discrete lingual gestures. With alternating and reduplicated consonant sequences on equal articulatory footing in child phonology, the processing advantage for assimilated consonant sequences can be expressed more freely, resulting in more extensive harmony processes.

4.4 The maturational elimination of mandibular dominance

Section 3 noted several changes that take place over the transition from unskilled to skilled motor control. Simple, stereotyped gestures are replaced with flexible movements that are differentiated to reflect the goal of a particular movement. While systemwide rigidity gives early movements a jerky quality, skilled motor control permits smoothly integrated sequences of movements. Extraneous activations are suppressed, and movement becomes efficient. Fletcher (1992) characterizes the transition from unskilled to skilled motor control as predominantly the consequence of practice and repetitive motor experience. He argues that learners attain skilled control through a process of *diversification*, whereby variations on a movement pattern are tried out in the search for the most efficient manner of execution. Repetitive practice may play a crucial role in enabling the diversification stage by allowing a movement sequence to become overlearned, since automatization frees attentional resources for the actor to test out adjustments in the direction or rate of a motion. As the learner arrives at increasingly efficient schemas for motor action, the energy expended in executing a given gesture will decline. In the phonology,

this change can be expressed through a decrease in the weight assigned to constraints that militate for minimization of articulatory effort.

Given our present focus on the role of mandibular dominance in constraining children's articulatory patterns, we are less interested in efficiency than in changes in precision and the number of degrees of movement freedom over the course of development. Some of these developments are influenced not only by motor control factors, but also by anatomical maturation throughout the course of infancy and early childhood (Fletcher, 1992). In the young infant, articulatory movements are tightly constrained because the large, forward-placed tongue fills the oral cavity almost completely (Fletcher, 1973; Kent, 1981; Crelin, 1987). Lingual maneuverability increases as the space occupied by the tongue is expanded by rapid growth at the facial sutures, broadening of the palatal-alveolar process and raising of the palatal vault, and lowering of the tongue and hyoid (Bosma, 1975; Fletcher, 1992). In addition, in early infancy the structures suspending the tongue occupy the same horizontal plane as the tongue itself, restricting motion to an anterior-posterior dimension, as observed in suckling. With the descent of the tongue and hyoid bone, the styloglossus and hyoglossus muscles are enabled to serve their mature function as lingual elevators and depressors (Fletcher, 1992).

Along with these anatomical changes, motor skill development permits the child to exercise increasingly refined control over discrete articulators. In the diversification process described by Fletcher, basic movements such as jaw-raising gestures become highly automatized over the course of repetitive practice. These overlearned sequences then come to represent a stable base from which the speaker can launch more refined movements of individual articulators. It is proposed that this increasing capacity for discrete articulatory control is accompanied by a decrease in the weight of MOVE-AS-UNIT. However, it will be necessary here to account for a contrast in behavior between MOVE-AS-UNIT and the family of effort-minimization constraints, which appear to take divergent paths over the course of motor development. The former is active in young children's phonology, but it appears to cease to play any role after the first few years of development. By contrast, effort-minimization constraints play an active role not only in child phonologies, but also in adult processes such as coarticulation and spirantization. We can account for the contrasting behavior of these two constraint types on the hypothesis that in the transition from child to adult grammar, MOVE-AS-UNIT comes to be outweighed by constraints on the expenditure of biomechanical energy. In the preceding discussion, it was noted that MOVE-AS-UNIT achieves simplicity and stability at the expense of efficiency: children's jaw-dominated gestures involve large movements of a heavy articulator, and the rigid posture of the tongue during movements of the tongue-jaw complex also requires expenditure of biomechanical energy. Thus, as soon as maximizing stability ceases to constitute a heavily weighted imperative in the grammar, the effects of MOVE-AS-UNIT will be blocked by the action of effort-minimization constraints.[5] The hypothesis that MOVE-AS-UNIT >> *EFFORT in child grammar, whereas *EFFORT >> MOVE-AS-UNIT in adult speakers, will be seen to play a role in explanation for the child-specific processes described in the previous section.

5. Perceptual consequences of child articulatory limitations

[5] To ensure that *EFFORT will outweigh MOVE-AS-UNIT in all adult phonologies, we can posit that the weight of MOVE-AS-UNIT acts as index of motor-control advantage for tongue-jaw over lingual movement. As this advantage drops near zero over the course of development, the weight of MOVE-AS-UNIT will become vanishingly small.

The primary focus of this dissertation is the role that articulatory limitations play in shaping child-specific phonological patterns. However, a second major theme has emerged over the course of the present efforts to model phenomena in child phonology, pertaining to the low reliability of impressionistic transcription as an indication of the acoustic and articulatory realities of child speech. Previous research has identified several reasons to view impressionistic transcription, unsupplemented by instrumental studies, as inadequate for the investigation of child phonology. First, transcription in general is limited in the amount of detail it can capture; instrumental analysis is necessary to obtain quantitative phonetic information. Second, an adult with a fully developed phonology is predisposed to impose his own phonemic categories on productions that may not in fact conform to those principles. Weismer (1984) posed the example of an English speaker who listens to Korean speech and hears a two-way laryngeal voiced/voiceless distinction, comparable to the English voicing contrast, when in fact a three-way contrast is represented by speakers of that language. Child speech poses a challenge that is similar in many ways: although the child is approximating adult speech in the target language, the anatomical, motor, and cognitive differences between children and adults are such that child productions are neither articulatorily nor acoustically convergent with adult targets. Thus, while the adult is likely to transcribe a child's productions using segments and contrasts familiar from his own phonology, this transcription may in fact stand at quite a distance from phonetic reality. Finally, studies have revealed high variability and poor inter-rater agreement among trained adult transcribers of child speech (Amorosa, von Benda, Wagner, & Keck, 1985). In short, there are many reasons to believe that a characterization of child speech based on transcription alone will contain distortions and omissions that may obscure crucial details about the underlying processes.

With these concerns in mind, a number of instrumental analyses have been undertaken to gather the precise phonetic data that are omitted from transcription studies of child speech (e.g. Weismer, 1984; Young & Gilbert, 1988; Tyler, Edwards, & Saxman, 1990; Tyler, Figurski, & Langsdale, 1993; Edwards, Gibbon, & Fourakis, 1997; Scobbie, 1998). With surprising frequency, these studies have shown that where the transcriber perceived a categorical error, such as omission of a segment or neutralization of a contrast, instrumental analysis can detect traces of the correct target. For instance, children who produced CVC targets with final consonant deletion were found to maintain an appropriate contrast in vowel length between targets with voiced and voiceless final consonants, suggesting that the "deleted" final consonants were in fact present in the child's plan for production (Weismer et al., 1981). In another well-known finding, children whose initial consonants were described as uniformly voiced were found to make a consistent distinction in VOT between voiced and voiceless targets, although both VOT values fell into the range that adults associate with voiced segments (Maxwell & Weismer, 1982). A meta-analysis of studies of covert contrast has suggested that the phenomenon is widespread, perhaps even representing a characteristic stage in the course of normal phonological development (Scobbie, 1998).

In light of these findings, throughout the present analysis an effort was made to supplement all transcribed results with acoustic instrumental investigations. Discrepancies between the child speaker's output and the form perceived by the adult will play a role in each of the analyses to be offered in the chapters to follow. Covert contrast plays an especially prominent role in the discussion of velar fronting in Chapter 4. Here it will be argued that children's fronted velars are produced using large, undifferentiated areas of linguopalatal contact. Gibbon (1999) reported electropalatographic evidence indicating that children who neutralize coronal-velar

contrasts can frequently be found to produce patterns of closure that span multiple places of articulation. However, adult listeners are inconsistent in their response to these anomalous patterns of production: Gibbon, Hardcastle, & Dent (1995) found that adult listeners transcribed children's undifferentiated lingual gestures variably as having coronal or velar place. It will be argued that velar targets transcribed with coronal place are actually produced with an undifferentiated pattern of lingual contact; the percept of coronal place is a consequence of a gestural phasing that is characteristic of jaw-dominated articulation.

As a final note, findings of covert contrast are sometimes taken to indicate that children's phonological knowledge is more extensive than what their output can reveal. However, it is important to note that perception-production discrepancies can also have the reverse effect, creating the impression of a more mature output system than what the child actually commands. For instance, Li, Beckman, & Edwards (2009) report that English-speaking adults will accept a strikingly wide range of acoustic forms as correspondents of an alveolar fricative target in child speech. A more immediate role for this discrepancy will be seen in Chapter 6, which will review Pouplier & Goldstein's (2005) finding that certain speech errors involving coproduction of speech gestures go undetected in impressionistic transcription. These results will be incorporated in the hypothesis that children with consonant harmony produce a pervasive pattern of gestural coproduction, with only some of these simultaneous articulations reaching the adult listener's threshold for detection.

6. Childhood apraxia of speech

Several of the analyses to be presented in subsequent chapters will draw on longitudinal and experimental data from a single case subject, B, who exhibits significant speech delay with the characteristics of childhood apraxia of speech. The properties of this developmental disorder will be reviewed in Section 6.1, and Section 6.2 will argue that insights for early stages of typical phonological development can be drawn from the patterns of production exhibited by older children with speech-motor deficits. Section 6.3 will introduce case study subject B.

6.1 Characterization of childhood apraxia of speech

Childhood apraxia of speech (CAS; also labeled developmental apraxia of speech or developmental verbal dyspraxia) is a speech sound disorder thought to reflect a diminished capacity for speech-motor planning. The disorder was originally labeled by Yoss & Darley (1974), who saw the condition as analogous to acquired apraxia of speech, a speech deficit stemming from damage to motor-planning centers of the brain. Consensus has since arisen that these two diagnostic categories, despite some commonalities, have rather divergent characteristics. As Kent (2000) points out, we expect different outcomes in the case of a child who builds his phonological system around disordered motor-planning abilities, versus an adult speaker with a fully established sound system that is disrupted by damage to motor centers. Despite its non-congruence with apraxia of speech as described in adults, the label of developmental apraxia of speech has remained relevant, although controversial, as a diagnostic category for speech sound disorders in children.

The notion of praxis (Ayres, 1985) refers to the generation of volitional motor actions; it encompasses selecting, planning, organizing, and initiating movement. Children with childhood apraxia of speech may exhibit deficits in general motor praxis, particularly nonverbal oral praxis (Hall, 2000). Given that speech is a particularly complex motor act, involving precise

sequencing and timing of movements that may span multiple functional systems, it is not surprising to find that children with a generalized motor deficit may also exhibit difficulty with speech production. However, cooccurrence of non-speech motor deficits is generally not considered necessary for a diagnosis of childhood apraxia of speech (Davis, Jakielski, & Marquardt, 1998; Shriberg, Aram, & Kwiatkowski, 1997).

While CAS was originally conceptualized as an isolated deficit affecting motor function, it is now widely acknowledged that children with the characteristic profile of apraxia of speech also tend to show some involvement in the language domain (Crary, 1984, 1993; Aram, 1984). Stackhouse (1992) suggested that the diagnosis of childhood apraxia of speech should only be assigned in the context of a full complex of symptoms, including motor, cognitive, and linguistic deficits as well as errors in speech production. Velleman & Strand (1994) hypothesized that the fundamental deficit in childhood apraxia of speech affects the ability to generate or employ hierarchical frames to organize content into structures of increasing complexity. This type of deficit is hypothesized to pervade the levels of speech-motor planning, phonological organization, syntactic assembly, and organization of language into discourse structures.

The most active area of research on childhood apraxia of speech, and perhaps also the most controversial, is the effort to establish definitive diagnostic criteria that can differentiate CAS from phonological delay of a non-apraxic type. A technical report issued by the American Speech-Language Hearing Association in 2007 concludes that "no one test score or behavioral characteristic has been validated to differentially diagnose CAS (i.e., there are no necessary and sufficient markers)." A number of problems arise in connection with our present inability to identify a feature or set of features that uniquely distinguish childhood apraxia of speech. Efforts to study the efficacy of treatment for CAS, as well further investigations into the nature of the disorder, are compromised by the lack of an accepted criterion for inclusion in a pool of subjects for study. The lack of clear diagnostic criteria also makes it difficult to estimate the prevalence of the disorder in the population. This section will review the leading candidates emerging from ongoing efforts to establish diagnostic criteria to distinguish childhood apraxia of speech from other speech impairments.

A leading proposal is that atypical speech prosody is distinguishing of childhood apraxia of speech. A number of studies have suggested that inappropriate stress, often characterized as excessive-equal or misplaced stress, appears with notable frequency in CAS populations. Shriberg, Green, Campbell, McSweeny, & Scheer (2003) noted that children with apraxia of speech are especially likely to show a pattern of "syllable segregation," in which words or syllables are produced as isolated entities, lacking a smooth transition to the following unit. Prosodic errors of this type are reported to occur with lower frequency in populations of speech-delayed children considered non-apraxic (Shriberg, Aram, & Kwiatkowski, 1997). Perceptual analyses in which listeners were asked to rate the appropriateness of a child speaker's prosody have found that children with apraxia of speech were rated less accurate than either their typically developing peers (Skinder, Strand, & Mignerey, 1999) or children with other types of phonological disorder (Munson, Bjorum, & Windsor, 2003). In both of these studies, however, acoustic analysis failed to return measurable correlates of the perceived prosodic disruptions. Velleman & Shriberg (1999) did not find a qualitative difference in prosodic characteristics between children diagnosed with childhood apraxia of speech and children with general phonological delay or younger children developing typically. Rather than atypical errors like excessive-equal stress, children diagnosed with apraxia tended to make typical errors such as

weak syllable omission. However, they did continue to make prosodic errors long after these had been eliminated from the speech of other groups of phonologically delayed children.

Other traits seen as hallmarks of deficits in speech-motor praxis include distortions and substitutions affecting vowels, with vowel quality thought to be relatively spared in children with general phonological delay (Pollock & Hall, 1991; Davis, Jakielski, & Marquardt, 1998). It has also been suggested that speech errors produced by children with apraxia have a particularly variable and inconsistent quality, versus more predictable error patterns in non-apraxic speech disorders (Dodd and McCormack, 1995; Davis et al., 1998; Forrest, 2003). Variable errors that increase in frequency as the length and complexity of a target utterance increases have been regarded as particularly emblematic of a deficit in speech-motor planning. On the other hand, an investigation of error consistency in apraxia of speech conducted by Betz & Stoel-Gammon (2005) did not support this claim. They found that children diagnosed with apraxia produced more frequent errors than a group of children diagnosed with phonological disorder, but the consistency of error types did not differ between the two groups. They also failed to find a correlation between error frequency and utterance length, although their use of repetitive carrier phrases may have caused the differences in motor-planning complexity across conditions to fall short of the intended level.

Finally, errors affecting consonant production are prominent in children with childhood apraxia of speech. Because children with non-apraxic speech disorders also are commonly observed to produce errors affecting consonants, more detailed characterization of consonant errors in apraxia of speech will be necessary to make this a useful criterion (Jacks, Marquardt, & Davis, 2006). One possibility is that children with apraxia of speech show more frequent consonant omissions, while general phonological delay more characteristically involves consonant substitution errors (Shriberg et al., 1997). Lewis, Freebairn, Hansen, Iyengar, and Taylor (2004) suggested that consonant omission errors are particularly prevalent in childhood apraxia of speech and reflect the need to limit the complexity of syllable structure through processes of cluster simplification or coda consonant deletion. Jacks et al. (2006) also concluded that "consonant errors in CAS are related to syllable-level deficits, namely difficulty constructing syllabic frames for speech production targets" (p. 424).

This section has shown that, in spite of extensive research, there is no consensus regarding the defining characteristics of childhood apraxia of speech. In particular, no diagnostic criterion reliably differentiates childhood apraxia of speech from general phonological delay. The following section will argue that the overlap between these two categories is in a certain sense advantageous for present purposes, since it will make it possible to draw inferences regarding early stages of typical development from older children with a pathology influencing speech-motor control.

6.2 Relevance of apraxia of speech for general phonological development

Having characterized the properties of childhood apraxia of speech as well as the controversies surrounding it, we are now in a position to examine what relevance CAS might have for our general understanding of phonological development. This comes down to a question of delay versus deviance. That is, is childhood apraxia of speech characterized by idiosyncratic patterns that are of relevance only to this specific population, or can we regard the output of children with CAS as analogous to the productions of typical children at a younger stage of development? There are numerous reasons to believe that, even if speech patterns in CAS are not

precisely identical to those of younger typically developing children, the two populations are similar enough that insights from one group can shed light on the other.

In the literature review above, we saw several studies indicating that error patterns in childhood apraxia of speech were qualitatively similar to those exhibited by younger typically developing children or children with a general phonological disorder (Velleman & Shriberg, 1999; Shriberg et al., 1997; Davis et al., 1998). In general, the controversy surrounding the distinction between childhood apraxia of speech and nonspecific phonological delay casts doubt on the notion that CAS is an entirely distinct, deviant category. In this dissertation, children with CAS will be conceptualized as exhibiting a phonological delay in which limitations on speech-motor planning play a substantial role. In these articulatory limitations, they resemble typically developing children in a very early stage of development. Children with CAS thus extend the window of time in which we can observe the consequences of the early, heavily constrained motor system. They also are more amenable to targeted investigations, producing longer and more varied utterances and participating more readily in controlled production and perception tasks than typically developing children with a comparable level of speech-motor ability. Finally, as children with apraxia of speech contend with their speech-motor limitations over a longer period of time, they may be more inclined than younger children to make phonological accommodations for their articulatory difficulties. Thus, while both young typically developing children and children with apraxia of speech might be expected to build their phonologies around their speech-motor limitations, we have an increased likelihood of observing this phenomenon in the CAS population. For these reasons, evidence from childhood apraxia of speech will figure prominently in the investigation of child-specific phonetic factors pursued in this dissertation. Several analyses will draw on case study data from a single child with a diagnosis of CAS whose phonology could be observed to interact with his speech-motor limitations in an interesting way. This subject, who figures prominently in Chapters 3 through 5, is introduced in the following section.

6.3 Case study subject

This dissertation will include a detailed review of several patterns of production and perception exhibited by a single child, B, over a period of approximately seven months between the ages of 3;9 and 4;4. B was given a clinical diagnosis of childhood apraxia of speech at three years, eight months of age. At the time testing was initiated, B's speech was severely unintelligible, even to familiar listeners. Numerous properties of his speech were consistent with the diagnosis of CAS, including simplified syllable structure, distorted vowel quality, and inconsistent articulatory errors that occurred more frequently in the context of longer utterances. Prosodic abnormalities were especially salient in his speech, which conformed to the canonical CAS pattern of excessive and/or inappropriate stress and segmented production in which individual syllables fail to combine smoothly into larger prosodic units. In the chapters to follow, special attention will be given to the processes of velar fronting (Chapter 4) and fricative gliding (Chapter 5) in B's output. Other phonological processes exhibited by B will receive less detailed treatment but were not necessarily less robustly attested; these include contextual voicing (prevocalic voicing and final devoicing), cluster simplification, glide epenthesis in onsetless syllables, and gliding/vocalization of liquids. B's intelligibility and articulatory accuracy improved considerably over the documented period of time, and changes in his patterns of production will be described in the analyses to follow.

B is an endearing and imaginative child whose cognitive and social-behavioral development have followed a normal progression. He also scored within the average range on measures of receptive language ability. When he was initially evaluated, B's expressive language ability was judged to fall grossly within the average range for his age, given certain accommodations for his diminished intelligibility. As his speech grew more intelligible, however, deficits in expressive grammar became more apparent. B's expressive grammatical abilities might best be characterized as falling in the low-average range for his age, a fairly typical presentation for a child with developmental apraxia of speech.

B received regular speech and language therapy from the author, a certified speech-language pathologist, throughout the interval documented in this study. These sessions, featuring B's interactions with the clinician and with his mother, who generally accompanied him to therapy, were recorded and transcribed for analysis. While sessions were in principle meant to be held every week, irregularities in scheduling meant that recordings were ultimately collected on a more nearly biweekly basis. These sessions were conducted in clinic rooms in a hospital setting and were recorded with a portable Sony ICD-SX57 portable recorder. In addition to regular therapy sessions, B participated in three targeted experimental sessions, carried out in his home environment and recorded with a Marantz Professional Portable Solid State Recorder (PMD671). More than twenty-four hours of recorded interactions were ultimately made available for the purposes of this study.

7. Conclusion

This chapter reviewed a number of factors that make speech production a qualitatively different process in child versus adult speakers. It was seen that child speech differs from that of adults along numerous parameters, including the consistency of production, the capacity for coordination among different articulators and functional systems, and the rate and rhythm of speech. However, the analyses to be presented in subsequent chapters will emphasize a single factor related to the emergence of differentiated control over individual articulators. It was argued that in early stages of motor development, the need to simplify motor planning causes the child to move multiple articulators in an undifferentiated unit, minimizing the degrees of movement freedom. Because motor control of the tongue is more complex than movement of the hinge joint of the mandible, early articulatory gestures are characterized by dominant mandibular activity, with a relatively passive role for the tongue. In the chapters that follow, young children's diminished ability to execute discrete lingual gestures will play a prominent role in our understanding of processes of velar fronting, fricative gliding, and major place harmony. The finding that impressionistic transcription can diverge substantially from the acoustic and articulatory reality of child speech will play an active role in the analyses to follow. The last section of this chapter reviewed the distinguishing characteristics of childhood apraxia of speech, a controversial developmental disorder affecting speech-motor control. It was argued that such deficits have the potential to shed light on the interface between speech-motor control and phonology, with implications for typical as well as disordered development. The chapters that follow will thus draw extensively on case study data from B, a four-year-old boy with childhood apraxia of speech, who was introduced in Section 7.3. It will be argued that our understanding of child-specific phonological processes exhibited by B as well as younger typically-developing children can be illuminated through consideration of the speech-motor factors described in this

chapter. With their roots in the particular phonetics of child speech, these processes are expected to fade from the grammar over the course of typical motor maturation; their absence from adult grammars thus ceases to pose a conceptual problem.

Chapter 3. Relating error patterns in perception and production

1. Overview

This dissertation aims to explain the phenomenon of child-specific phonological processes that neutralize contrast in strong position. In the chapters that follow, it will be argued that these processes can best be understood as the consequence of speech-motor limitations particular to the child speaker. However, the present chapter will entertain an alternative hypothesis, whereby children's patterns of positional neutralization are the consequence of perceptual asymmetries. This is in keeping with analyses of positional neutralization in adults as a response to differences in the strength of perceptual cues across different phonetic and prosodic contexts (Jun, 1995; Steriade, 1999, 2001). Of course, the claim that child processes are motivated by perceptual biases faces an immediate challenge in that children tend to neutralize contrast in precisely those contexts that have been found to support the most reliable perceptual cues in studies of adult perception. Thus, additional assumptions regarding the perceptual preferences of child listeners are required. This approach was adopted by Dinnsen & Farris-Trimble (2008), who argued that children's patterns of neutralization in strong position can be given a unified account under their proposal of a child-specific pattern of perceptual preference. On this analysis, children are like adults in that they tend to neutralize contrasts in production in the environment that has the lowest perceptual prominence; the difference is that in child speakers, non-initial contexts have greater perceptual prominence than initial contexts. Dinnsen & Farris-Trimble's proposal will be reviewed in detail in Section 2.

Section 3 will test Dinnsen & Farris-Trimble's hypothesis that children who neutralize contrasts in strong position in production are responding to a perceptual advantage for contrasts in word-final contexts. The experiment reported here is a single-subject design assessing nonword discrimination in B, introduced in the previous chapter, who exhibited multiple processes of pattern of neutralization in strong position. It will be demonstrated that B perceived word-final contrasts with lower accuracy than word-initial contrasts, contra the predictions of Dinnsen & Farris-Trimble's hypothesis. This strongly suggests that the motivation for B's patterns of neutralization in strong positions were motivated by articulatory rather than perceptual considerations.

However, the hypothesis that child-specific speech processes are articulatory in origin is complicated by the finding that B's perceptual performance was not in all respects congruent with adult patterns. It will be shown that B perceived the coronal-velar contrast with significantly lower accuracy than two contrasts that he differentiated appropriately in production. This result will be presented in connection with a body of previous evidence indicating that children with phonological disorders tend to exhibit parallel deficits across the domains of perception and production. Up to the present, there has been a paucity of evidence to indicate whether deficits in perception give rise to errors in production, or whether the reverse relationship holds. Both possibilities will be entertained in the effort to account for B's pattern of performance across perception and production tasks. The hypothesis of a primary perceptual deficit will be rejected on the grounds that it fails to account for B's differential discrimination of coronal-velar and coronal-labial pairs, which have been found to have similar intrinsic discriminability in studies of adult perception. Instead, it will be argued that children's perceptual deficits can be influenced by the same forces of markedness that tend to cause neutralizations in production. Because

formalization of this proposal is both complex and peripheral to the primary focus of this dissertation, implementation of a model in which production-oriented markedness constrains perception will be deferred to a discussion of directions for future investigation in Chapter 7.

2. A perceptual account of neutralization in strong position

The first chapter of this dissertation reviewed evidence that adult languages tend to permit a wider range of contrasts in strong relative to weak positions.[6] On the well-supported hypothesis that positional neutralization in adult phonology reflects the generally greater perceptibility of phonetic contrasts in strong contexts, it is surprising to find that many processes in child phonology neutralize contrasts in strong positions while preserving the same contrast in weak contexts. These child-specific processes not only call for constraints that are unattested in adult phonologies, but also suggest that children do not respond to the relative perceptibility of contrasts in the same way as adults. It is possible that child phonology encodes discriminability differences in the manner of the adult P-map, but factors separate from perception, such as constraints on articulation, prevent these perceptual sensitivities from surfacing. An alternative possibility is that children have different perceptual sensitivities than adults, translating to a qualitatively different P-map in the child speaker.

This latter possibility was explored by Dinnsen & Farris-Trimble (2008). They referred to children's tendency to neutralize contrasts in strong position as a "prominence paradox," since it violates the implicational relationship (the "prominence hypothesis") whereby a language that preserves contrast in a weak position must also preserve it in a strong position. Chapter 1 reviewed several of Dinnsen & Farris-Trimble's examples of child speech phenomena that might be viewed as violations of the prominence hypothesis. Having established empirical support for the claim that some children preferentially preserve phonemic contrasts in weak contexts, Dinnsen & Farris-Trimble argued that neither positional faithfulness nor positional markedness constraints, as conventionally formulated, will suffice to capture the child pattern of performance. Dinnsen & Farris-Trimble suggest that the puzzle posed by child processes of neutralization in strong position can be resolved by positing a child-specific pattern of perception that favors word-final over word-initial contexts. This hypothesis is related to the demands of word segmentation faced by young children in the process of building a lexicon; psycholinguistic evidence for the proposal is reviewed below. To encode this perceptual reversal in the grammar, Dinnsen & Farris-Trimble proposed that the distinction between strong and weak contexts emerges as the product of ranked constraints, INITIALPROM and FINALPROM, repeated in (1).

(1) Prominence-assigning constraints (Dinnsen & Farris-Trimble 2008, p. 288):
   a. INITIALPROM: The initial constituent of a syllable, foot, or prosodic word must be prominent.

[6] Traditionally, strong positions are word- or foot-initial, while weak contexts are non-initial. Steriade (2001) argued that strong versus weak contexts are more accurately differentiated by the strength of perceptual cues, which does not always align with the initial/non-initial distinction. For all of the constrasts to be considered here, however, the traditional definition will be sufficient. Dinnsen & Farris-Trimble (2008) acknowledge the challenge posed by Steriade's observation that the distinction between strong and weak positions varies with the phonetic contrast in question, but they do not offer an elaborated means of incorporating this result into their model.

b. FINALPROM: The final constituent of a syllable, foot, or prosodic word must be prominent.

When INITIALPROM dominates FINALPROM, as in adult grammars, domain-initial contexts are treated as prominent; under the reverse ranking, it is domain-final contexts that have the status of prominent positions. In place of positional faithfulness constraints, Dinnsen & Farris-Trimble suggest that asymmetries in neutralization can be captured through constraints that militate for faithfulness to prominent positions, as seen in (2).

(2) ID-PROM: "Corresponding segments in prominent contexts must have identical voice, place, or manner features."

Tables 1-2, repeated from Dinnsen & Farris-Trimble (p. 290), illustrate the operation of the prominence-assigning constraints in a process of positional neutralization; the process depicted here is velar fronting in initial position. The prominent domain of each form is indicated in bold. Candidates (a) and (c) in each tableau are ruled out because they assign prominence to the initial domain, violating FINALPROM, which in child speakers is posited to be high-ranked. When the velar place feature is located in the non-prominent (initial) domain, the faithful candidate is ruled out by the markedness constraint banning velar place. Thus, Table 1 illustrates that fronting applies to a velar target in word-initial position. However a velar target in word-final position occupies a prominent context and is protected by the high-ranked faithfulness constraint ID-PROM[place].

Table 1. Place contrast is neutralized in a word-initial (non-prominent) context.

/kɔ b/ 'cob'	FINALPROM	ID-PROM[place]	INITIALPROM	*k[place]	ID[place]
a. **k**ɔ b	*!			*	
b. kɔ **b**			*	*!	
c. **t**ɔ b	*!	*			*
d. ☞ tɔ **b**			*		*

Table 2. Place contrast is preserved in a word-final (prominent) context.

/bʊ k/'book'	FINALPROM	ID-PROM[place]	INITIALPROM	*k[place]	ID[place]
a. **b**ʊ k	*!			*	
b. ☞ bʊ **k**			*	*	
c. **b**ʊ t	*!				*
d. bʊ **t**		*!	*		*

With the assumptions stated previously, Dinnsen & Farris-Trimble's model succeeds in deriving the positional properties of a child-specific process such as velar fronting. However, the problem for adult typology is not immediately solved by positing separate constraints for initial and final prominence, since it remains necessary to explain why there are no adult languages that rank FINAL-PROM above INITIAL-PROM. Dinnsen & Farris-Trimble propose that in the initial, default ranking of a child's phonology, FINAL-PROM dominates INITIAL-PROM, but FINAL-PROM is necessarily demoted as children experience a change in perceptual sensitivity over the course of subsequent development. To support this claim, Dinnsen & Farris-Trimble cite experimental

evidence that younger children are more responsive to the content of the rime of a syllable, whereas older children respond preferentially to the content of the syllable onset. For example, Brooks & MacWhinney (2000) reported that five-year-old children exhibit stronger priming effects when the prime and target word have matching rimes, while older children were more effectively primed by a match in onset position.[7] Similar evidence was adduced from the results of a nonword repetition study investigating two groups of children aged 2;6 and 3;6 (Coady & Aslin, 2004). Coady & Aslin found that both groups of children were sensitive to the frequency of phonemes in nonword targets, repeating nonwords with greater accuracy when they contained high-frequency phonemes. However, when they used stimuli that were matched for frequency in the rime but had onsets of differing frequency, only the older group of children showed sensitivity to this distinction. This was taken to indicate that the younger children generated holistic representations of nonword targets and did not encode the segmental contrast in onset position. Dinnsen & Farris-Trimble have suggested that the emergence of fine-grained representation of onset consonants corresponds with the shift from final to initial prominence. Further, they note that the transition from holistic to detailed representations is regarded as a consequence of vocabulary growth: as phonological neighborhood density increases, more detailed representations are required to differentiate between adjacent items. Dinnsen & Farris-Trimble maintain that because this transition is motivated by vocabulary growth, and vocabulary size will only continue to increase over the course of development, there will never be a motivation for reranking FINAL-PROM and INITIAL-PROM. Accordingly, "the ranking of these constraints essentially becomes fixed with onsets remaining prominent in fully developed languages" (p. 288).

While it will ultimately be argued that there are more effective ways to capture children's patterns of neutralization in strong position, there is intuitive appeal to Dinnsen & Farris-Trimble's claim of a child-specific pattern of perception favoring word-final contexts. The notion that children pay particular attention to the ends of words has been advanced in previous literature (Slobin, 1973; Echols & Newport, 1992; Velleman, 1996; Aslin, Woodward, LaMendola, & Bever, 1996; Aslin, 1999). This claim is often linked to the observation that infants and young children face the task of word segmentation, i.e. identifying where the boundaries between words fall when many of the forms they hear are not yet represented in their lexicon. Aslin (1999) argued that children segment words most reliably in utterance-final contexts. Children's greater sensitivity to the ends rather than beginnings of words may be related to psycholinguistic processing constraints, such as the advantage for recently processed material (Aslin, Woodward, LaMendola, & Bever, 1996). On the assumption that children do devote particular attention to the ends of words, it is reasonable to suppose that they perceive word-initial contrasts less well, leading to possible neutralization in initial position.

At the same time, there are numerous questions to be asked regarding both the mechanism of and the motivation for Dinnsen & Farris-Trimble's proposal of a maturational shift in perceptual prominence from final to initial contexts. In particular, there seems to be a problematic conflation of the prominence of the entirety of the rime with the prominence of individual segments in coda position. It is entirely reasonable to suppose that young children should perceive the rime, the most prominent portion of the syllable, more accurately than an

[7] It is unclear why FINAL-PROM should be playing an active role in the performance of Brooks & MacWhinney's group of typically developing five-year-olds. Processes of neutralization in strong position, including consonant harmony and velar fronting, are typically eliminated when children are around three years of age (Grunwell, 1981), suggesting that the children in the study should already have undergone the posited reversal in prominence.

individual segment in onset position. However, to account for a child-specific process such as velar fronting, which preserves featural contrast in a coda consonant while neutralizing in onset, it is necessary to assume that individual coda consonants have a enhanced perceptual status at a time when onset consonants are not reliably encoded. This claim is not supported by studies of infant perception. Jusczyk, Goodman and Bauman (1999) reported that 9-month-old infants were sensitive to similarities in word-onset position, but not in word-final contexts. Similarly, Zamuner (2006) found that 10-month-old infants were not able to discriminate word-final contrasts, but they were able to discriminate the same contrasts presented in word-initial position. Thus, it is unclear that Dinnsen & Farris-Trimble's hypothesis regarding the prominence of the rime is an appropriate model for a child who preferentially preserves featural contrasts in coda position. Experimental results in the following section will demonstrate that a child who neutralized contrast word-initially in production exhibited the reverse pattern in a perception task, discriminating word-initial contrasts with greater accuracy than equivalent contrasts in word-final position.

3. Experimental Investigation of Perception and Production

3.1 Purpose of experiment

Despite some concerns regarding the specific implementation of Dinnsen & Farris-Trimble's proposal that child-specific phonological processes reflect a child-specific pattern of perception, the hypothesis that children pay greater attention to contrasts in word-final contexts merits further investigation. The experiment to be reported here explores the relation between perceptual and production abilities in a single subject with atypical speech production. The subject of this investigation was B, the four-year-old child diagnosed with childhood apraxia of speech whose characteristics were laid out in the previous chapter. While childhood apraxia of speech is viewed as a disorder primarily affecting speech production, there have been reports of concomitant perceptual difficulties in childhood apraxia (Groenen, Maassen, Crul, & Thoonen, 1996). Indeed, over the course of B's therapy, there was an accumulation of qualitative evidence that his difficulties were not limited to production, but also affected perception and discrimination of phonemic contrasts. The experiment reported here tests the hypothesis that at least some of the properties of B's errors in production would be found to co-occur with parallel deficits in perception.

3.2 Methods

3.2.1 Participant

The data reported here were collected from B over a series of three sessions, which took place at the ages of 4;2.23, 4;3.6, and 4;5.2. B's speech at the time of this investigation was severely unintelligible. Processes that were active in his phonology at the time of the experiment included velar fronting in prosodically strong positions, contextual voicing, cluster simplification, and gliding/vocalization of liquids. Processes of glide replacement and glide epenthesis affecting prevocalic fricatives, which will be discussed in detail in Chapter 5, were in the process of being eliminated from B's productions.

At the outset of this discussion, it is worth making note of Dinnsen & Farris-Trimble's comment that if "there are cases where a child might, for example, merge one contrast in initial position and merge a different contrast in final position…it would be necessary to modify our proposal" (p. 303). B would appear to represent just such a case. When B was around three years, nine months of age, he consistently neutralized fricative-glide and coronal-velar contrasts exclusively in initial position. At the same time, he neutralized all place of articulation contrasts for oral stops in final position only. Thus, B's pattern of production poses an immediate challenge for the final prominence hypothesis; in the results to be presented below, it will be seen that his perceptual biases also fail to conform to the predictions of the proposal.

3.2.2 Stimulus generation

A nonword discrimination task was designed to offer a fine-grained measure of B's perceptual abilities. In this task, B heard pairs of monosyllabic nonwords embedded in a carrier-phrase context ("I can say *word a*. I can say *word b*.") These pairs were either identical or differed by a single segment, and B was instructed to indicate whether the words he heard were the same or different. The nonword targets employed in this task were carefully matched for their phonological properties. Properties that were controlled in stimulus generation included the position in the word of the target contrast, the place and/or manner features involved in the contrast, the voicing of the target segments, and the presence or absence of a potentially harmonizing consonant, as described below. Stimulus words were additionally controlled for phonological neighborhood density. All of these properties of the stimuli will be described in detail in this section.

In light of Dinnsen & Farris-Trimble's (2008) proposal that neutralization in strong position reflects young children's selective attention to contrasts in non-initial positions, a primary goal of this experiment was to test the influence of word-initial versus word-final position on the accuracy of contrast detection. The monosyllabic stimuli used in this experiment were balanced to include equal numbers of items in which the target featural contrast was located in word-initial onset versus word-final coda position, as illustrated in (3). An exception to this balanced presentation was made for one contrast, fricative versus glide manner, which was tested in initial position alone. Thus, the total number of items with a contrast in initial position was greater than the number of items with a contrast in final position. Following Dinnsen & Farris-Trimble (2008), it was hypothesized that contrasts in word-final position would be perceived with greater accuracy than contrasts in word-initial position.

(3) a. Contrast in word-initial position: [**t**ug]—[**k**ug]; [**b**ɛ ŋ]—[**d**ɛ ŋ]; [**j**ɪ ʃ]—[**z**ɪ ʃ]
b. Contrast in word-final position: [woʊ **d**]—[woʊ **g**]; [dʒ u**t**]—[dʒ u**p**]

A second hypothesis investigated the features that differentiate the members of a stimulus pair. Previous research, which will be reviewed in detail in Section 5 of this chapter, has suggested that children who characteristically neutralize some contrast in production tend to have difficulty perceiving that same contrast (Hoffman et al., 1985; Raaymakers & Crul, 1988; Rvachew & Jamieson, 1989; Whitehill, Francis & Ching, 2003). Based on these findings, it was posited that B would perceive contrasts that he neutralized in production less accurately than contrasts he produced faithfully. Three contrasts were studied as part of this experiment: coronal

versus velar place, coronal versus labial place, and fricative versus glide manner, as shown in (4).

(4) a. Coronal versus velar place: [**k**æŋ]—[**t**æŋ]; [**d**ɪz]—[**g**ɪz]; [jeɪ **k**]—[jeɪ **t**]
b. Labial versus coronal place: [**t**ob]—[**p**ob]; [gʌ **d**]—[gʌ **b**]; [kɔɪ **p**]—[kɔɪ **t**]
c. Fricative versus glide manner: [**j**ɪʃ]—[**z**ɪʃ]; [**s**uk]—[**j**uk]

The three contrasts represented in (2) were chosen to reflect differing degrees of accuracy in B's output. At the start of the experiment, B consistently neutralized syllable-initial velars and coronals in the direction of coronals (e.g. [doʊ] for *go*, [du] for *do*), although he made an appropriate velar-coronal distinction in coda position (e.g. [dʌk] for *duck*, [nʌt] for *nut*). The fricative-glide contrast was of interest because B had recently begun to produce this contrast faithfully in careful speech; four to six months before the first testing session, B consistently neutralized word-initial fricatives and glides in the direction of the palatal glide (e.g. [joʊ] for *sew*, [joʊjoʊ] for *yoyo*). In the first testing session, only coronal-velar and fricative-glide pairs were presented. However, B's discrimination of stimulus pairs in the first session was poorer than had been anticipated, and in an effort to elicit a larger number of correct discrimination responses, the stimulus set was expanded to include coronal-labial pairs, which were never observed to be neutralized in B's output. Inclusion of the coronal-labial contrast was also important to ascertain whether B could successfully detect any single-feature contrast, since his discrimination of coronal-velar pairs was extremely low, whereas the fricative-glide contrast, which he perceived more accurately, has the advantage of differing by several features. It was predicted that B would discriminate coronal-labial pairs with the highest accuracy, while coronal-velar pairs would be associated with the lowest accuracy in discrimination.

A third factor controlled in the creation of stimulus materials was the voicing feature of the target contrast. While it is not clear that voiced versus voiceless status should impact the discriminability of place contrasts, it might be hypothesized that the stronger consonant burst in the production of voiceless plosives would create a perceptual advantage for voiceless over voiced stops. To control for a possible effect of voicing, target contrasts in stimulus pairs were evenly divided between [+voice] and [-voice] specifications, as illustrated in (5). Note that once again, there is nonuniformity in the stimulus set stemming from the category of fricative-glide contrasts. Because the glide member of these pairs is redundantly voiced, only the fricative member could be manipulated for the factor of voicing. This asymmetry will be kept in mind in the discussion of results in Section 6. Abstracting away from this complication, it was predicted that voiceless targets would be associated with more accurate discrimination than voiced pairs in B's performance.

(5) a. Voiced targets: [gaʊ **d**]—[gaʊ **g**]; [tʃɛ **d**]—[tʃɛ **g**]; [**z**ʌg]—[**j**ʌg]
b. Voiceless targets: [**k**ʌv]—[**t**ʌv]; [kɔ i**p**]—[kɔ i**t**]; [**s**æl]—[**j**æl]

A fourth factor that was controlled in stimulus generation pertained to the identity of the non-target consonant in a stimulus pair, such as the non-target velar in the pair [**z**ʌg]—[**j**ʌg] or the labial fricative in the pair [**k**ʌv]—[**t**ʌv]. Because even nonlocal phonetic context may influence the discriminability of segments, an effort was made to control for the possibility of interaction between target and non-target consonants in the discrimination task. This possibility was coded based on the presence or absence of an environment for assimilation via consonant

harmony. Consonant harmony, which will be described in detail in Chapter 6, involves long-distance assimilation of consonants, typically with respect to place or manner features. It is possible that the motivation behind child consonant harmony is at least partly perceptual. For instance, a consonant produced in a context for harmony, such as a coronal onset preceding a velar coda, might tend to be neutralized to velar place because coronals and velars in this environment are less perceptually distinct than in a non-harmonizing context. In this case, we would expect consonants in an environment for consonant harmony to be more difficult to discriminate than consonants in a non-harmonizing environment. Examples illustrating the hypothesized influence of consonant harmony are presented in (6).

(6) a. Coronal-velar contrast: [**t**i**g**]—[**k**i**g**] (Predicted percept: [kig]—[kig])

b. Labial-coronal contrast: [**t**oʊ **b**]—[**p**oʊ **b**] (Predicted percept: [poʊ b] — [poʊ b])

c. Fricative-glide contrast: [**s**ʌ **ʃ**]—[**j**ʌ **ʃ**] (Predicted percept: [sʌ ʃ]—[sʌ ʃ])

For present purposes, environments that were defined as potentially harmonizing included a coronal-velar or a coronal-labial pair occurring opposite a velar (e.g. [**t**ig]—[**k**ig]; [gʌ **b**]—[gʌ **d**]), as well as a coronal-labial pair opposite a labial (e.g. [**t**oʊ b]—[**p**oʊ b]). Likewise, environments for manner harmony were created within the set of fricative-glide targets, with five out of ten glides occurring with a final fricative that could potentially serve as a trigger for fricative manner harmony (e.g. [**s**ʌ ʃ]—[**j**ʌ ʃ]). While all of these contexts for harmony were treated as equivalent in the analysis reported below, it is important to note that previous research has indicated that different combinations of consonants participate in harmony with differing degrees of strength. Harmony from a velar trigger to a coronal target tends to apply with greater frequency and persist until a later stage of development than harmony from a velar trigger to a labial target or from a labial trigger to a coronal target (Pater & Werle, 2001, 2003; Pater, 2002). In addition, the present analysis does not distinguish between environments for harmony based on the word-initial versus word-final status of the potentially triggering consonant, but it is known that harmony operates more robustly in a regressive direction, i.e. from a final trigger to an initial target (Pater & Werle, 2001, 2003; Pater, 2002; Goad,1997, 2004). Meanwhile, assimilation of a glide target to a fricative trigger is an entirely different type of harmony affecting manner rather than place of articulation. While the relative frequencies of manner harmony and place harmony are not known, the latter process is described in the literature with much greater frequency. In spite of these complications, it was hypothesized that perception of a given featural contrast in an environment for consonant harmony would be decreased relative to perception of that contrast in a non-harmonizing environment. The differences across various types and directions of consonant harmony described here could be expected to emerge as interactions between harmony and syllable position or featural contrast, or as a three-way interaction among all three.

A final factor that was controlled during stimulus construction was phonological neighborhood density, which has been demonstrated to influence phonological processing. Swingley & Aslin (2007) demonstrated that children were significantly less successful in learning novel words that were phonological neighbors of familiar words than nonwords that were not neighbors to any words in the child lexicon. If one of the nonwords used in the present study was a phonological neighbor of a familiar word, it might be assimilated to that familiar

target; for instance, a nonword [tɔ g] might be perceived as *dog*. A word misperceived in this way could differ by more or fewer features than the intended nonword, either enhancing or obscuring the target contrast. Thus, nonwords were chosen that were not neighbors to any high-frequency words that were likely to be familiar to children.[8]

A neighborhood density calculation algorithm was used to compare frequency-weighted neighborhood density across nonword stimuli. Frequency counts derived from written corpora were deemed inadequate to model the familiarity of words to young child speakers. Instead, frequency counts were extracted from the child-directed speech portion of the Providence corpus of child speech (Demuth, Culbertson & Atler, 2006), available as part of the CHILDES online database. The Providence Corpus contains approximately 363 hours of spontaneous speech interactions recorded from six English-speaking mother-child dyads in the New England region, followed longitudinally when the children were approximately one to three years of age. The orthographic forms of words retrieved from the corpus were paired with their phonetic transcription using the Carnegie Mellon University Pronouncing Dictionary, version cmudict.0.7a (Carnegie Mellon University, 2007). To eliminate nonword forms from this somewhat noisy corpus, the wordlist was additionally converted to DISC transcription format and compared against wordforms attested in the Celex corpus (Baayen, Piepenbrock, & van Rijn, 1993). The resulting database contained 8,135 words in transcription. The file containing the transcribed pronunciation and the child-directed frequency of each word in the database was then used as the input to a neighborhood density calculation algorithm (Albright, unpublished Perl script). For each target nonword, the algorithm located all phonological neighbors in the input corpus. Neighbors were real words at a one-step difference from the nonword target, including single-segment deletions, additions, and substitutions. The algorithm then computed the neighborhood density of each item, weighted by frequency in the child-directed corpus. Stimuli were adjusted until there was no significant difference in frequency-weighted neighborhood density across the following comparisons: control (match) versus experimental (mismatch) pairs, initial versus final, coronal-velar versus fricative-glide, coronal-velar versus labial-coronal, fricative-glide versus labial-coronal. Table 3 lists the mean and standard deviation of the number of neighbors and the frequency-weighted neighborhood density for each subset, as well as the results of Student's *t*-test for the abovementioned comparisons.

Table 3. Comparison of frequency-weighted neighborhood density across stimulus categories

Target	Mean Number of Neighbors (SD)	Mean Frequency-Weighted Neighborhood Density	*T*-test over weighted neighborhood

[8] Some of the "nonwords" included in the task were real words that were unlikely to be familiar to child speakers, such as *gape* or *sop*. All such words that were included in the stimulus set had a frequency of zero or one in the Providence corpus of child-directed speech (Demuth, Culbertson & Atler, 2006).

		(SD)	density
Control (Match)	11.7 (5.4)	32.4 (17.6)	p = 0.80
Experimental (Mismatch)	11.9 (4.8)	33.3 (15.6)	
Initial	11.5 (5.2)	33.2 (18.4)	p = 0.93
Final	12.0 (4.8)	32.9 (14.8)	
Coronal-Velar (T-K)	12.2 (5.0)	34.4 (16.3)	T-K vs P-T, p = 0.59 T-K vs S-J, p = 0.78 P-T vs S-J, p = 0.32
Labial-Coronal (P-T)	11.4 (4.6)	32.1 (15.8)	
Fricative-Glide (S-J)	11.2 (5.2)	30.8 (16.2)	

In addition to the phonological variables described above, the date of data collection was expected to be a significant predictor of B's performance. Fluctuations in attention might create non-uniformity across several sessions; we might also expect some level of improvement in B's performance as he became more familiar with the testing task. More pertinently for present purposes, between the second and third sessions B began to show increased accuracy in the production of the coronal-velar contrast; while he rarely was fully successful in replicating the adult contrast, he made a discernable effort to differentiate these sounds in his own output. It was hypothesized that the awareness of contrast signaled by these efforts in production would be associated with a greater capacity for discrimination in later sessions relative to earlier sessions. Specifically, it was predicted that there would be a significant difference in B's ability to differentiate coronal and velar pairs between the first session, when he neutralized this contrast completely, and the last session, when he made an active effort to produce these targets as distinct. A summary of independent variables considered in the perception task, with the corresponding null and experimental hypotheses, is presented in Table 4. A total of 40 experimental stimulus pairs were recorded, but one pair was discarded prior to implementation of the experiment due to insufficient recording quality. The complete list of experimental stimuli used is reported in Appendix A.

Table 4. Summary of independent variables and hypotheses

Independent Variable	**Levels**	**Null Hypothesis**	**Experimental Hypothesis**
Age at Testing Session	4;2.23 4;3.6 4;5.2	Perceptual abilities remain constant over time.	Contrasts are perceived more accurately in later sessions.
Position in Word/ Syllable	Onset Coda	Contrasts are perceived equally well in initial and final position.	Contrasts are perceived with greater accuracy in final than in initial position (following Dinnsen & Farris-Trimble, 2008).
Featural Contrast	Coronal-Velar Fricative-Glide Coronal-Labial	All contrasts are perceived equally well, independent of their status in production.	A contrast that is actively neutralized in production is perceived with lower accuracy than a contrast realized faithfully.

Voicing	Voiced Voiceless	Contrasts are perceived equally well in the context of [+voice] or [-voice] segments.	Contrasts between [+voice] segments are perceived less well than contrasts between [-voice] segments.
Consonant Harmony	CH environment Non-CH environment	Contrasts are perceived equally well in harmonizing and nonharmonizing environments.	Contrasts are perceived less well in an environment for harmony than in a non-harmonizing environment.

Along with the contrasting stimulus pairs described above, pairs of identical nonwords were created to serve as the control in the discrimination task. These items were constructed to match the basic phonetic properties of the experimental targets. Thus, a set consisting of five identical pairs with initial coronal stops and five pairs with initial velar stops was created as a control for the set of ten pairs with contrasting coronal and velar sounds in initial position. Examples of control stimuli are presented in (7).

(7) a. Control for coronal-velar contrast: [lɪ g]—[lɪ g]; [dik]—[dik]
b. Control for labial-coronal contrast: [kɛ b]—[kɛ b]; [tʌ d]—[tʌ d]
c. Control for fricative-glide contrast: [zɛ p]—[zɛ p]; [jam]—[jam]

Like experimental stimuli, control stimuli were divided equally between voiced and voiceless target consonants. However, environments for consonant harmony could not be systematically represented in the control pairs due to the limited number of permissible nonwords of the shape KVK (with initial and final velar consonants) or SVS (with initial and final fricative consonants). Instead, all mismatch stimuli in a harmonizing environment were balanced with matched pairs that shared the same vowel environment as the mismatch items. The complete list of control stimuli is presented in Appendix B.

3.3 Experimental design

Stimuli were recorded by a female adult native speaker of English (northern California dialect) who was naïve to the purpose of the experiment. The speaker was instructed to use a slow rate of speech and a child-directed pattern of intonation, and feedback was provided during practice trials to encourage her to produce target words with an extended duration and to release the final consonant. Target nonwords were produced in the context of a carrier-phrase, *I can say WORD*.[9] Stimuli were elicited via a randomly ordered written list of nonce words presented in conventional English orthography. The complete stimulus list was recorded three times across two sessions. All sound stimuli were digitized with a 44.1 kHz audio sample rate and 16 bit audio sample size and were rms-equalized and saved as AIFF files. All tokens were then reviewed by the experimenter, who chose two of out of three recorded tokens for each target that

[9] The carrier phrase was used to encourage phonological encoding and discourage reliance on a more superficial level of auditory discrimination. In addition, carrier phrases served to discourage B from repeating the stimulus words, as he had been observed to do in a pilot version of the study, since his own unfaithful productions might disrupt his capacity for accurate perceptual discrimination.

were judged to be most clearly articulated and best matched with respect to suprasegmental properties. Stimuli were then spliced together in match or mismatch pairs. In mismatch pairs, the order of presentation (e.g. coronal first or velar first) was randomized across items. A silent interval .5 seconds in duration was inserted between the two carrier phrases in a pair.

The total set of items was divided into two lists in pseudorandom order. In the first and second testing sessions, B heard one list per session. In the third session, when the task had become well-practiced, B completed both lists in a single session. Sound stimuli were presented using Praat software (Boersma & Weenink, 2008) on a Toshiba Satellite M305D laptop operating Windows Vista. The auditory stimuli were presented through portable speakers at a comfortable listening volume determined by the subject. Before playing each stimulus, the experimenter gained B's attention using one or more verbal or visual prompts. B was cued to respond by placing a small toy on one of two pages to indicate whether the words he had heard were the same or different. The page indicating a "same" response depicted two identical smiling faces, while the "different" response page featured non-identical faces. To allow the experimenter to interact with B and encourage him to respond without cueing a particular target, the experimenter and B faced one other on opposite sides of a low cardboard barrier. This barrier allowed eye contact between B and the experimenter while blocking the experimenter's view of his response. Because the experimenter was unable to see B's response, a third party (B's mother, who was naïve to the specific design and purpose of the task) was enlisted to record the page on which B placed the toy in response to each stimulus pair. The accuracy of the recorded response served as the sole dependent variable in the investigation.

Before experimental stimuli were presented, several measures were taken to ensure that B was able to understand the task. First the experimenter verbally presented two pairs of real words in isolation (e.g. *cat—cat*; *ball—doll*) and cued B to choose either the "same" or the "different" page. The experimenter then presented two real-word pairs in the carrier phrase context (e.g. *I can say bake—I can say make*). Computerized presentation of stimuli was then introduced. Five sample pairs, including both real words and nonwords in both match and mismatch conditions, were presented before continuing on to experimental stimuli. Finally, the cardboard barrier was introduced for the last three sample pairs presented by the computer. Feedback on the accuracy of B's responses was provided throughout this process, along with targeted encouragement (e.g. prompts to choose only one response page). This process was abbreviated slightly in the second and third sessions, when B demonstrated familiarity with the task.

4. Results of the perception experiment

4.1 Influence of task difficulty and response bias

In the first two testing sessions, B's performance on the discrimination task was suggestive of a highly limited capacity for discrimination of minimally differing nonwords, particularly those containing a coronal-velar contrast. For instance, as it will be seen below, B gave no correct responses to coronal-velar mismatch pairs during the first experimental session. However, it would be misguided to infer from this finding that B possessed no sensitivity to the coronal-velar phonemic contrast at this stage of development. After all, he did demonstrate some control of the coronal-velar distinction in production at the onset of testing, although the contrast was realized only in coda position. For a proper understanding of B's diminished performance on

the present task, it will be necessary to consider the influence of task difficulty and response bias, which are separate from the primary factor of interest, namely perceptual sensitivity.

Several factors combined to make this experimental task fairly challenging for a child with B's limitations. Because target words were embedded in a carrier phrase in this experiment, B was prevented from comparing stimuli at a superficial level of phonetic detail; phonological encoding is necessary to hold the target words in memory and compare them. B exhibited a greater capacity for coronal-velar discrimination in an informal task where minimal pairs were presented with no carrier phrase. Prior to the administration of the experiment reported here, B had been engaged in a simple discrimination task in which he was asked to choose one of two objects in response to single words spoken by the experimenter (e.g. *tea, key*). Once familiarized with this task, B was able to differentiate a coronal-velar pair with ceiling-level accuracy. B's contrasting performance in contexts with and without a carrier phrase suggests that he may possess relatively preserved phonetic-level discrimination while experiencing difficulty at the level of phonological encoding. However, the other variables distinguishing the two tasks prevent any strong conclusions regarding the locus of B's perceptual difficulty.

Since small children are less than ideal experimental subjects, it is important to consider the role of response bias in the pattern of performance observed here. As a preliminary indication of bias, B's responses across all sessions and stimulus types (including both match and mismatch conditions) were categorized as hits, misses, false alarms, and correct rejections. Because the ability to perceive segmental contrast was the parameter of interest, a hit was defined as correct detection of a contrast; a miss as a failure to detect contrast; a false alarm as a reported contrast where none was present; and correct rejection as an accurate report of no contrast. The total number of responses, across all conditions and including both control (match) and experimental (mismatch) stimuli, was 128. Table 5 suggests that B was biased to report the absence of contrast. He produced only two false alarm responses, correctly providing the "same" response for the remaining 48 matched-pair stimuli. However, his frequent use of the "same" response also extended into mismatch stimuli, and he incorrectly identified 33 out of 78 experimental pairs as having no contrast.

Table 5. Frequency of response categories, experiment-wide

	Mismatched Stimuli e.g. [tug]—[kug]	**Matched Stimuli** e.g. [kug]—[kug]
"Different"	45 (Hit)	2 (False Alarm)
"Same"	33 (Miss)	48 (Correct Rejection)

Because B exhibited a response bias, it would be ideal to report his performance using the d-prime statistic, which identifies separate components of sensitivity and bias in a response pattern. However, this approach could not be adopted because it was necessary to exclude control (match) trials from the comparison of B's accuracy across stimulus conditions. This step had to be taken because matched pairs of control stimuli, unlike mismatch pairs, could not be classified into a unique category. Consider a matched stimulus pair such as [zɔ id]—[zɔ id]. This pair was generated as a control for the coronal-velar contrast in word-final position, such as the pair [kɔ ik]—[kɔ it]. However, it could also be counted as a control for the initial fricative-glide contrast (e.g. [zɔ in]—[jɔ in]), as well as for the coronal-labial contrast in word-final position (e.g. [kɔ ip]—[kɔ it]). Furthermore, it is not possible to target a particular position in the syllable in control stimuli; if B gave the response "different" to the control pair [zɔ id]—[zɔ id], we have

no way of knowing whether he was responding to the coda consonants, the onset consonants, or something else altogether. Thus, assigning control items into a single category for the purpose of statistical analysis would be in some measure arbitrary and hence undesirable. Fortunately, B's responses to control stimuli were uniform across the various categories represented in the experiment. Thus, for the purpose of the statistical analyses reported below, all control (match) trials were excluded, and accuracy was calculated as the ability to detect contrast when contrast was present.

4.2 Statistical analysis

The results of the nonword discrimination experiment were analyzed using logistic regression. B's accuracy in detecting phonemic contrast when a contrast was present served as the dependent variable (1 = correct detection of contrast, 0 = failure to detect contrast). The independent variables were the five parameters identified above, namely featural contrast, position of contrast, consonant harmony environment, voicing, and session date.

Table 6 presents the results of the logistic regression analysis. The significance of each factor was determined using the likelihood ratio test on the residual deviance statistic, with terms added sequentially to the model in the order indicated. Results significant at the $p < .05$ level are marked in bold. In this model, the factors of session, syllable position, and featural contrast emerged as significant predictors of discrimination accuracy. In addition, the logistic regression revealed significant interactions between syllable position and consonant harmony and between featural contrast and voicing.

Table 6. Results of logistic regression analysis, nonword discrimination task

Factor	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	***p* > |Chi|**
Session	2	25.6	75	80.7	**<.000**
Syllable Position	1	9.8	74	70.9	**0.002**
Featural Contrast	2	18.7	72	52.3	**<.000**
Voice	1	0.06	71	52.2	0.80
Consonant Harmony	1	2.3	70	49.9	0.13
Session : Position	2	4.0	68	45.9	0.14
Session : Featural Contrast	3	1.9	65	44.0	0.60
Session : Voice	2	1.2	63	42.8	0.55
Session : Harmony	2	2.9	61	40.0	0.24
Position : Featural Contrast	1	0.0	60	40.0	1.0

Position : Voice	1	0.27	59	39.7	0.61
Position : Harmony	1	5.2	58	34.5	**0.02**
Featural Contrast : Voice	2	8.7	56	25.9	**0.01**
Featural Contrast : Harmony	2	0.0	54	25.9	1.0
Voice : Harmony	1	0.14	53	25.7	0.70

However, in the discussion of independent variables in Section 3.2.2, it was noted that the factors of syllable position, voicing, and consonant harmony were not uniform across the three sets representing coronal-velar, coronal-labial, and fricative-glide contrasts. Recall, for example, that a uniform label was applied to contexts for consonant harmony, irrespective of the segments participating in the harmony process or the direction of the posited assimilation. One means of dealing with these discrepancies is to examine interaction effects involving the factors in question. For instance, a significant interaction of syllable position with consonant harmony, as reported above, may reflect the differing strengths with which consonant harmony applies in a progressive versus a regressive direction. For the factor of voicing, however, the discrepancy between stop place categories and the fricative-glide category is more problematic, since only one member of the fricative-glide pair could be manipulated for voicing. Given the non-equivalent definition of the voiced-voiceless contrast across the two cases, it is not meaningful to compare the effect of voicing on fricative-glide discrimination with its effect on stop place discrimination. For this reason, the logistic regression analysis was additionally run with the set of fricative-glide stimuli excluded. The results of this analysis are presented in Table 7. In fact, Table 7 shows that the results of this analysis were effectively equivalent to the results of the analysis computed over the full data set. Significant main effects of session, syllable position, and featural contrast continued to emerge, and significant interactions of syllable position with consonant harmony and featural contrast with voicing were still attested. Given the equivalent behavior of both versions of the analysis, the discussion to follow will draw on the full data set containing fricative-glide as well as stop place pairs.

Table 7. Results of logistic regression analysis with fricative-glide contrast excluded

Factor	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	***p* > |Chi|**
Session	2	27.1	55	53.3	**<.000**
Syllable Position	1	4.4	54	48.9	**0.04**
Featural Contrast	1	11.4	53	37.5	**0.001**
Voice	1	0.0	52	37.4	0.84
Consonant Harmony	1	0.5	51	36.9	0.49
Session : Position	2	4.1	49	32.8	0.13
Session : Featural Contrast	1	0.0	48	32.8	1.0
Session : Voice	2	0.3	46	32.5	0.87
Session : Harmony	2	1.1	44	31.5	0.59
Position : Featural Contrast	1	0.0	43	31.5	1.0

Position : Voice	1	0.2	42	31.3	0.66
Position : Harmony	1	4.6	41	26.7	**0.03**
Featural Contrast : Voice	1	8.5	40	18.2	**0.004**
Featural Contrast : Harmony	1	0.0	39	18.2	1.0
Voice : Harmony	1	0.5	38	17.7	0.46

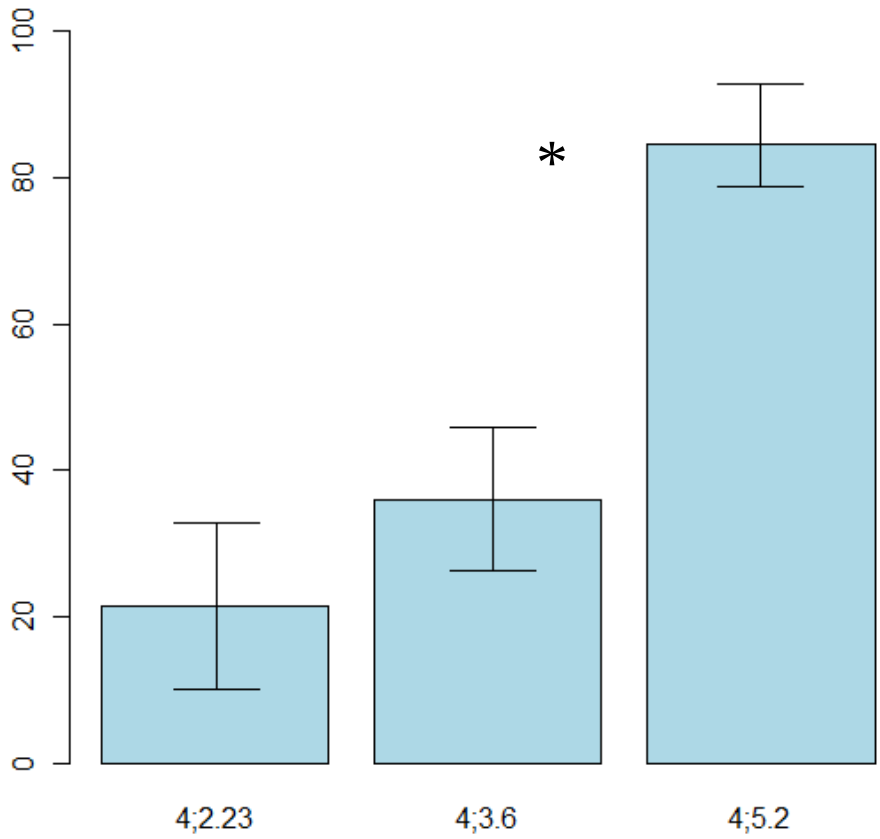
4.3 Discussion of factors conditioning discrimination accuracy

This section will offer a detailed review of each of the factors found to influence B's accuracy in the nonword discrimination task. As noted previously, the figures to follow will represent only the percent detection of contrast when contrast was present, with control (match) conditions excluded.

4.3.1 Session

The factor of testing session emerged as a significant predictor of B's accuracy on the discrimination task. Figure 2 shows that his performance improved over time. Post-hoc comparisons showed that the difference in performance between the first two sessions did not reach significance, whereas the third session was associated with significantly greater accuracy than the first two sessions. In Figure 1 and all graphs to follow, error bars indicate standard error.

Figure 1. Percent discrimination accuracy by testing session (chronological age)



As noted previously, several factors can be presumed to have contributed to B's difference in performance across sessions. First, a subject's performance could be expected to improve over successive sessions as he becomes increasingly familiar with the experimental task. Second, fluctuations in a subject's alertness and concentration might give rise to differences in performance across testing sessions. In B's case, although all testing sessions were held at the same time of day, his level of attention and compliance was qualitatively judged to be lower during the second session relative to the other two testing dates. However, B was able to participate appropriately in the experimental task given redirection and reinforcement, and it was estimated that the influence of behavioral variables on his performance during this session was relatively minor.

Finally, in the case of a child subject, we can entertain the possibility that increasing performance across sessions is a reflection of grammatical maturation. In the present experiment, the first two testing sessions occurred in rather close proximity to one another, taking place when B was 4;2.23 and 4;3.6, respectively. Given the small amount of elapsed time between these two dates, a significant degree of maturation would not be anticipated. On the other hand, the third session was conducted at a rather later date (B's age 4;5.2) in response to evidence of a change in B's grammar related to the production of coronal and velar targets. During the first two sessions, B's production of coronal and velar targets was perceptually judged to be completely neutralized. Shortly before the third session, although B still did not produce the coronal-velar contrast in a target-appropriate fashion, he did make a discernable effort to realize a distinction between these targets. His increased awareness of the coronal-velar contrast, as evidenced by this change in production, is hypothesized to have contributed to his improved discrimination accuracy in the

final session. However, the results of the present experiment are inconclusive with regard to the proposed relation between perception and production accuracy. While the reasoning above creates an expectation for a significant interaction between testing session and target contrast in the perception task, Table 7 showed that no such interaction was present. On the other hand, statistical analysis of this interaction was problematic due to the absence of data for the labial-coronal contrast in the first session and ceiling effects for fricative-glide and labial-coronal pairs in the last session. Figure 2 allows for visual inspection of the interaction of featural contrast with session date. Note that the first testing session features only a single bar representing discrimination of fricative-glide pairs. Labial-coronal pairs were not presented in this session, as noted above, whereas coronal-velar pairs do not appear because they were discriminated with 0% accuracy.

Figure 2. Percent discrimination accuracy by featural contrast, divided by session

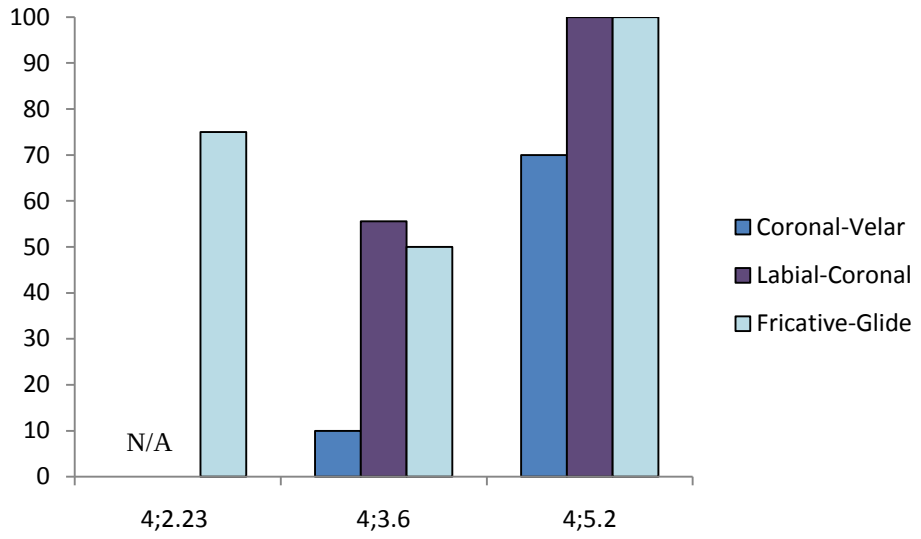
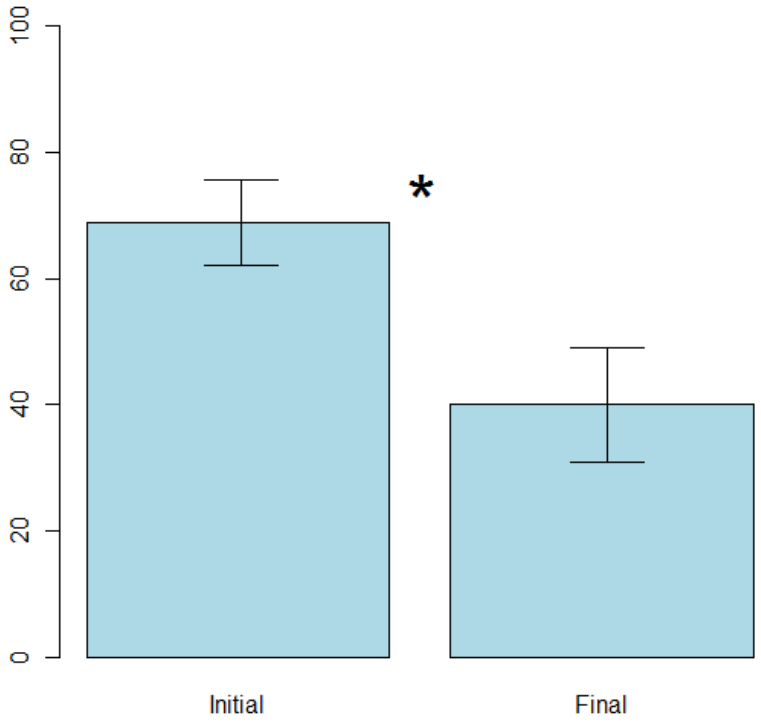


Figure 2 shows that although no coronal-velar contrasts were detected in the first session, the fricative-glide distinction was perceived with fairly high accuracy. The labial-coronal contrast was introduced in the second session. As noted above, B's overall performance in this session was fairly low, a finding possibly related to a diminished level of attention on this date. The third session is notable for substantial improvement across all contrasts. Discrimination of coronal-velar pairs made a striking jump from 10% to 70% accuracy. However, ceiling effects in B's discrimination of labial-coronal and fricative-glide pairs prohibit comparison of the extent of his gains across featural contrasts. Thus, while it is speculated that B's striking gains in coronal-velar discrimination were tied to his improved accuracy in producing this contrast, the present data do not allow firm conclusions to be drawn on this subject. The relationship between perceptual and production knowledge of a phonemic contrast will be explored in greater detail in Section 5 of this chapter and in Chapter 7.

4.3.2 Position in syllable/word[10]

Occurrence in word-initial versus word-final position was found to be a significant predictor of variance in the logistic regression analysis (p = .002). Figure 3 shows that B detected featural contrasts in word-initial position with significantly greater accuracy than contrasts in word-final position.

Figure 3. Percent discrimination accuracy by position in the syllable, all data



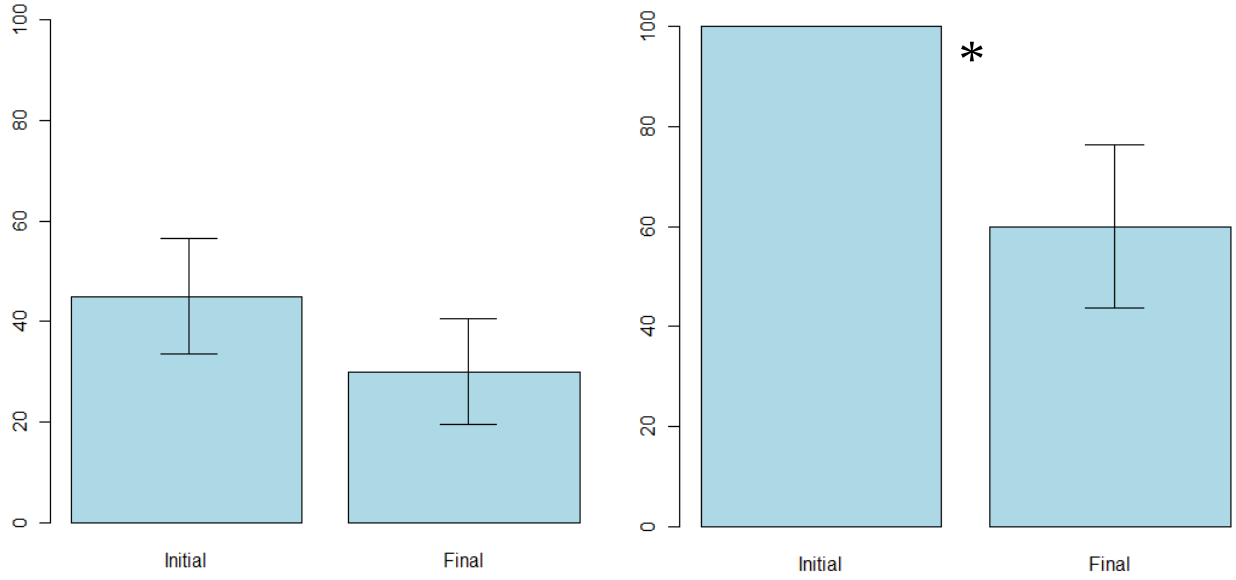
However, in light of our previous observation that the three contrasts tested were not represented equally across initial and final contexts, it will be essential to examine the interaction of syllable position with featural contrast. Recall that in initial position, there were ten coronal-velar contrasts, ten fricative-glide contrasts, and four labial-coronal contrasts, while final position was represented only by ten coronal-velar contrasts and five labial-coronal contrasts. This raises the possibility that discrimination accuracy was lower for word-final contrasts simply because this set was loaded with coronal-velar pairs, which were associated with the lowest accuracy among featural contrasts. In fact, there was no significant interaction of syllable position and featural contrast in the model reported above (p = 1.0). The factor of initial versus final position did participate in a significant interaction with the factor of consonant harmony. This interaction will be attributed to the particular properties of consonant harmony and thus will be discussed in connection with that factor in Section 4.3.4.

Figure 4 offers visual support for the independence of syllable position and featural contrast. For both coronal-velar and coronal-labial comparisons, word-initial position was associated with greater accuracy than word-final position. This difference did not reach

[10] Because only monosyllabic nonwords were utilized, syllable-initial/final and word-initial/final have equivalent status throughout this discussion.

significance in the case of the coronal-velar comparison. However, Student's *t*-test did reveal a significant difference between initial and final positions in the labial-coronal comparison (p = .04). Standard error could not be calculated for discrimination of labial-coronal pairs in word-initial position due to a ceiling effect. These findings indicate that decreased discrimination of contrasts in word-final position should not be regarded as an artifact of the greater representation of coronal-velar contrasts in this context.

Figure 4. Percent discrimination accuracy by position in the word, divided by featural contrast
a. Coronal-velar contrast b. Labial-coronal contrast



Thus, the finding that B discriminated phonemic contrast with greater accuracy in word-initial relative to word-final position can be considered robust in spite of differences in the representation of target contrasts across positions in the syllable. B's pattern of performance is consistent with our understanding of perceptual asymmetries in adult listeners, who demonstrate greater sensitivity to consonant-vowel transitions than vowel-consonant transitions (Fujimura, Macchi, & Streeter, 1978). This finding is especially striking in light of the fact that the subject of this study consistently neutralized coronal and velar sounds in word-initial but not word-final position. The present results thus provide evidence against Dinnsen & Farris-Trimble's hypothesis that children engage in processes of strong neutralization because they perceive contrasts more accurately in word-final than in word-initial position. Instead, B exhibited neutralization in strong position in production in spite of a perceptual bias in the opposite direction. It might be argued that B, at age 4, is older than the group of children typically associated with the hypothesized constraint ranking FINAL-PROM >> INITIAL-PROM. However, his chronological age is inconsequential in light of the fact that he was actively producing patterns of neutralization in strong position of the type discussed by Dinnsen & Farris-Trimble. Given the asymmetry between B's biases in production and perception, we reject a perceptual explanation for his pattern of neutralization in strong position. Instead, the present findings strongly suggest an articulatory motivation for B's neutralization of the coronal-velar contrast in strong positions. Chapter 4 will analyze this velar fronting pattern in terms of child-specific articulatory limitations. For the moment, it is concluded that the present results do not support

Dinnsen & Farris-Trimble's proposal of a child-specific pattern of perception that favors word-final position.

4.3.3 Featural contrast

Figure 5 represents percent correct detection of contrast for coronal-velar, fricative-glide, and labial-coronal pairs, collapsed across other variables.

Figure 5. Percent discrimination accuracy by featural contrast

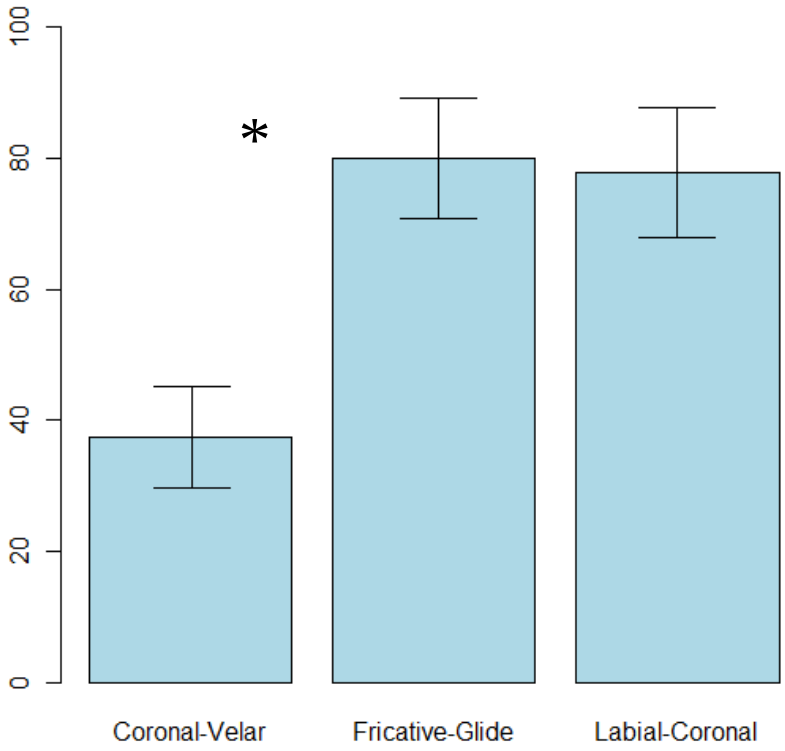
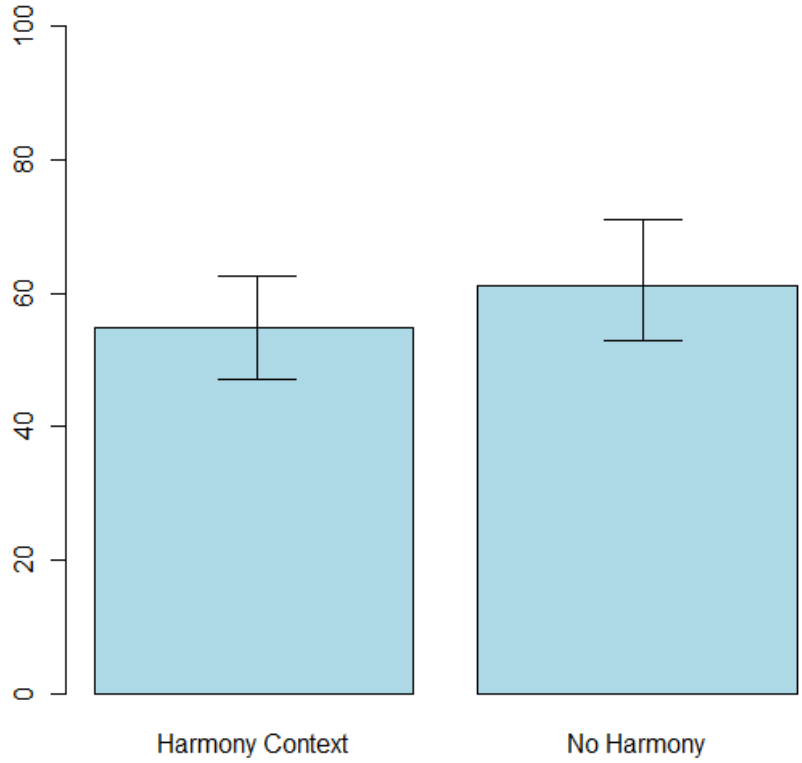


Figure 5 is notable for the low rate of detection of the coronal-velar contrast relative to the other two contrasts. Post-hoc analysis using Student's *t*-test with Bonferroni correction for multiple comparisons revealed that both labial-coronal and fricative-glide contrasts were discriminated with significantly greater accuracy than coronal-velar pairs. Thus, B was found to exhibit difficulty discriminating precisely those contrasts that he neutralized in production. This effect was predicted based on previous literature indicating that children with phonological disorders frequently exhibit parallel deficits across the domains of perception and production. Because the relationship between errors in perception and production is a complex topic, it will be addressed separately in Section 6 below.

4.3.4 Environments for consonant harmony

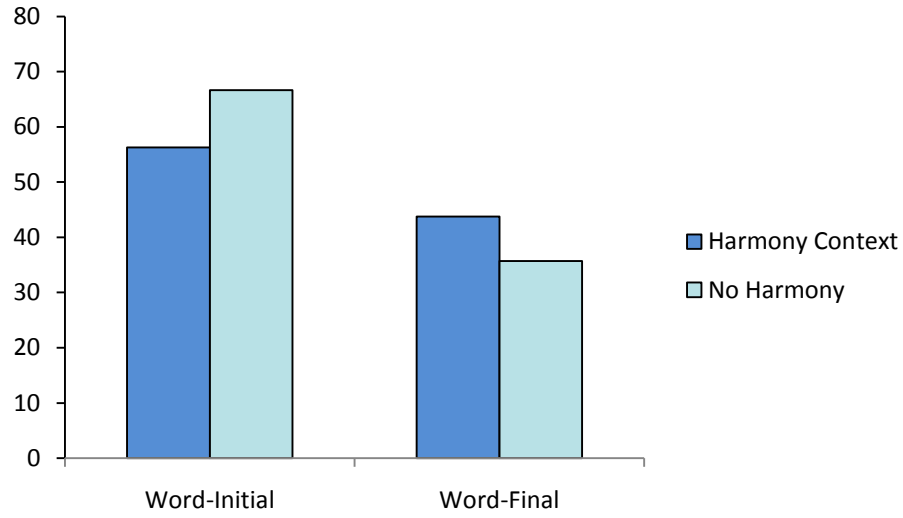
Figure 6 depicts the relative accuracy of contrast detection in environments for consonant harmony versus non-harmonizing contexts. Presence versus absence of a harmonizing environment did not appear as a significant predictor of discrimination accuracy in either of the statistical analyses reported above.

Figure 6. Percent discrimination accuracy by environment for consonant harmony



However, the analysis of deviance did reveal a significant interaction between consonant harmony and syllable position (p = .02); this interaction was also significant in the analysis with fricative-glide pairs excluded. Below, Figure 7 depicts the relative accuracy of discrimination for tokens with and without a consonant harmony context across word-initial and word-final positions. In word-initial position, contrasts were perceived somewhat less accurately in a context for consonant harmony, whereas in word-final position, there was a small difference in the opposite direction. The behavior of contrasts in word-initial position is consistent with the original hypothesis that contrasts would be perceived less well in an environment for harmony than in a non-harmonizing environment. The observation that the presence of a harmonizing environment has an effect on the discrimination of initial but not final contrasts recalls the finding that consonant harmony operates more frequently and more powerfully in a regressive relative to a progressive direction (Smith, 1973; Pater & Werle, 2001; Pater, 2002). This is an interesting finding, particularly in that consonant harmony was not identified as a productive process in B's phonology at the time this experiment was administered. However, subtle indications of harmony processes did emerge in the analysis of B's process of velar fronting, presented in the following chapter. The topic of child consonant harmony, including the emerging effects detected in B's velar production accuracy, will be examined in detail in Chapter 6.

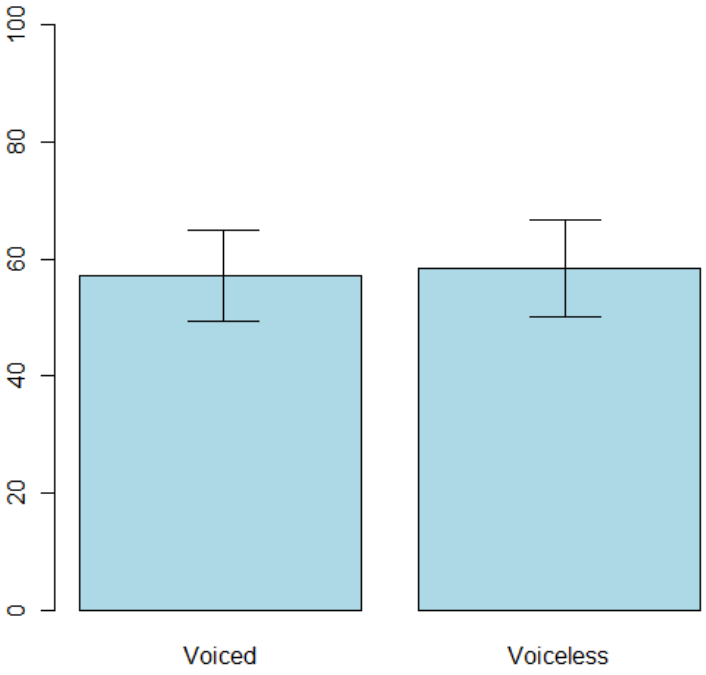
Figure 7. Effect of environment for consonant harmony, divided by syllable position



4.3.5 Voicing

Finally, Figure 8 provides visual support for the finding that there was no difference in discrimination accuracy based on the voicing status of the target contrast. This result was upheld across all three testing sessions. The factor of voicing did participate in a significant interaction with the factor of featural contrast. Inspection of the interaction revealed that the difference in accuracy between labial-coronal and coronal-velar pairs was slightly greater when targets were voiced rather than voiceless. This finding conforms to evidence from a study of adult performance on a phoneme confusability task; it will be revisited in Section 5.4 of this chapter.

Figure 8. Percent discrimination accuracy by voicing feature



5. Interrelated errors in perception and production

Above, it was shown that B perceived word-initial contrasts with significantly greater accuracy than word-final contrasts. This was taken to indicate that child patterns of neutralization in strong position cannot be attributed to a child-specific pattern of perception in the manner posited by Dinnsen & Farris-Trimble. Subsequent chapters will identify articulatory factors that give rise to processes of neutralization in strong position in child phonology. However, it was not the case that B's perceptual performance patterned with adult perception in a completely uniform fashion. Rather, B showed signs of a deficit in perception of the contrast between coronal and velar place, discriminating coronal-velar pairs with significantly lower accuracy than either labial-coronal and fricative-glide stimulus pairs. Thus, B showed a diminished ability to discriminate precisely the contrast that he neutralized in production. This result joins a considerable literature demonstrating that children who neutralize contrasts in production have an increased likelihood of perceptual deficits affecting precisely those contrasts that they produce in error (Hoffman, Daniloff, Bengoa, & Schuckers, 1985; Raaymakers & Crul, 1988; Rvachew & Jamieson, 1989; Whitehill, Francis, & Ching, 2003). A brief overview of previous research will be presented in Section 5.1, with subsequent sections reflecting on the implications of the specific pattern of perceptual and production deficits exhibited by B.

5.1 Markedness in production as the source of perceptual difficulty

The reports of parallel errors in perception and production to be reported in this section are drawn heavily from studies of children with phonological delay or disorders. This body of research is invoked because comparable results from the literature on typical phonological development are nearly nonexistent. This raises a question as to whether perceptual difficulties of the type reported here are unique to children with phonological disorders. However, it is notoriously difficult to identify criteria differentiating phonological delay or disorder from the normal range of variation in typical phonological development. This blurring of the boundaries between groups makes it unlikely that such a clear-cut distinction could be drawn regarding their perceptual abilities. There is a need for further investigation of the hypothesis that typically developing children, like the children with disorders described here, will show perceptual vulnerability specifically affecting the contrasts they neutralize in production. While experimental results from typically developing children were not collected as part of the present investigation, the model that will be pursued here predicts that at least some stages of typical development will be characterized by parallel errors in perception and production.

Early research regarding the perceptual abilities of children with phonological disorders returned highly mixed results. Studies by Cohen & Diehl (1963) and Sherman & Geith (1967) reported a correlation between articulatory delay and decreased performance on measures of auditory discrimination. However, no such correlation was found by Aungst & Frick (1964), McReynolds, Kohn, & Williams (1975), or Waldman, Singh, & Hayden (1978). Attempting to make order of these conflicting results, Locke (1980) suggested that correlation between receptive and expressive deficits fails to emerge when broad standardized tests of auditory discrimination are used as the measure of perceptual ability. He proposed that an investigation of perceptual deficits should target those contrasts that are affected in the child's output. Rvachew & Jamieson (1989) endorsed Locke's conclusions, arguing that when perceptual tests specifically target those contrasts that are affected in the subjects' output, a positive correlation between

speech perception and speech production abilities emerges. In their 2002 study, Edwards, Fox & Rogers concluded that research up to that point had arrived at a general consensus that children with disordered phonology do show a decreased ability to discriminate those sounds that they produce incorrectly.

5.2 Production and perception of liquid-glide contrasts

Preliminary evidence of parallel deficits in perception and production comes from several studies of [r]-[w] perception in children seen to neutralize that contrast in production. Monnin & Huntington (1974) reported that children with /r/-gliding exhibited perceptual abnormalities that affected these phonemes but not other speech sounds that the children produced correctly. The misarticulating children's performance on the identification task also was disrupted to a greater degree than their typical counterparts' when distortion was introduced into the acoustic signal. Further investigation of this perception-production correlation was carried out by Hoffman, Daniloff, Bengoa, & Schuckers (1985). Subjects in this study were twenty-two 6-year-old children with consistent /r/-gliding and thirteen age-matched controls with normal articulation. Synthetic stimuli were created in a seven-step [r]-[w] continuum in which the heights of the first three formants were adjusted across tokens. In the identification task, responses were elicited in a forced-choice paradigm using color-coded written words (*ray* and *way*). When the two groups' responses to the synthetic stimuli were plotted across the stimulus continuum, the children who neutralized [r] and [w] in production showed a significantly flatter identification curve, indicating less consistent identification. Children in the [r]-[w] neutralizing group also scored significantly worse than the control group when contrasting synthetic stimuli were presented in an AX discrimination task. Hoffman et al. concluded that the misarticulating children's diminished ability to distinguish synthetic [r] and [w] targets indicated incomplete knowledge of the phonetic properties of this contrast.

However, there was variability within the results of Hoffman et al.'s study. First, there was heterogeneity in the performance of children in the misarticulating group, with six children who exhibited effectively normal identification curves, eleven who assigned the same label to all stimuli, and two who were at chance for all items. Furthermore, all children in the [r]-[w] neutralizing group were able to meet a criterion of eight consecutive correct identifications in response to live-voice stimuli. The authors suggested that misarticulating subjects' relatively intact response to live-voice stimuli may have reflected compensatory measures such as attention to visual cues. However, the variability of performance within the misarticulating group prohibits a strong conclusion regarding the perceptual abilities of children with disordered production.

5.3 Perception and production of fricative-affricate contrasts

Raaymakers & Crul (1988) also investigated the perception-production relation in child speech. This work was framed in part as an investigation of the motor theory of speech perception (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967), which holds that perception is mediated by production and therefore predicts that errors in perception should be tightly and specifically correlated with errors in production. The authors studied perception and production of a final /ts/ cluster in Dutch-speaking children and adults. This target requires fine coordination of laryngeal and supralaryngeal gestures to control the duration of the silence before the onset of frication noise and is frequently misarticulated as /s/ by child speakers. In this study, speech-impaired children who exhibited /s/-/ts/ neutralization in production were

compared against typically developing children and adults, as well as a group of misarticulating children whose errors affected sounds other than /ts/. Stimuli for the perception task, a two-picture forced-choice design, were created in an artificial 10-step continuum from *mus* ("sparrow") to *muts* ("cap"). Steps along the continuum were created by adding 10-ms spans to the interval of silence before the onset of frication. Analysis of perceptual results revealed that the identification function of the /ts/-impaired children deviated substantially from that of the adult listeners. Children with other articulatory impairment deviated from the adult pattern of identification to a lesser degree, while typically developing children exhibited minimal deviation. Overall, the authors interpreted their results as providing support for the claim that deficits in production do co-occur with perceptual deficits affecting the misarticulated segments.

5.4 Perception and production of fricative place contrasts

Rvachew & Jamieson (1989) tested the relation between perception and production in English-speaking children seen to neutralize the contrast between alveolar and postalveolar fricative place in production. They synthetically generated a seven-point continuum from *seat* to *sheet*, modulating the /s/-/ʃ/ difference by successively lowering the frequency of the amplitude peak of the spectral noise. Their perceptual identification task was administered to a group of speech-disordered children with a mean age of 5;4 who produced an atypical /s/-/ʃ/ contrast, an age-matched group of typically developing children, and an adult comparison group. Among typically developing children, the /s/-/ʃ/ identification function conformed reasonably well to the curve mapped for ten adults, although typically developing children were slightly more likely than adults to label /ʃ/-like stimuli as /s/. Within the articulation-disordered group, five children demonstrated normal /s/-/ʃ/ discrimination, while the remaining seven children produced clearly abnormal identification curves. Some of these children showed a clear bias toward labeling fricatives as /s/, while others appeared to reply at chance. Similar results were obtained when Rvachew & Jamieson carried out a comparable measure using a seven-point continuum from /s/ to /θ/, modulating the duration of frication noise and the amplitude of frication. In this case, however, all children with disordered articulation were also found to exhibit atypical /s/-/θ/ discrimination abilities.

The results of Rvachew & Jamieson's experiments support the hypothesis that some children with disorders of articulation present with a concomitant perceptual disorder. However, here too there was variability in the perceptual performance of misarticulating children, with some disordered children showing roughly typical /s/-/ʃ/ discrimination. There also were different response patterns among children with perceptual difficulty, such that some appeared to respond at random while others showed a strong bias to identify the phoneme that they habitually produced.

5.5 Perception and production of coda place contrasts

Edwards, Fox & Rogers (2002) aimed to address a shortcoming in the foregoing research investigating the perception-production relationship in phonological disorders. While accumulating considerable evidence that children with disordered phonology do possess a diminished ability to discriminate the sounds that they produce incorrectly, the literature has remained inconclusive on the question of whether these children's perceptual difficulties extended to contrasts unaffected by their specific error processes in production. Previous studies had tended to assume, following Locke (1980), that contrasts targeting a particular production

error are necessary to identify perceptual deficits in children with disordered articulation. However, there is some body of research suggesting that children with phonological delay do experience generalized perceptual difficulties. Edwards et al. paraphrase Forrest, Chin, Pisoni, & Barlow's (1995) claim that "children with phonological disorders have difficulty in distinguishing between linguistically relevant variability in the acoustic signal and linguistically irrelevant variability (such as speaker characteristics)" (p. 232). Phonologically disordered children also appear to rely on redundancy in the signal, as reflected in their difficulty with tasks using synthesized speech stimuli.

To look for evidence of a generalized perceptual deficit in children with articulatory disorders, Edwards et al. used a backwards-gated identification task with minimally different word pairs (*cat/cap* and *tap/tack*). Along with a whole-word condition, three gating conditions were created by deleting successive 5-ms segments from the end of the word. The identification task was administered to a sizable subject pool including both typically developing and phonologically disordered children at various ages. All subjects were administered a standardized measure of articulatory ability, the *Goldman-Fristoe Test of Articulation*, or *GFTA* (Goldman & Fristoe, 1986), as well as tests of receptive and expressive vocabulary knowledge. A regression analysis revealed that both receptive vocabulary and overall articulatory ability (*GFTA* score) were significant predictors of performance on the discrimination task, while age and expressive vocabulary size did not emerge as significant predictors. A three-way ANOVA revealed main effects of phoneme contrast, gating condition, and age group on discrimination accuracy. There was also a significant gating-condition-by-group interaction effect, with younger children requiring more acoustic information to identify a stimulus than older children and especially adults. Finally, to assess the specificity of the relation between deficits in perception and production, Edwards et al. compared the performance of a group of nine phonologically disordered children showing NoCoda effects (consistent deletion of final consonants) versus nine phonologically disordered children who did not exhibit this particular pattern. These two groups did not differ significantly on the backwards-gating task.

Edwards, Fox & Rogers' findings indicate that young children require more phonetic detail to identify words than older speakers. This suggests that perceptual maturation does take place over the course of development, contra the hypothesis that children show adultlike perceptual skills from the earliest stage of development (e.g. Smolensky, 1996). Edwards et al. also interpreted their results as indicating that at least some children with phonological disability have a generalized deficit affecting speech perception. First, their investigation showed that *GFTA* score, a broad index of articulatory ability, served as a significant predictor of perceptual performance on both whole-word and gated conditions. In addition, their investigation failed to reveal a relationship between a particular error pattern (final consonant deletion) and the corresponding perceptual discrimination task (final consonant discrimination). In the case of this latter finding, there is room for further investigation, particularly to consider the possibility that some of the children in the NoCoda group were maintaining a covert contrast between targets with and without a final consonant (cf. Weismer, Dinnsen, & Elbert, 1981).

5.6 Perception and production of the coronal-velar contrast

A striking example of the perception-production relation was reported by Whitehill, Francis, & Ching (2003) in an investigation of coronal backing in children with repaired cleft lip

and palate (CLP). While coronal backing is not a common process in typically developing children, it is described as a characteristic process in CLP speakers. There is some contention regarding the motivation for posterior placement in CLP, but the most common explanation holds that the point of stricture is moved back in the oral cavity in an effort to achieve valving before pressure is lost out the dysfunctional velopharyngeal port. This account is sometimes called into question on the grounds that posterior placement often persists after the speaker has undergone surgical repair and appears to possess a fully functional speech mechanism. There seem to be two plausible explanations for this persistent pattern of backing: either the compensatory tongue position has become a fixed motor routine that remains unchanged even after anatomical correction, or the backing process has become a part of the child's phonology, independent of articulatory limitations. Whitehill et al. undertook their study of velar-alveolar perception in children with CLP in an effort to shed light on this dichotomy. Along with a control group of typically developing children, their subject pool included two groups of children with repaired cleft palate, one group that exhibited an active process of coronal backing, and a matched group that produced a different set of phonological errors. All children in this study were native speakers of Cantonese.

Whitehill et al. designed a perceptual identification task using the words *tau* ("head") and *kau* ("ball"), a minimal pair with the same tone in Cantonese. A recorded syllable *tau* was used as the basis for a synthetic eight-interval *tau*-to-*kau* continuum, with steps generated by altering only the frequency of the third formant in perceptually equal steps. When responses were plotted as an identification function, typically developing children and children with CLP who did not produce coronal backing exhibited a similar pattern of discrimination, with a steep transition from /t/ to /k/ roughly midway through the synthetic continuum. However, the identification function for the group of children with posterior placement was effectively flat, with 51-65% of stimuli identified as /k/ across the continuum. In the group with posterior placement, two patterns of atypical perception were observed: one in which children appeared to choose randomly between /t/ and /k/, and one where stimuli were labeled as /k/ across the board. Overall, Whitehill et al. provided strong support for the claim that children's speech sound neutralizations can be accompanied by perceptual deficits affecting the same targets. They argued that their results supported a model in which children's errors in production can give rise to perceptual difficulties affecting the erroneously produced contrasts. Because a similar model will be advocated here, we will return to Whitehill, Francis, & Ching's claim in Section 5.5 below.

6. Parallel deficits in perception and production: Which comes first?

Having established a reliable correlation between children's areas of perceptual weakness and their errors in production, it is certainly desirable to know whether one of these phenomena can be identified as the cause of the other. One possibility is that perception errors give rise to errors in production. Children might neutralize contrasts in production because they do not appreciate a strong perceptual difference between them, or they might take articulatory shortcuts when producing contrasts that they know from their own experience to be of low perceptual salience. On the other hand, it is conceivable that errors in perception are a side consequence of a deficit that has its primary roots in production. The directionality of the relationship between errors in production and perception has proved a particularly recalcitrant problem in this literature. Some analyses have offered preliminary arguments for a primary perceptual deficit

(Broen, Strange, Doyle, & Heller, 1983; Rvachew & Jamieson, 1989), while others have argued the opposite position (Whitehill et al., 2003), but arguments from both sides have amounted largely to conjecture. The present findings have potential to offer more concrete evidence pertaining to the nature of the perception-production relationship due to the non-congruence of perceptual and articulatory biases in our subject. All of the experiments cited above demonstrated that children who neutralized sounds in production also had difficulty with perceptual discrimination of the same sounds in the same position. By contrast, B was shown to produce coronal-velar contrasts more accurately in word-final position at the same time that he perceived this and other contrasts more accurately in word-initial position. To account for this pattern, it will be necessary to invoke separate articulatory and perceptual factors; it is not possible to reduce one entirely to a consequence of the other. Nevertheless, coronal-velar neutralizations in B's production patterned with coronal-velar confusions in perception both in frequency (relative to errors affecting other contrasts) and in time (with perceptual confusions decreasing dramatically at around the same time that an attempted differentiation emerged in production).

The sections that follow will reflect on the implications of B's pattern of performance for our understanding of the perception-production relationship. Section 5.3 will propose a mechanism by which a primary perceptual deficit might influence patterns of production errors even when articulatory constraints represent the primary motivating force behind output errors. However, modeling B's perceptual performance in this way requires certain assumptions regarding the inherent discriminability of phoneme pairs used in the experimental task. Section 5.4 will show that these assumptions are not supported by studies of phoneme confusability in adult perception. It will thus be concluded that a primary deficit in production can give rise to parallel errors in perception, although speculation regarding a mechanism for this relationship will be deferred until Chapter 7.

6.1 Production deficits as the consequence of a primary perceptual deficit

It is useful to ask whether a model in which perception influences production has relevance for a pattern of errors like B's, where perceptual difficulty exists side-by-side with a production error with a clearly articulatory motivation. Since B produced a coronal-velar distinction quite reliably in word-final position, it cannot be maintained that a perceptual deficit prevented him from establishing a sufficiently detailed representation of the phonetic properties of this contrast. However, there is still a possibility that his articulatory difficulty affecting coronal-velar production interacted with his knowledge of the relative perceptibility of contrasts, in the manner of the P-map hypothesis (Steriade, 1999, 2001). The following is a brief sketch of the form that such an analysis might take.

For articulatory reasons that will be presented in greater detail in a Chapter 4, children have difficulty producing velar consonants in word- or foot-initial contexts. For the purpose of the present discussion, this constraint will be schematized simply as *K/#_ ("No velars in word-initial position"). This positional constraint dominates the corresponding general constraint, *K. When B attempts to produce a velar-initial word, his high-ranked constraint *K/#_ will force him to make some adjustment to the initial consonant. To select one of the many possible repairs for this markedness violation, he might consult his stored knowledge of the relative perceptibility of contrasts. A fragment of the relevant P-map is proposed in Figure 9 below; the size of the text corresponds with the relative perceptibility of the contrast. Figure 9 suggests that the coronal-velar contrast is inherently difficult to perceive, more so in word-final than in word-initial

position. For the moment, a purely hypothetical depiction of the relative perceptibility of contrasts is used, and the coronal-labial contrast that was tested in the perception task has been replaced with a velar-labial contrast for the sake of simplicity. The following section will attach empirical data to the relative salience of the contrasts used in the experiment.

Figure 9. Hypothetical P-map fragment comparing repairs for velar segments

Word-Initial	*Word-Final*
k/t	k/t
k/p	k/p
k/ø	k/ø

We can now formulate faithfulness constraints as suggested in Steriade (1999), with higher-ranked constraints protecting more salient contrasts. Combining these faithfulness constraints with the markedness constraints posited above, we arrive at (8) as an approximate local representation of a very early stage of B's grammar. In this stage, all markedness constraints dominate all faithfulness constraints, preventing velar sounds from surfacing in any position in the syllable. The relative ranking of the two perceptually motivated faithfulness constraints (FAITH-k/p >> FAITH-k/t, reflecting the hypothesized greater salience of the velar-labial contrast) determines that coronals will represent the preferred repair for velars in both positions.

(8) *K/#_ >> *K >> FAITH-k/p(Init) >> FAITH-k/t(Init) >> FAITH-k/p(Fin) >> FAITH-k/t(Fin)

Consider next the stage in which B produced the coronal-velar contrast faithfully in word-final position only. Suppose that with targeted exposure, he had achieved increased awareness of the role played by the coronal-velar contrast in differentiating lexical items. This is represented by the demotion of the general markedness constraint *K beneath both faithfulness constraints governing the coronal-velar contrast. Due to the independent articulatory imperative to neutralize this contrast word-initially, *K/#_ remains high-ranked.

(9) *K/#_ >> FAITH-k/p(Init) >> FAITH-k/t(Init) >> FAITH-k/p(Fin) >> FAITH-k/t(Fin) >> *K

In the third and final stage, shown in (10), both markedness constraints are demoted beneath all of the faithfulness constraints.

(10) FAITH-k/p(Init) >> FAITH-k/t(Init) >> FAITH-k/p(Fin) >> FAITH-k/t(Fin) >> *K/#_ >> *K

This analysis demonstrates that it is theoretically possible for differences in perceptual salience to play a role in a pattern of positional velar fronting like that exhibited by B, even on

the assumption that this process is driven primarily by articulatory rather than perceptual factors. However, the solution proposed here depends on the assumption that the contrast between coronal and velar place is intrinsically less perceptually salient than other contrasts. In particular, given that B discriminated coronal-velar pairs with significantly lower accuracy than either the other two contrasts tested in the nonword discrimination task, it will be necessary to demonstrate that the inherent salience of the coronal-velar contrast is lower than that of either coronal-labial or fricative-glide contrasts. The following section will test the viability of the proposed contrast in perceptibility using data from a study of phoneme identification in adults. It will be demonstrated that current evidence from adult perception does not support the proposal that the coronal-velar contrast is intrinsically more difficult to perceive than other consonant place contrasts.

6.2 Testing the relative perceptibility of contrasts

While there is limited empirical evidence regarding the relative perceptibility of contrasts to child listeners, there is a considerable literature documenting adults' accuracy in discriminating a range of phonemic contrasts under various listening conditions. These studies provide data on the relative confusability of sounds, where the confusability of sounds X and Y is the probability that a listener will identify target X as Y, or vice versa. Classic surveys of phoneme confusability include work by Peterson & Barney (1952), Miller & Nicely (1955), and Wang & Bilger (1973), while more recent analyses have been offered by Hillenbrand, Getty, Clark, & Wheeler (1995), Redford & Diehl (1999), Benkí (2003), and Cutler, Weber, Smits, & Cooper (2004). To answer our specific question regarding the perceptual salience of coronal-velar contrasts relative to other place contrasts, data were drawn from Cutler et al.'s extensive survey of consonant discrimination across varying vowel contexts and noise conditions.

The stimuli used by Cutler et al. were CV and VC strings representing nearly all possible combinations in American English. All stimuli were recorded by a single female native speaker of English, who was instructed to release coda consonants. Background noise in the form of multitalker babble was added to create signal-to-noise ratios of 0, 8, and 16 dB. A total of 1935 tokens were generated, each of which was presented in each of the three signal-to-noise ratios. Sixteen American English-speaking adults and sixteen native speakers of Dutch were subjects in the study, but only results from native English speakers will be taken into account here. Listeners were asked to identify the consonant they heard in the stimulus word; they did so by clicking on an exemplar word containing the consonant they heard (e.g. *pie* for [p], *tie* for [t]) in a self-paced listening task.

An online supplement to the Cutler et al. paper offers nearly comprehensive results of their experiment in the form of confusion matrices. Response accuracy in the online data was collapsed across subject and vowel context, whereas both combined and separate data were available for the several signal-to-noise ratios and syllable positions. For illustration, Figure 10 depicts an excerpt from the confusion matrix for all signal-to-noise ratios in initial (CV) position only. Rows represent the identity of the stimulus consonant presented, while columns reflect the subjects' response to that stimulus. The cells along the diagonal, with bold text, reflect correct responses, while cells off the diagonal represent perceptual confusions. The cells that are relevant for the present investigation (/p/-/t/, /b/-/d/, /t/-/k/, and /d/-/g/ confusions), are shaded light gray.

Figure 10. Confusion matrix in CV context, all SNR (Cutler et al., 2004, online supplement)

	Response											
Stimulus	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**	**h**	**b**	**d**	**g**
p	**275**	8	19	44	17				257	24	4	6
t	35	**444**	50	17	27	3	2	3	75	8	3	11
k	51	35	**449**	6	5		1	4	117	6	2	10
f	67	6	10	**391**	67	3		1	44	28	4	6
th	45	20	9	100	**274**	4		1	37	28	5	3
s	1	5	2	24	34	**559**	11	1	5	6		
sh	1		1			11	**607**	94				1
ch		17	6	4	2		4	**668**	1			1
h	83	13	23	42	18	1		1	**428**	36	2	4
b	11	3	4	47	32	1			85	**285**	10	10
d	1	15		6	52	1		2	14	24	**399**	19
g	4	2	13	11	11	1			38	19	7	**458**

In their analysis, Cutler et al. (2004) reported the accuracy (percent correct) with which subjects recognized each consonant target. However, we are interested in comparing the relative discriminability of pairs of sounds, i.e. whether one sound contrast is more perceptually salient than another. To estimate the inherent perceptual distance between targets, we need to factor out the influence of listener bias, which can be accomplished using techniques from signal detection theory or choice theory. Here, perceptual distances between coronal-velar and coronal-labial targets were calculated using the Biased Choice Model, or BCM, proposed by Luce (1963). To obtain the present results, the BCM algorithm was applied for coronal-labial, coronal-velar, and fricative-glide pairs in the fully collapsed table, where results were combined across CV and VC contexts and all three signal-to-noise ratios. The results of this computation are presented in Table 8.

Table 8. Results of BCM algorithm applied across collapsed results from Cutler et al. (2004)

Phonemic Contrast	**Perceptual Distance**
/p/-/t/	2.83
/b/-/d/	2.96
/t/-/k/	2.74
/d/-/g/	3.29
/s/-/j/	7.43
/z/-/j/	5.48

These values can be used to create a P-map to compare against the hypothetical P-map offered in Figure 9. To create this P-map fragment, the smallest perceptual distance (/t/-/k/) was set to 1, and all other perceptual distances were expressed as factors of the /t/-/k/ contrast. Values ranged from a minimum of 1.03 to a maximum of 2.7. These factors were used to determine relative font sizes in the P-map fragment presented in Figure 11.

Figure 11. P-map fragment reflecting perceptual distances derived from Cutler et al., 2004

Coronal-Velar	*Coronal-Labial*	*Fricative-Glide*

t/k	t/p	S/j
d/g	d/b	z/j

Recall that a larger font in a P-map indicates a more perceptually salient contrast. This depiction makes it apparent that the fricative-glide contrast was inherently more discriminable than the two stop place contrasts tested. In Section 6, it was shown that B discriminated fricative-glide pairs with significantly greater accuracy than coronal-velar pairs (Figure 5). Figure 11 suggests that this difference in B's performance was in part a consequence of intrinsic differences in the perceptibility of the two feature contrasts. On the other hand, the advantage for labial-coronal pairs over coronal-velar pairs in B's discrimination accuracy did not find a counterpart in the adult perceptibility data. Figure 11 shows minimal difference in the discriminability of /t/-/k/ and /p/-/t/ pairs, whereas /d/-/g/ pairs appear to have a slight advantage over /d/-/b/ pairs. In fact, the greater perceptibility of /d/-/g/ relative to other stop contrasts appears to emerge in B's performance in the form of a significant interaction between featural contrast and voicing, noted in Section 4.3.5. This interaction revealed that the difference in accuracy between labial-coronal and coronal-velar pairs was slightly greater when targets were voiced rather than voiceless, consistent with the indications of the P-map in Figure 11. Assuming that the data reported by Cutler et al. (2004) are representative, the robust discrepancy between coronal-labial and coronal-velar discrimination in B's performance cannot be interpreted as a consequence of intrinsic differences in perceptibility of these contrasts.

6.3 Perceptual deficits as the consequence of a primary production deficit

Having demonstrated that B's pattern of performance is not amenable to analysis as the consequence of a primary deficit in perception, we are motivated to pursue the opposite hypothesis, that child limitations on production may have the side consequence of diminishing performance in the perceptual domain. While relatively little evidence is presently available to support this position, preliminary substantiation comes from the study of children with cleft lip and palate conducted by Whitehill, Francis, & Ching (2003). Section 5.1.5 reviewed their finding that children with repaired cleft lip and palate who exhibited coronal backing in production showed diminished perception of the coronal-velar contrast relative to a group of children with cleft lip and palate who exhibited other articulatory errors. Whitehill et al. argued that perceptual abnormalities in children with cleft lip and palate who exhibit coronal backing can best be understood as "a perceptual bias related to their own production error" (p. 458). This is an appealing analysis for two reasons. First, coronal backing in cleft lip and palate invites an articulatory motivation, namely the need to create a more posterior closure in order to reduce the loss of intraoral pressure through the velopharyngeal port.[11] Secondly, the finding that children

[11] While it is true that for all of the children participating in Whitehill et al.'s study, the intrinsic structural deficit had been corrected years previously, the motivation for this error is nevertheless fundamentally articulatory. Potentially more concerning is the fact that craniofacial abnormalities often affect the shape and orientation of the

with perceptual deficits tended to identify both coronal and velar tokens as /k/ suggested that they were replicating their own production error in the perceptual domain. Whitehill et al. discussed two mechanisms that could possibly explain how production errors come to have a deforming influence on perception. They briefly invoke the motor theory of speech (Liberman et al., 1967), which holds that perception is directly mediated by production. If a single gestural representation underlies both perception and production of a speech sound, however, we predict essentially perfect correspondence between errors in the two domains. The motor theory thus makes too strong a prediction in light of the fact that perception-production gaps are robustly documented in other contexts (see summary in Pater, 2004). Alternatively, Whitehill et al. suggested that a misarticulating child might fail to monitor the difference between his output and the pronunciations used by adults in his environment, ultimately replacing the underlying representation of a word with a new form based on his own errorful output. However, the pattern of perception exhibited by B cannot straightforwardly be explained under the hypothesis that exposure to one's own errorful productions gradually erodes a previously accurate underlying representation. This is because B's deficits were apparent in a nonword discrimination task, where stimuli do not have a preexisting underlying representation. Here it will be argued that Whitehill et al. are correct in positing that neutralizations in production can give rise to parallel deficits in perception. The insight will be implemented through a different mechanism, invoking Pater's (1999, 2004) proposal that both perception and production should be constrained under a single set of markedness constraints. However, many questions arise in connection with this effort to model perception-production relations, and the resulting discussion will take us rather far afield from the primary focus of this dissertation, namely the role that children's articulatory limitations play in shaping child-specific phonological processes. This discussion will accordingly be deferred to Chapter 7, which concludes the dissertation and identifies areas that would benefit from further investigation and reflection.

7. Conclusion

A nonword discrimination task was designed and administered to examine the perceptual abilities of a four-year-old child, B, whose speech output was characterized by frequent neutralization of phonemic contrasts, including neutralization of coronal and velar place in strong positions. As the primary experimental hypothesis, following Dinnsen & Farris-Trimble (2008), it was posited that contrasts in word-final position would be perceived with greater accuracy than word-initial contrasts. Contrary to this proposal, B showed significantly greater discrimination of word-initial contrasts relative to word-final contrasts, consistent with the pattern of perceptual bias that has been described in adults. This perceptual bias obtained despite a pattern of production in which word-final contrasts were produced more accurately than word-initial contrasts. Thus, Dinnsen & Farris-Trimble's proposal that children's patterns of neutralization in strong position can be understood as a consequence of child-specific patterns of

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Eustachian tubules, giving rise to an elevated incidence of otitis media (middle ear infections) in this population. Frequent experience of ear infections could contribute to generally diminished perceptual abilities. While Whitehill et al. reported comparable history of otitis media across their two subject groups, they acknowledge that further research should include more detailed documentation of participants' history of otitis media—or, more directly, additional measures testing general perceptual abilities—to ensure that the two groups did not differ in these respects.

perception was not supported. Having rejected a perceptual account of children's patterns of neutralization in strong position, subsequent chapters of this dissertation will investigate articulatory motivations for these neutralizations.

A second hypothesis was made based on previous research indicating that children who neutralize some contrast in production tend to exhibit comparable errors in perception. It was posited that a contrast that B neutralized in production (coronal and velar place) would be perceived less well than contrasts that had distinct realizations in B's output (coronal and labial place, fricative and glide manner). While B's performance on measures of perceptual sensitivity was observed to vary across three testing sessions, his ability to distinguish the coronal-velar contrast was consistently decreased relative to his perception of other minimal contrasts. B thus presents an intriguing pattern of convergence and divergence of preferences across perception and production. While he tended to neutralize contrasts in strong positions in his output, he appeared fundamentally adultlike in his perceptual preference for initial over final contrasts. On the other hand, B's capacity for discrimination of place contrasts was impaired in a manner that specifically recalled his pattern of neutralization in production. This echoes a general finding in the literature on phonological disorders, whereby children who neutralize some contrast in production tend to have difficulty encoding that same contrast perceptually. The possibility that parallel errors in perception and production stem from a primary deficit in perception was considered, and it was demonstrated that perceptual factors could play a role even in a case like B, where articulatory limitations are independently necessary. However, this approach assumes that the contrasts affected in perception are lower in intrinsic discriminability than contrasts that are perceived accurately. This prediction was not supported in an investigation of the inherent perceptual salience of coronal-velar versus coronal-labial contrasts, which were associated with significantly different discrimination accuracy in B's performance. With the hypothesis of a primary perceptual deficit not supported, it was proposed that a primary deficit in production can give rise to parallel errors in perception. A preliminary proposal for the mechanism mediating this relationship will be offered in Chapter 7.

Chapter 4.Velar Fronting in Strong Position in Child Phonology

1. Introduction and background

1.1 Overview of velar fronting

Velar fronting is an example of a well-attested process in child speech that lacks correspondents in the adult phonologies of the world. Children with velar fronting are perceived to produce target velar sounds with a coronal place of articulation. While palatalization of velars in the environment of front vowels is attested both synchronically and diachronically in adult languages, there is no counterpart for the canonical child pattern, which is independent of vowel context. Examples of velar fronting in the speech of case study subject B are provided in (1).

(1) a. [dæ so] ‘castle’
b. [dʊ tao] ‘guitar’
c. [dabus] ‘caboose’

Velar fronting is commonly observed in the course of normal development as well as in children with articulatory-phonological disorders. Stoel-Gammon (1985) demonstrated that velar place was less commonly attested in late babbling than either coronal or labial place, and Stoel-Gammon & Stemberger (1994) reported that velar fronting was present in at least some utterances produced by 24 out of a sample of 51 typically developing toddlers. Lowe, Knutson, & Monson (1985) investigated the incidence of fronting processes in a group of more than 1,000 American English-speaking children between two years, seven months, and four years, six months of age. While the incidence of fronting in the group as a whole was approximately 6%, fronting was present in the productions of 23.3% of the youngest group (31-36 months). Grunwell (1981) proposed that velar fronting should be considered typical in children up to three years, six months of age.

Despite this accumulation of evidence that velar place has a marked status in phonological acquisition, Stoel-Gammon (1996) has pointed out that velar place cannot really be considered a late-emerging feature. Analyzing the earliest word approximations of a group of 52 typically-developing children, Bernhardt & Stoel-Gammon (1996) found that velar place was attested within the first ten words of roughly half of the children in the sample. In another sample of 32 toddlers, all but two had produced some velars by the age of 24 months (Stoel-Gammon, 1985). Further complication for the supposed universally marked status of velar place is posed by the attestation of the reverse process, backing of coronals to velar place. While coronal backing is significantly less common than velar fronting and is considered more likely to signal the presence of phonological disorder, coronal backing errors or exclusion of coronals from consonant inventories have also been described in the speech of young typically developing children (Bernhardt & Stoel-Gammon, 1996). Estimates of its prevalence vary widely. In a sample of more than two hundred children with phonological delays, Morisette, Dinnsen, & Gierut (2003) found that velar fronting was present in 39% of cases, while coronal backing was attested in only 4% of the group. While Bernhardt & Stoel-Gammon (1996) reported a similar incidence of velar fronting (41%) in a different group of phonologically delayed children, the

frequency of occurrence of backing in their sample was 18%. Moreover, there are indications that the relative markedness of coronal and velar place in acquisition is subject to cross-linguistic variation. Beckman, Yoneyama, & Edwards (2003) have maintained that velars emerge before coronals in the acquisition of Japanese. They demonstrated that coronal backing errors occurred with significantly greater frequency than velar fronting errors in a sample of typically developing children learning Japanese. Beckman et al. suggested that this contrast may reflect differences in the relative frequency of coronal and velar targets across the two languages, with the Japanese lexicon containing a particularly large number of velar-initial words. Alternatively, it has been suggested that the cross-linguistic difference might reflect an influence of the typical vowel context in each language, with back vowels occurring with particularly high frequency in the Japanese lexicon (Nicolaidis, Edwards, Beckman, & Tserdanelis, 2003). Although interesting issues are raised by the phenomenon of coronal backing and its variable incidence across languages, these questions will be set aside for the present in order to focus on the factors that condition velar fronting in English.

The overarching aim of this dissertation is to account for problematic processes in child phonology, notably those involving neutralization of phonemic contrast in strong positions. It is thus of great interest that previous literature describing velar fronting in English has emphasized the positional nature of the phenomenon, which canonically applies to velar targets in prosodically strong positions (Chiat, 1983; Stoel-Gammon, 1996; Morisette, Dinnsen, & Gierut, 2003; Inkelas & Rose, 2008). The first portion of this chapter will review previous investigations documenting positional velar fronting in the acquisition of English. Special attention will be given to studies that have identified articulatory factors of relevance to velar fronting (Forrest et al., 1990; Edwards Fourakis, Beckman, & Fox, 1999; Gibbon, 1999) or have incorporated such factors into a phonological model (Inkelas & Rose, 2008). This review of previous literature will be followed by a longitudinal case study of one child, B, as he went through of stage positional velar fronting. Detailed investigation will reveal that B's velar production accuracy was conditioned not only by prosodic context but also by laryngeal factors, including voicing and the presence of glottal closure preceding or following the velar constriction. It will be demonstrated that all of contexts seen to facilitate velar place are associated with a relatively low level of intraoral pressure. Because elevated levels of intraoral pressure require more forceful articulatory closure in order to avoid spirantization, it will be shown that B's velar production accuracy falls off with increasing height of the articulatory target. This recalls our discussion of the constraint MOVE-AS-UNIT in Chapter 2. It was argued that children have a limited capacity to move the tongue independent of the jaw, and this difficulty was increases as the tongue moves further from the jaw. To avoid a MOVE-AS-UNIT violation, the tongue plays a passive role, relying on the action of the jaw to bring it into contact with the palate. These jaw-dominated gestures result in an undifferentiated pattern of contact in which closure spans coronal and velar regions. For reasons to be discussed in detail below, patterns of undifferentiated linguopalatal contact tend to be perceived as having coronal place, giving rise to the velar fronting phenomenon. Thus, by invoking a constraint grounded in child-specific speech-motor limitations, it will be possible to explain the positional nature of velar fronting, as well as an otherwise puzzling range of additional factors seen to condition B's velar production accuracy.

2. Previous studies documenting positional velar fronting

Chiat (1983) collected velar fronting data from both spontaneous and elicited utterances produced by one monolingual English-speaking child, Stephen. This child had a diagnosis of phonological delay and was 5 years, 8 months of age at the time the investigation was conducted. Stephen nearly always fronted velar targets with in word-initial position, although interestingly, he was noted to produce word-initial velar consonants accurately in the context of consonant harmony (e.g. [gʌ k] for *duck*). Velars were realized accurately in word-final position. Word-medial velars were fronted before main stress and produced accurately before a stressless vowel. Chiat found no difference in the incidence of velar fronting across syntactic contexts (lexical versus functional words in sentence-level utterances). She did note what she characterized as lexical exceptions to the velar fronting process, a somewhat idiosyncratic set of twelve words (e.g. *car*, *gun*, *camel*) that were produced correctly whenever they were attempted.

An additional task was administered to screen Stephen's ability to discriminate the alveolar-velar contrasts that he neutralized in production. He was presented with five tokens each of a velar-initial and an alveolar-initial word, in random order, with instructions to place an object of a particular color in a box on hearing a word starting with /d/, and a different colored object when he heard a word starting with /g/. After this process was repeated for two additional minimal pairs, he was given three additional pairs to discriminate without direct instruction as to which color should correspond with which place of articulation. Thus, the task tapped his ability to recognize and recall a natural class (velar/coronal) as well as to discriminate the sounds in immediate juxtaposition. Stephen responded correctly to all 48 items on the test, including the items for which the sound-color mapping was not explicitly stated. It was concluded that Stephen possessed an age-appropriate ability to distinguish the contrast that he neutralized in his output.

Stoel-Gammon (1996) described implicational relationships in children's realizations of velar consonant targets. She investigated both velar fronting and velar consonant harmony in longitudinal and cross-sectional data drawn from 67 typically developing children between 15 and 32 months of age. Across this sample, she found that if velars were realized correctly in some but not all contexts, it was the coda position that supported accurate velar production. No children were found to exhibit velar fronting in coda but not onset position. Stoel-Gammon noted a split in the behavior of word-medial velars, with posttonic targets patterning with coda velars, while pretonic targets behaved like word-initial velars. Based on these data, Stoel-Gammon argued that the acquisition of velar consonants is governed by an implicational universal: "The presence of Velar Fronting in word-final position implies its presence in word-initial position" (p. 192). Based on this implicational relationship, she asserted that the acquisition of velars should follow a universal order beginning with fronting in all positions, followed by fronting in onset positions only, then accurate velar production in all positions. She does acknowledge that children may enter this progression at any stage and thus might skip a stage such as across-the-board fronting. Other analyses (e.g. Inkelas & Rose, 2008) have cautioned against interpreting the various levels of application of velar fronting as a universal series of stages, since the full progression has yet to be documented within a single subject as opposed to a cross-sectional study.

Bills & Golston (2002) provided a detailed account of positional velar fronting in one child, Sine, between the ages of 2;6 and 3;6. Like other subjects discussed so far, Sine consistently applied velar fronting word-initially and word-medially before a syllable with primary or secondary stress. However, Sine's case was noteworthy in that she passed through an

intermediate stage in which word-initial velars were realized faithfully only when they occurred in a consonant cluster before a sonorant consonant involving elevation of the tongue dorsum (i.e. /w/, retroflex /r/, and velarized /l/). Thus, a word like *quack*, previously pronounced [dæ k], came to be produced faithfully as [kwæ k], while other velar-initial words such as *cat* continued to undergo fronting. Based on these observations, Bills & Golston argued that Sine's process of velar fronting cannot be described either as uniquely prosodically conditioned or uniquely segmentally conditioned, but must be explained using a combination of prosodic and segmental factors. Bills & Golston analyzed velar fronting as a phenomenon of licensing, where a velar feature can only be licensed by association to a dorsal feature within the same domain of the foot. However, below we will see a case study of one child whose velar production accuracy, like Sine's, was conditioned by both segmental and prosodic factors; it will be argued that this pattern is best explained as the consequence of constraints rooted in child-specific articulatory limitations. In the following section, we turn to studies that have posited speech-motor factors as the source of coronal-velar neutralization in child speech.

3. Motor-control factors relevant to coronal-velar neutralization

While most previous analyses have explained children's velar fronting patterns strictly in terms of phonological features, a small number of studies have identified limitations on speech-motor control that could play a role in children's coronal-velar neutralizations. Evidence for the importance of motor-control factors has been adduced from findings of covert contrast in children's productions, where coronal and velar targets that are perceived to be neutralized are actually associated with significant differences at the level of instrumental analysis. This suggests that children with velar fronting do have knowledge of the coronal-velar distinction but are prevented at some level from implementing this contrast. This section will review several experimental findings pertaining to motor control in velar-coronal neutralization.

3.1 Edwards, Fourakis, Beckman, & Fox (1999)

Chapter 2 reviewed research by Edwards, Fourakis, Beckman, & Fox (1999) suggesting that children tend to produce lingual consonants with a ballistic movement of the entire tongue-jaw complex. Edwards et al. used a formant transition slope metric to investigate the acquisition of consonant place in adults, typically developing children, and children with phonological disorders, including two children with velar fronting. The rate of change in F2 frequency over time has previously been used as an index of articulatory control (Weismer, Martin, Kent, & Kent, 1992), and Edwards et al. posited that a steep-sloped F2 transition is indicative of a rapid, ballistic gestural release. Both typically developing and phonologically disordered children in this study were found to produce alveolar consonants with a significantly steeper F2 slope than the adult comparison group, and for children with phonological disorders, the F2 slope for velar consonants was similarly high. Edwards et al. concluded that child speakers, especially those with a phonological disorder, make more extensive use of ballistic gestures than adults. They proposed that overuse of a ballistic manner of production can be understood as a consequence of diminished tongue and jaw coordination. With limited control of discrete articulators, these speakers tend to move the entire tongue-jaw complex, resulting in a particularly rapid slope transition.

With respect to the coronal-velar neutralization, Edwards et al. noted that steep F2 transitions were particularly prominent in two children who were perceived to substitute alveolar for velar stops. They suggested that it was the uncontrolled, ballistic nature of these children's articulation that was responsible for the perceived substitution. That is, the children with velar fronting failed to produce a proper velar target due to the imprecise nature of their ballistic consonant productions. While this is an intuitively logical proposal, there is a need for further explanation as to why the less controlled gesture should be produced and/or perceived as more anterior. This issue will be taken up in greater detail in the analysis proposed in Section 7 below.

3.2 Electropalatographic investigations of coronal-velar neutralization

We can extend our understanding of velar fronting using insights from electropalatography, particularly work by Gibbon and colleagues (Gibbon, 1990, 1999; Gibbon, Dent, & Hardcastle, 1993; Gibbon, Hardcastle, & Dent, 1995). In particular, electropalatographic data have indicated that children perceived to neutralize the coronal-velar contrast may use an undifferentiated pattern of linguopalatal contact, as described in Chapter 2. It should be noted that much of the work conducted by Gibbon and colleagues has focused not on children with velar fronting, but on children both with and without a history of cleft lip and palate who exhibit the process of coronal backing. Coronal backing, where the coronal-velar contrast is neutralized in the direction of velar place, is commonly observed in children with craniofacial abnormalities but is considered quite atypical in other contexts. While the present focus is on velar fronting rather than coronal backing, insights from work by Gibbon and colleagues will nevertheless have relevance for our purposes.

Gibbon (1990) used electropalatography to investigate the acquisition of the velar-alveolar contrast in two siblings, one who produced the contrast appropriately and one who was perceived to neutralize the contrast in a coronal backing pattern. However, electropalatographic data revealed a covert contrast in the productions of the child with coronal backing, who reliably produced these two categories with significantly different patterns of tongue contact. In fact, both children were noted to produce alveolar sounds with an atypical pattern of linguopalatal contact, which Gibbon characterized as a "double articulation" involving simultaneous velar and alveolar points of closure. To account the fact that only one of the two siblings was perceived to neutralize the coronal-velar contrast, Gibbon speculated that the discrepancy came down to a difference in the two children's phasing of release gestures. Looking at dynamic properties of the regions of linguopalatal contact, Gibbon argued that child who produced an overt contrast had mastered an appropriate sequence in which velar contact preceded coronal closure, placing the audible release of a coronal target in the coronal region. The child who was perceived to neutralize coronal and velar contrasts exhibited more variable sequencing in his release of the two articulatory constrictions involved in the production of the doubly articulated consonant.

The dynamic nature of undifferentiated gesture productions was also explored in Gibbon, Dent, & Hardcastle's (1993) study of one phonologically disordered child with a pattern of coronal backing. Electropalatographic data revealed that he was producing coronal targets using a mid-palatal locus of constriction that differed significantly from the adult pattern of linguopalatal contact for alveolar stops. Specifically, the EPG results indicated that this child typically initiated coronal stop targets with closure in the velar region, while the locus of the

point of release was more variable.[12] Gibbon et al. additionally examined the perceptual consequences of undifferentiated gesture production, soliciting transcriptions of their subject's backed coronal productions from twenty trained listeners. There was substantial disagreement among these listeners as to which tokens were appropriate coronals and which were backed. It is noteworthy that the abnormal pattern of linguopalatal contact revealed by electropalatography was present even during tokens that some listeners perceived to have appropriate coronal place.

3.3 Forrest, Weismer, Hodge, Dinnsen, & Elbert (1990)

The claim that velar fronting is a reflection of speech-motor limitations rather than the output of a categorical process of phonological substitution receives support from evidence of covert contrast in children's neutralized productions of velar and coronal targets. Analyzing the spectral moments of the consonant burst, Forrest, Weismer, Hodge, Dinnsen, and Elbert (1990) did find evidence of covert contrast in a subset of children with velar fronting. Subjects in their study were four children with phonological disorders between three years, six months and six years, six months of age. The children in this study were perceived to front velar targets to coronal place in all positions in the syllable. Four age-matched typically developing children were also recruited to serve as controls. Forrest et al. investigated the first, third, and fourth spectral moments (centroid frequency, skewness, and kurtosis), which are considered sufficient to differentiate /t/ and /k/ in normal adult production. Typically, /t/ is associated with a higher centroid frequency, a negative skewness (indicating a greater concentration of energy in high frequencies), and a moderate level of kurtosis (indicating that energy is spread fairly broadly through the spectrum). On the other hand, /k/ is typically produced with a centroid frequency in the middle range, minimal skewness, and a high kurtosis indicating a concentrated band of energy, or compact spectrum. Forrest et al. reported that these three parameters were sufficient to classify 82% of the coronal and velar targets produced by the typically developing group of children. In the phonologically disordered subject group, three children were found to maintain no significant difference between /t/ and /k/ tokens in any spectral parameter. However, in the fourth child in this group, coronal and velar targets were found to differ significantly in the parameters of kurtosis and skewness. Thus, even though this child's /t/ and /k/ productions were perceived as neutralized, discriminant analysis based on kurtosis and skewness could differentiate her productions with 87% accuracy. Thus, Forrest et al. offered acoustic evidence that at least some children who exhibit velar fronting do in fact preserve a covert contrast between coronal and velar targets.

3.4 Summary of motor-control factors

All of the studies detailed above offered evidence that coronal-velar neutralization in child speech can result from motor-control limitations specific to child speakers. Edwards et al. (1999) argued that velar fronting can be observed in children whose motor limitations force them to use ballistic gestures involving the entire tongue-body complex. This analysis can be extended using the EPG results reported by Gibbon and colleagues, who found that children exhibiting coronal-velar neutralization frequently use an undifferentiated pattern of gesture production that

[12] Gibbon et al. noted that coronal targets tended to be released in a more posterior location word-initially, while word-final coronals tended to be released at a more anterior point. This is precisely the opposite of the articulatory pattern posited by Inkelas & Rose (2008) to explain a pattern of velar fronting in word-initial position.

spans coronal and velar regions. Gibbon and colleagues also reported that adults are not reliable in their perception of undifferentiated gestures, transcribing either coronal or velar place depending on the phasing of release gestures in the child's production. Finally, the idea that velar fronting reflects something other than the categorical substitution of coronal place for velar place—possibly a consequence of motor-control limitations—is supported by findings of covert contrast in perceptually neutralized coronal and velar targets, including the acoustic contrast reported by Forrest et al. (1990) and the articulatory contrast described by Gibbon et al. (1993).

4. A phonetically informed analysis of velar fronting

Inkelas & Rose (2003, 2008) combined phonological and speech-motor factors in their analysis of one typically developing child's pattern of velar fronting. They characterized velar fronting as a consequence of articulatory strengthening in prosodically strong positions. Studies of adult articulation have demonstrated that consonant gestures are produced with greater magnitude in initial and stressed syllables; in velars, consonant strengthening has also been associated with a more anterior region of linguopalatal contact (Fougeron & Keating, 1996). Inkelas & Rose argued that velar fronting emerges when a child's phonologically appropriate effort to enhance a consonant gesture in a strong position interacts with his immature articulatory anatomy and speech-motor control.

4.1 Description of data

Data for Inkelas & Rose's study were gathered in a diary fashion from one American English-speaking child, E, who exhibited velar fronting between the ages of 1;0 and 2;2. Interestingly, the process was not present in E's late babbling or early word productions (e.g. [kæ] for *catch* at nine months of age). Throughout this period, E exhibited velar fronting in strong positions, similar to the pattern described by Chiat (1983) and Bills & Golston (2002). The examples in (2) illustrate E's velar fronting in word-initial and pretonic positions. (3) shows that the coronal-velar distinction was maintained in final and unstressed medial contexts.

(2) Velars are fronted word-initially or in word-medial onsets of stressed syllables.

a.	[do:]	'go'
b.	[tʌ ndʌ ktə]	'conductor'
c.	[ə dɪ n]	'again'

(3) Velars are not fronted word-finally or in word-medial onsets of unstressed syllables.

a.	[bejgu]	'bagel'
b.	[bɪ g]	'big'

4.2 Phonetic motivation for velar fronting

Inkelas & Rose proposed that E's pattern of positional velar fronting could best be understood as a "phonologized, grammatical artifact of the physiological and related motor difficulties inherent to the articulation of velar consonants in prosodically strong positions." This analysis rests on two crucial assumptions. First, children must be sensitive to the phenomenon of

prosodically conditioned strengthening of consonants, especially velars, in adult speech. Second, limitations imposed by the different proportions and motor control abilities of the young child's articulatory mechanism must interfere with faithful realization of the strengthening process. Although child-specific articulatory limitations were discussed in detail in Chapter 2 and in previous sections of this chapter, the specific factors invoked by Inkelas & Rose are reviewed briefly below.

4.2.1 Child-specific articulatory limitations and velar fronting

Inkelas & Rose identified several aspects of the vocal anatomy and physiology of the young child that might contribute to a process of velar fronting. First, the child's tongue is larger in proportion to his vocal tract than the adult's (Fletcher, 1973; Kent, 1981; Crelin, 1987), and the child's tongue additionally occupies a more anterior position in the oral cavity (Kent, 1992). The palate of a child speaker is narrower and lower than that of the adult. Thus, from infancy to around two years of age, the tongue fills the oral cavity almost completely (Crelin, 1987). While a shift in vocal tract anatomy begins after the child reaches two years of age, this process is characterized as slow and gradual, typically not reaching completion before the child is six years of age. Given these differences in the shape and placement of the articulators, we might expect all young children to produce velar consonants with a more anterior point of constriction, even in the absence of a phonological process of velar fronting. This claim was supported in Fletcher's (1989) electropalatographic study of linguopalatal contact in consonant production across age groups, which showed that the point of constriction for a velar stop shifted posteriorly with increasing age. In spite of this evidence, it is not possible to characterize velar fronting as a necessary consequence of the dimensions of the infant vocal tract, since not all children go through of application of the process.

In addition to anatomical differences, Inkelas & Rose suggested that changes in speech-motor control make a contribution to the child-specific process of velar fronting. Like Edwards et al. (1999), they invoke Kent's (1992) hypothesis that simple, ballistic gestures emerge before controlled gestures in the course of articulatory maturation. Inkelas & Rose proposed that children produce coronal and velar stops with a ballistic gesture that lacks more subtle aspects of tongue-shaping and force modulation. However, they point out that their analysis differs from accounts that have explained coronal-velar neutralization purely as a consequence of decreased articulatory control (e.g. Gibbon, 1999), since they additionally invoke phonological factors, to be described below.

4.2.2 Prosodically conditioned strengthening

The asymmetric nature of the canonical pattern of velar fronting, which neutralizes the coronal-velar contrast in onset but not coda position, is not well explained by the motor limitation accounts discussed previously. To account for E's pattern of positional velar fronting, Inkelas & Rose invoked the phenomenon of articulatory strengthening in prosodically strong positions, which has been extensively documented in adult speech. Fougeron & Keating (1997) used electropalatography to measure the degree of linguopalatal constriction associated with a single segment realized across different prosodic positions. They used a reiterant-speech method in which subjects were instructed to echo a sentence, replacing all syllables with the dummy syllable "no." The strength of consonant articulation was measured simply as the maximum number of electrodes contacted during the peak of consonantal closure. Fougeron & Keating

provided evidence for differences in the magnitude of consonant closure across the levels of Utterance, Intonational Phrase, Intermediate/Phonological Phrase, Word, and Syllable. Other EPG studies of prosodically conditioned strengthening have demonstrated that gestural enhancement applies differentially to different segment types. Fougeron & Keating (1997) and Fougeron (1999) found that velars are particularly susceptible to prosodic strengthening effects. In addition to a stronger closure, velars in strong position are reported to be produced with a more anterior place of linguopalatal contact.

Inkelas & Rose proposed that positional velar fronting can be understood as the child's response to this strengthening pattern in adult speech. They argued that, given children's apparently acute sensitivity to subtle phonetic contrasts (e.g., Jusczyk, 1997), it is plausible to suppose that they detect the perceptual consequences of positional strengthening in adult productions. Children are also known to show particular faithfulness to strong syllables, as when they differentially preserve the content of stressed syllables in truncating processes (Kehoe & Stoel-Gammon, 1997). This suggests that child speakers may be motivated to remain faithful to strengthening, a prosodically informative contrast affecting stressed syllables. However, faithful realization of positional strengthening in the child speaker is complicated by the child's "imperfect articulatory control, bigger tongue size…combined with a relatively shorter palate" (p. 724). That is, the child speaker's attempt to produce a larger velar gesture in a prosodically strong context causes the domain of linguopalatal contact to extend into the coronal region. When the closure is released in this position, the listener perceives a coronal rather than a velar consonant.

4.3 Phonologization of velar fronting

Despite the important role that articulatory limitations play in their analysis, Inkelas & Rose argued specifically that positional velar fronting processes should be regarded as a phonologized response to phonetic pressures, not a performance limitation at the level of motor execution. One piece of evidence for the phonologized status of velar fronting is the fact that many children never exhibit the process (Smit, 1993). Since typically developing children face grossly equivalent articulatory limitations, we are prevented from analyzing fronting as a necessary consequence of the articulatory anatomy and physiology of the young child. On the other hand, it is expected that children may differ in their grammatical response to these universal speech-motor limitations. If a child speaker's early attempts to strengthen velar consonants in prosodically prominent positions result in a phonetically coronal release, the child faces a decision: he may remain faithful to velar place but forgo prosodically conditioned strengthening, or he may preserve high-ranked faith to prosodically conditioned enhancement, sacrificing the segmental accuracy of the velar.

Inkelas & Rose also argue that the manner in which velar fronting was eliminated from E's speech suggests a phonological change rather than a continuous process of speech-motor maturation. E exhibited consistent positional velar fronting when he was between one year and two years, three months of age. At 2;3 there was an abrupt change, with velar fronting ceasing entirely between two recording sessions spaced five days apart. The authors additionally noted that "on two occasions around this transitional period…E's mother witnessed him producing nonsense words containing velars in stressed syllables." Their interpretation is that E became aware of the discrepancy between his realization of prosodically strong velars and that of the adults in his environment. Since this realization came at a time when he had advanced both in

anatomy and in motor-planning ability, he was able with a brief period of practice to make a rapid and categorical transition from fronting to accurate velar production.

4.4 Discussion and issues for further consideration

By invoking child-specific articulatory limitations in their analysis of velar fronting, Inkelas & Rose have offered an appealing solution to a difficult problem in child phonology. As they note, their account can explain three puzzling aspects of positional velar fronting: why it affects strong rather than weak positions, why the outcome of the neutralization is coronal rather than velar, and why it is specific to child speakers. Regarding the preferential occurrence of velar fronting in strong positions, Inkelas & Rose pointed out that if velar fronting reflects an inability to achieve a sufficiently posterior point of linguopalatal contact, the problem can only be exacerbated in prosodically strong positions, which are characteristically produced with a more anterior closure. Children with positional velar fronting can be seen as spanning a boundary in articulatory ability: they can produce appropriate velar closure under ideal circumstances, but not in the more demanding context of prosodically conditioned strengthening. Meanwhile, the preferential neutralization of coronal and velar consonants in the direction of coronal place is argued to follow directly from the fact that the child's tongue occupies a more anterior position in the oral cavity than the adult's. Finally, the absence of velar fronting effects in adult phonology is unsurprising on an account that analyzes fronting as a response to the peculiar properties of the immature vocal tract.

The analysis to be pursued in this chapter borrows much from Inkelas & Rose's account of positional velar fronting. In particular, the insight that children's forceful velar articulation of velar stops may cause the area of linguopalatal contact to extend into the coronal region will play a key role in the present account. Here an effort will also be made to expand on Inkelas & Rose's analysis, first and foremost by attaching constraint formalism to the pressures posited to give rise to velar fronting. Whereas Inkelas & Rose placed more emphasis on the differently proportioned anatomy of the child speaker, here it will be argued that child-specific motor constraints play the most active role in driving velar fronting. Specifically, the child preference for jaw-dominated movement, expressed by the constraint MOVE-AS-UNIT, will play the most important role in differentiating child and adult patterns of velar articulation. The present analysis also deviates from Inkelas & Rose's interpretation of velar fronting as the child's specific response to the phenomenon of prosodically conditioned strengthening in adult speech. In Chapter 2 it was proposed that MOVE-AS-UNIT is a directly phonetic constraint, influenced by gradient differences in the height of the articulatory target. Prosodic context plays a key role in dictating this value. However, it will be demonstrated that other factors, such as voicing and glottalization, contribute to the determination of target height and hence to the application of velar fronting. This analysis will draw crucially on evidence from case study subject B, whose pattern of velar fronting will be shown to respond to voicing contrasts and other factors in addition to prosodic position. The evidence from B's acquisition of velar place is laid forth in the following section.

5. Velar fronting: Case study

The analysis of velar fronting proposed in this chapter is informed by case study data from B, the four-year-old child with apraxia of speech who has been discussed in previous

chapters. Unlike Inkelas & Rose's subject, B did not exhibit a uniform pattern of velar fronting followed by an abrupt and categorical transition to faithful velar place. Instead, his mastery of velar stop production was a gradual process spanning more than eight months of development. In addition to fronted and faithful velar production, B used other repair strategies including glottal replacement and pre- or postglottalized velar production. This section will describe B's pattern of positional velar fronting, including changes in the application of fronting over time. In subsequent sections, the various factors seen to condition his velar production accuracy will be unified as the consequence of differing levels of articulatory force and intraoral pressure, which dictate the magnitude of violations of the child-specific constraint MOVE-AS-UNIT.

5.1 Methods

The general characteristics of the case study subject, B, were laid out in Chapter 2. Data for the velar fronting analysis were collected during B's hour-long speech therapy sessions, which occurred on a roughly biweekly basis. The present analysis includes data from all sessions recorded when B was between three years, nine months and four years, four months of age. During therapy sessions, B's interactions with his mother and the clinician were recorded with a Sony ICD-SX57 portable recorder. From the recordings, all of B's identifiable utterances were narrowly transcribed and glossed as completely as possible. Items for which a definitive gloss could not be established were excluded from consideration. In the therapy setting, some velar targets were elicited in immediate imitation of an adult model, while others occurred in the context of spontaneous connected speech. Until the final stages of the recorded period, however, B was not stimulable for velar sounds in prosodically strong positions; that is, he generally did not produce appropriate velar place even with maximal cueing from the clinician. This suggests that the presence or absence of an immediate adult model was not a significant predictor of his performance.[13]

The glossed transcription was used to identify all words for which the adult target form contained a velar consonant in any of three positions in the syllable: initial, word-medial pretonic (preceding a main stress), and word-medial posttonic (following a main stress). Word-final consonants were not included in the analysis because B produced them with near ceiling-level accuracy after an early stage of development. When B's velar codas were not fully faithful, they generally were not fronted but rather were replaced with glottal stop, reflecting a process of coda debuccalization that applied across stops with all places of articulation.[14] B's responses were classified in one of several production categories and were coded for other phonetic characteristics, described below. In total, 1,696 velar targets were catalogued using this system.

[13] The absence of an immediate effect of modeling is not to be interpreted as a claim that adult models had no impact on B's velar production at any level. In fact, B's exposure to hyperarticulated adult models of initial velar stops did appear to heighten his attention to the coronal-velar contrast, and it may have encouraged him to attempt exaggerated velar stops (e.g. with strong closure and long or noisy aspiration)

[14] It is possible that B did go through a brief stage of word-final velar fronting when he first acquired oral place for coda consonants. In one session at 3;11, B produced 7/25 word-final velar targets with coronal place, which exceeded the number of final velars that were faithful (5); 13 were debuccalized. However, this was the only session where fronting made a significant appearance in word-final position. This makes it difficult to determine whether B had a genuine process of fronting for word-final velars, or whether he simply went through a stage of confusion regarding the place specification of word-final consonants when he first began to produce them with oral place.

5.2 Results of the investigation

5.2.1 Attested patterns of production

B's attempted velar productions were classified under four major categories: fronted (coronal) place, "segmented" production (in which a glottal stop or other segment separated the velar from an adjacent vowel), glottal replacement, and faithful velar place. An "Other" category included deletion of velar targets as well as infrequently attested substitutions. Examples of the three common error categories are presented below.

The phenomenon of positional velar fronting has already been described in detail in this chapter. Like subjects described by Chiat (1983), Bills & Golston (2002), and Inkelas & Rose (2008), B applied velar fronting preferentially in strong (initial and word-medial pretonic) positions. (4) and (5) below provide examples of velar fronting in strong position in B's output.

(4) Word-initial velars are fronted to coronal place.

a.	[dat]	'cut'
b.	[dʌ p]	'cup'

(5) Word-medial pretonic velars are fronted to coronal place.

a.	[bidas]	'because'
b.	[odej]	'okay'

Consistent with previous descriptions of positional velar fronting, B was rarely perceived to produce target velars with coronal place in word-final or medial posttonic contexts. In an early stage, these typically underwent glottal replacement (debuccalization), where the oral place features of the target consonant were eliminated altogether. As noted above, debuccalization was observed for coronal and labial as well as velar stops in these contexts. At a later stage of development, B exhibited faithful production of velar targets in prosodically weak contexts. Examples of word-final and medial posttonic velars are provided in (6) and (7).

(6) Word-final velars are debuccalized or realized faithfully.

a.	[jaʔ]	'like'
b.	[bʌ ʔ]	'big'
c.	[dak]	'duck'
d.	[bʊ k]	'big'

(7) Word-medial posttonic velars are debuccalized or realized faithfully.

a.	[doʔ onat]	'coconut'
b.	[daʔ oʊ]	'tiger'
c.	[wakiŋ]	'walking'
d.	[dʌ gi]	'doggie'

However, B diverged from the canonical pattern of velar fronting in that he also exhibited fronting of some word-medial velars in posttonic contexts, as seen in (8). The occurrence of fronting in this context in B's speech can probably be attributed to atypicalities in his

prosodification, whereby individual syllables appear to have taken on the status of prosodic words or even intonational phrases.

(8) Word-medial velars in posttonic (weak) contexts are occasionally fronted.
   a. [dado] ‘tiger’
   b. [wɔ dij] ‘froggie’

Finally, several different processes were grouped under the category heading of segmented production. For posttonic medial velars, segmentation was achieved by producing glottal closure either before or after the target velar, as in (9) and (10), respectively. Pre- and post-glottalization were used with roughly equal frequency in word-medial posttonic contexts. In one stage of B’s development, postglottalized production was also attested in word-initial position (10c). While glottalization in varying degrees was widespread in B’s production, for present purposes tokens were coded as pre- or post-glottalized only if a glottal stop was transcribed on the first pass through the recorded data, before any hypotheses regarding B’s patterns of velar production had been formulated.

(9) Pre-glottalization in word-medial posttonic contexts
   a. [mʌ ʔ kij] ‘monkey’
   b. [bʊ ʔ ko] ‘pickle’

(10) Post-glottalization in word-medial posttonic and initial contexts
   a. [dakʔ oʊ] ‘tiger’
   b. [dʊ kʔ ɛ n] ‘chicken’
   c. [kʔ ʌ t] ‘cut’

For illustration, Figure 1 presents a spectrogram featuring preglottalized manner in B’s production of a word-medial velar ([dɔ ʔ kan] for *chicken*). In Figure 1, glottal closure is apparent in the abrupt offset of the first vowel, which is cut off while still gaining in amplitude. Glottal striations are visible in this context but are partly obscured by reverberation. Note also that the first formant remains flat moving into the consonant closure, indicating that closure is achieved without altering the shape of the vocal tract above the vocal source. The preglottalized production can be contrasted with B’s more typical manner of producing a disyllable, seen in Figure 2 ([daduw] for *tattoo*). In the utterance without preglottalization, consonant closure is achieved after a transition period in which the first formant falls while the amplitude of the vowel decreases gradually.

Figure 1. Spectrogram illustrating preglottalized production ([dɔ ʔ kan] for *chicken*)

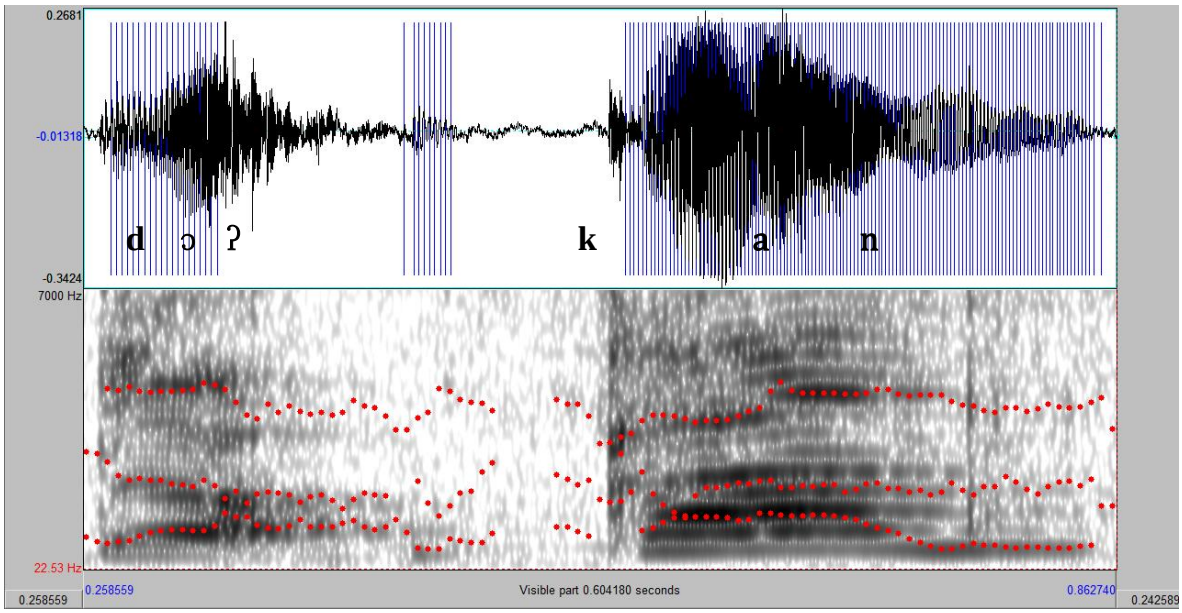
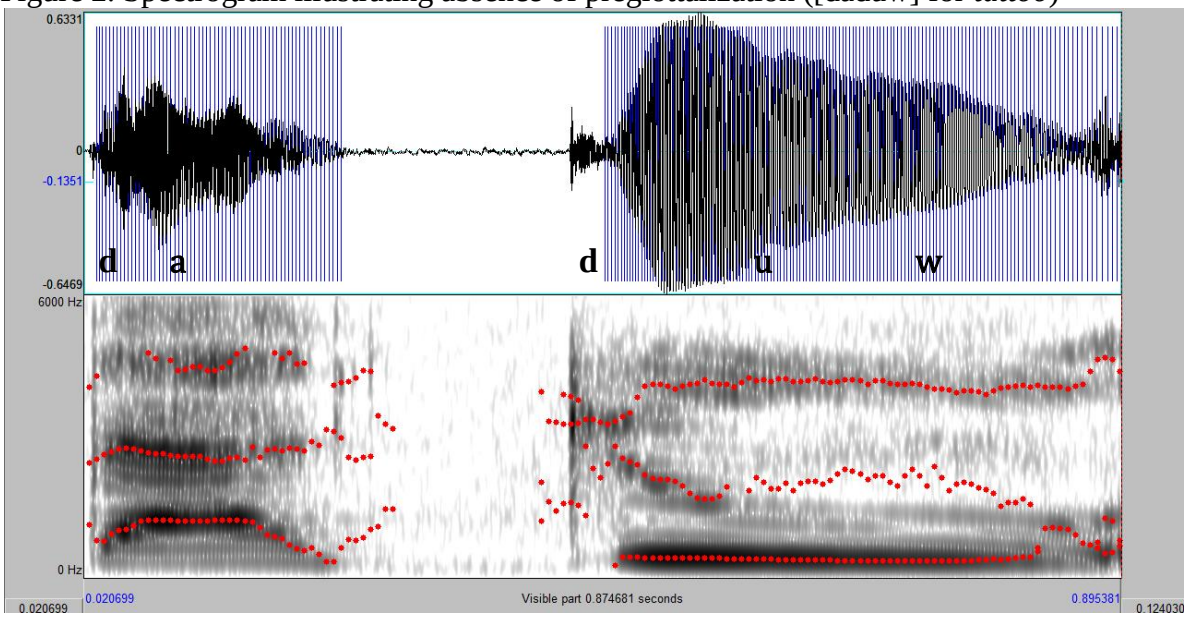
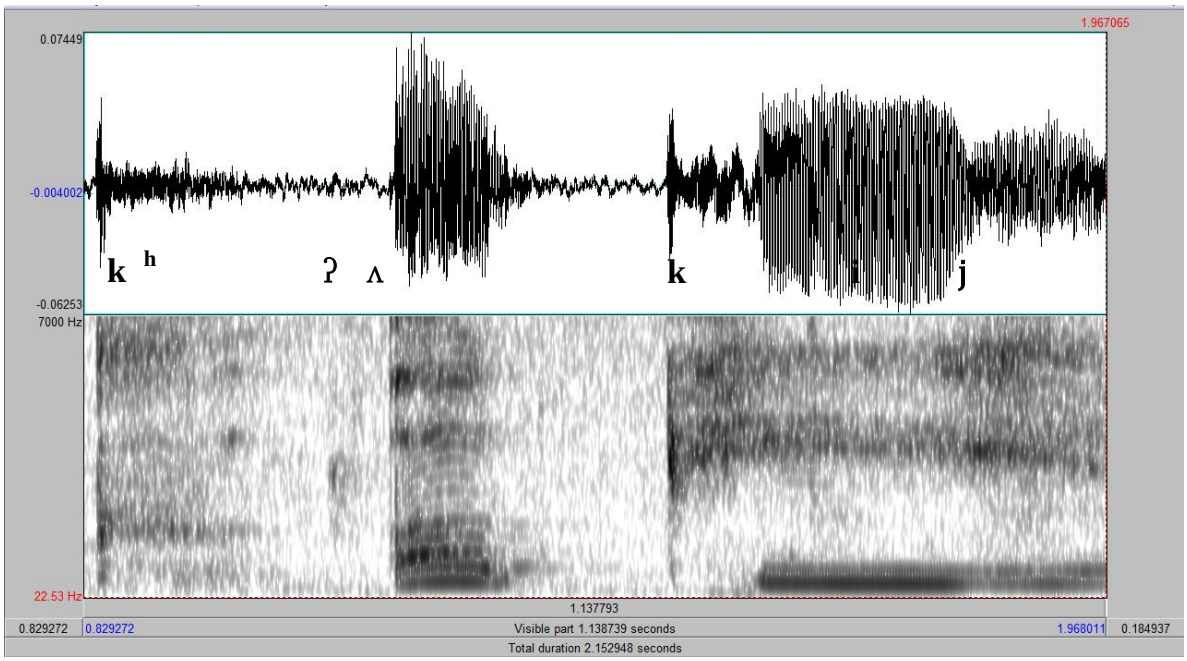


Figure 2. Spectrogram illustrating absence of preglottalization ([daduw] for *tattoo*)



Finally, Figure 3 provides an example of postglottalized production of a word-initial velar ([kʔʌkij] for *cookie*). As the spectrogram shows, postglottalized initial productions were characterized by isolated release of the oral place constriction with a distinct following pause. The onset of the following vowel was typically glottalized. Note that it is only the word-initial velar in *cookie* that is realized in a segmented fashion in Figure 3; at this stage in B's development, word-medial posttonic velars were typically realized target-appropriately.

Figure 3. Spectrogram illustrating postglottalization in word-initial velars ([kʔʌkij] for *cookie*)



A final note concerns the realization of pretonic word-medial velars with a segmented manner. Segmented production was only infrequently attested as a repair strategy in this context. However, B did use a form of segmented production for 31 out of 35 word-medial velar targets that occurred between a secondary and primary stressed syllable. In these doubled productions, seen in (11), B produced the velar target appropriately in the coda of the first syllable, then repeated the consonant with fronted place in the onset of the following stressed syllable. Due to the paucity of imageable disyllabic words with a secondary-primary pattern of stress, it was difficult to determine whether the consonant doubling pattern was productive or had simply been lexicalized for the word *raccoon* (and extended by analogy to highly similar words).

(11) Consonant doubling in between secondary and primary stress

a. [waktun] ‘raccoon’

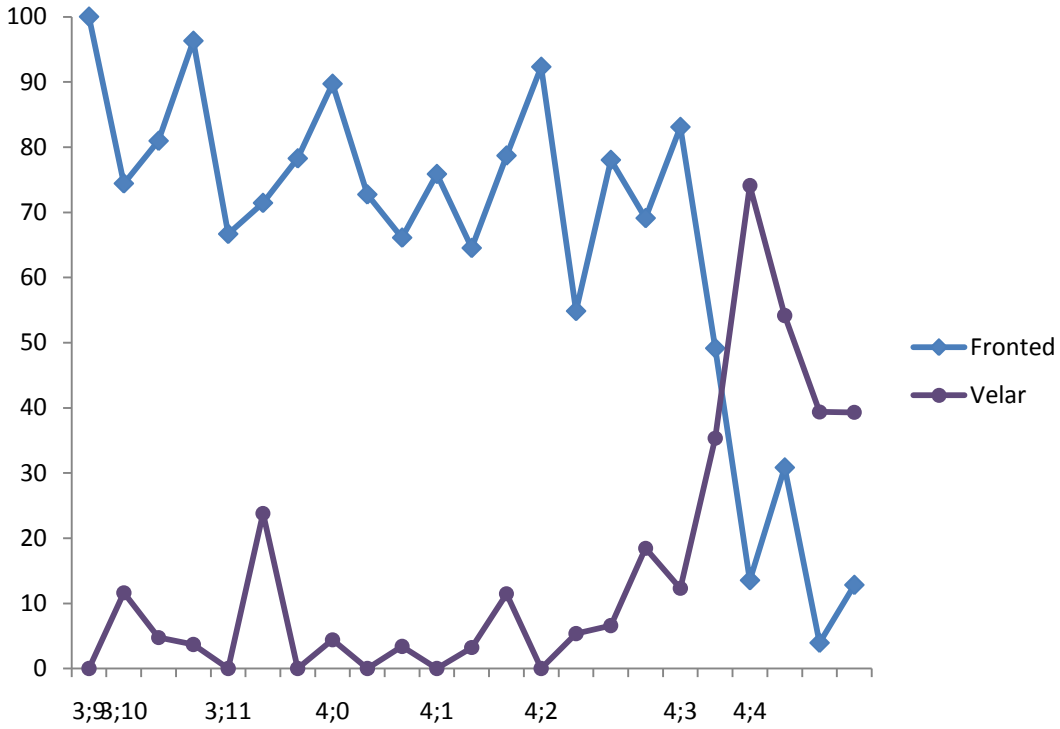
b. [wakduw] ‘ragout’

5.2.2 Identifying developmental stages in B’s acquisition of velars

Because of the longitudinal nature of the present investigation, it was possible to observe changes in the relative frequency of B’s various repair processes over time. This section will identify several stages of development in B’s acquisition of velar place. Figure 4 offers the graphic gestalt of changes in B’s velar productions over time, collapsed across positions in the syllable. For simplicity, only fronted and accurate productions are represented here; subsequent graphs will provide additional detail regarding the prevalence of other repair strategies. Throughout most of the documented period, B produced the great majority of velar targets with fronting. However, in the final two months of the observed period, the frequency of velar fronting fell off sharply. Accurate velar fronting rose in accordance with the fall-off in fronting, but other repair strategies, to be described below, continued to represent a sizable portion of tokens in the period investigated. Thus, velar production does not reach a ceiling level of

accuracy in Figure 4. While B did eventually attain ceiling-level accuracy in velar production across positions, this change took place after the end of the period of study.

Figure 4. Percentage of tokens transcribed as fronted versus accurate velars, all positions



B's several repair strategies were applied to differing extents across the three prosodic contexts considered. Thus, separate graphs will be presented depicting the relative prevalence of repair strategies over time for velar targets in initial, medial pretonic, and medial posttonic contexts. These graphs will be used to identify points of transition in B's pattern of velar production, which roughly demarcate stages in his acquisition of velar place. Note that these stages are merely rough estimates that will be used to facilitate further analysis; they are not claimed to correspond with discrete events in B's phonology.

It is also important to bear in mind that analyses of output patterns calculated over these prosodic contexts are based on different numbers of observations. Figure 5 depicts the number of velar targets that B attempted over the course of the recorded interval, divided by prosodic context. Across prosodic contexts, the number of tokens elicited tended to increase across sessions; from age 4;2 on, large numbers of fricative targets were elicited in connection with repetitive practice in the therapy setting, with the spike shortly before 4;3 reflecting one especially productive session. With very few exceptions, initial velars outnumbered word-medial velars in either pretonic or posttonic contexts, often by a substantial margin. Word-medial pretonic velars were particularly rare because the proportion of iambic words in the child English vocabulary is quite small; this category was generally limited to tokens of a very small set of lexical items (e.g. "because," "okay," "again"). The smaller number of observations can be seen to contribute to the greater variability of velars in word-medial pretonic and posttonic contexts (Figures 7 and 8, below) relative to initial position (Figure 6).

Figure 5. Number of attempted velar targets over time, divided by prosodic context

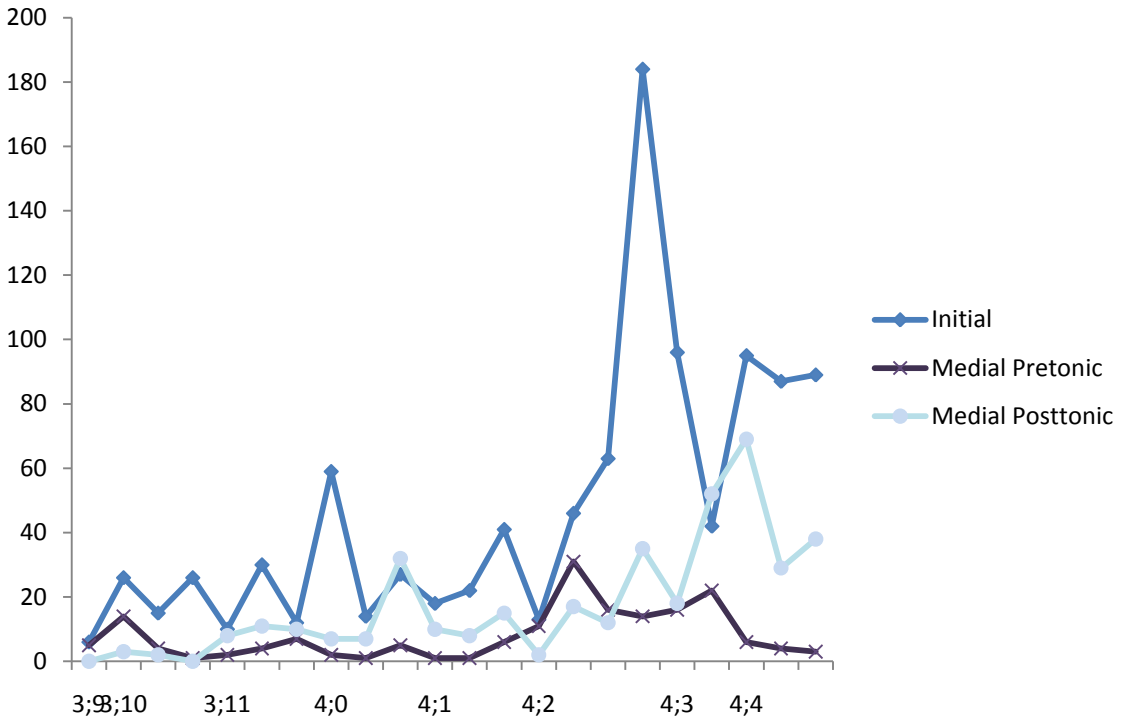


Figure 6 depicts the frequency of each of three output categories (fronted, segmented, and velar) in word-initial position.[15] Because word-initial velars occurred overwhelmingly in stressed syllables, mostly monosyllables, they have not been divided according to stress. In the word-initial context, B exhibited a consistently high level of fronting throughout the great majority of the recorded period. It is interesting to note that he produced word-initial velars with small but non-trivial frequency in the first few months of the study before lapsing into an extended period characterized by more uniform fronting. A similar pattern was also described in Inkelas & Rose's subject E, who began to exhibit a uniform pattern of velar fronting after producing faithful velar place in his late babbling and some early words. Apart from these early deviations, B's performance remained constant until he was between 4;3 and 4;4, at which point his application of fronting dropped precipitously while accurate velar production, as well as a new pattern of segmented production, ascended rapidly. It seems reasonable to mark this point as the transition to a new stage in B's velar production grammar. A dotted line has been placed on the graph in Figure 6 to represent the initial boundary of the fourth and final stage in the developmental course followed in this study. This category boundary will be carried over to subsequent graphs.

Figure 6. Percentage of tokens transcribed in four response categories, word-initial position

[15] Glottalized production was not observed in this context. The "Other" category was inconsistently attested in B's velar data and will not be depicted in this or any of the graphs to follow.

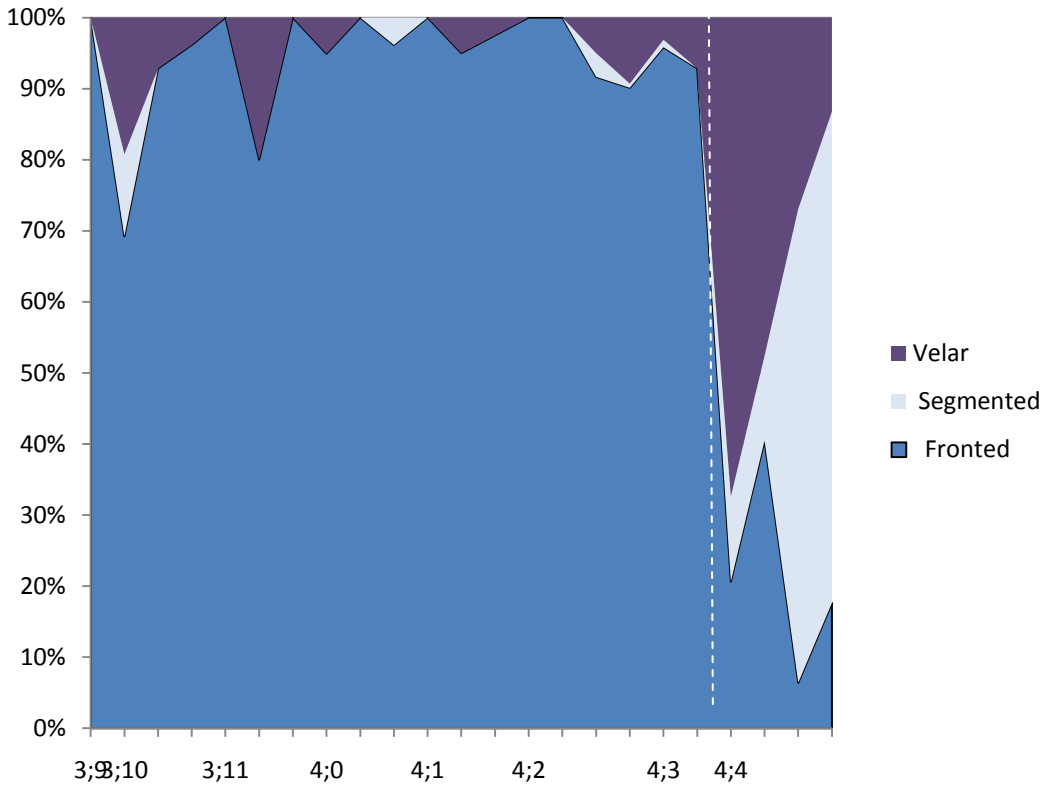
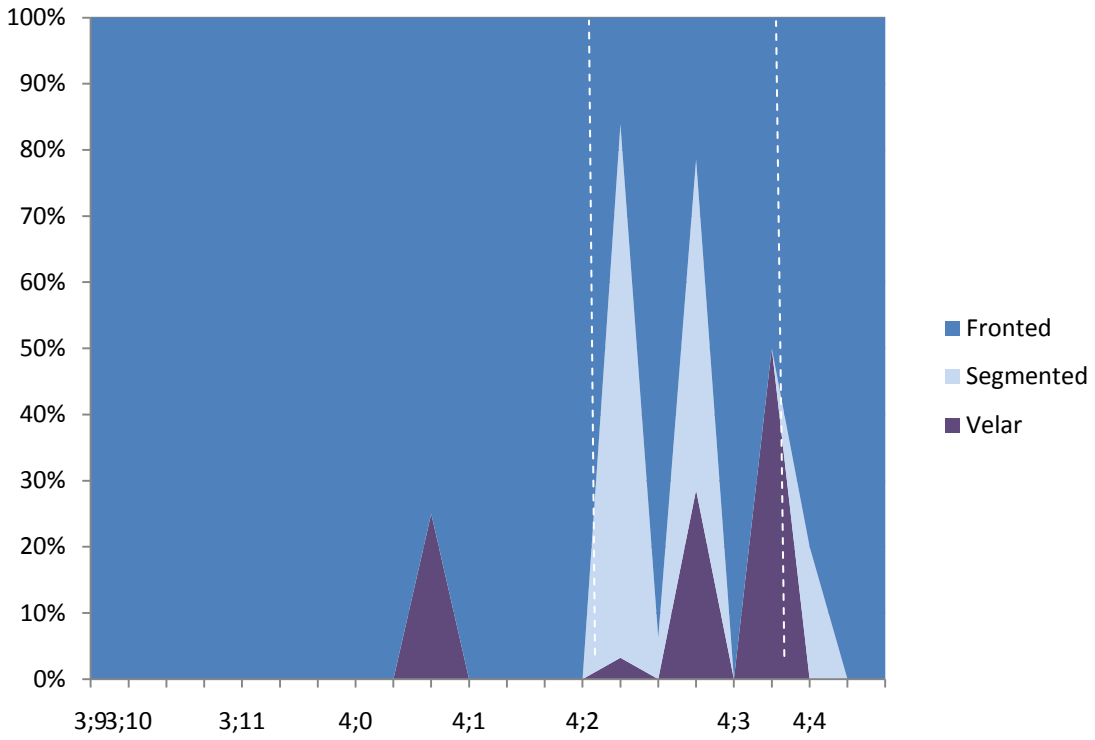


Figure 7 depicts the frequency of the same three output categories in the pretonic (strong) word-medial position. For more than half of the recorded period, B was consistent in applying fronting in this position, which thus patterned with the word-initial context. However, in the medial posttonic context a transition became apparent starting at around four years, two months of age. At this point, B began to make use of a segmented pattern of production for velars in the word-medial pretonic context. Accurate velar production began to emerge shortly thereafter. Thus, in addition to the stage boundary that was inserted in the previous graph, here a second stage boundary can be added between 4;2 and 4;3. This boundary corresponds with the emergence of velar place (with either segmented or fully accurate manner) in word-medial pretonic contexts.

This graph is somewhat more difficult to interpret than the previous one due to substantial session-to-session variability throughout B's Stage 3. Recall that the percentages calculated for this prosodic context are based on variable but generally small numbers of observations. The uniform application of fronting in the last session appears to reflect a chance fluctuation in a session with especially few tokens, since only three pretonic medial velars were recorded on this date. On the other hand, an average of 18 tokens were recorded per session during the period from 4;2 to 4;3, suggesting that the increasing attestation of segmented and accurate velar productions over this period was not accidental.

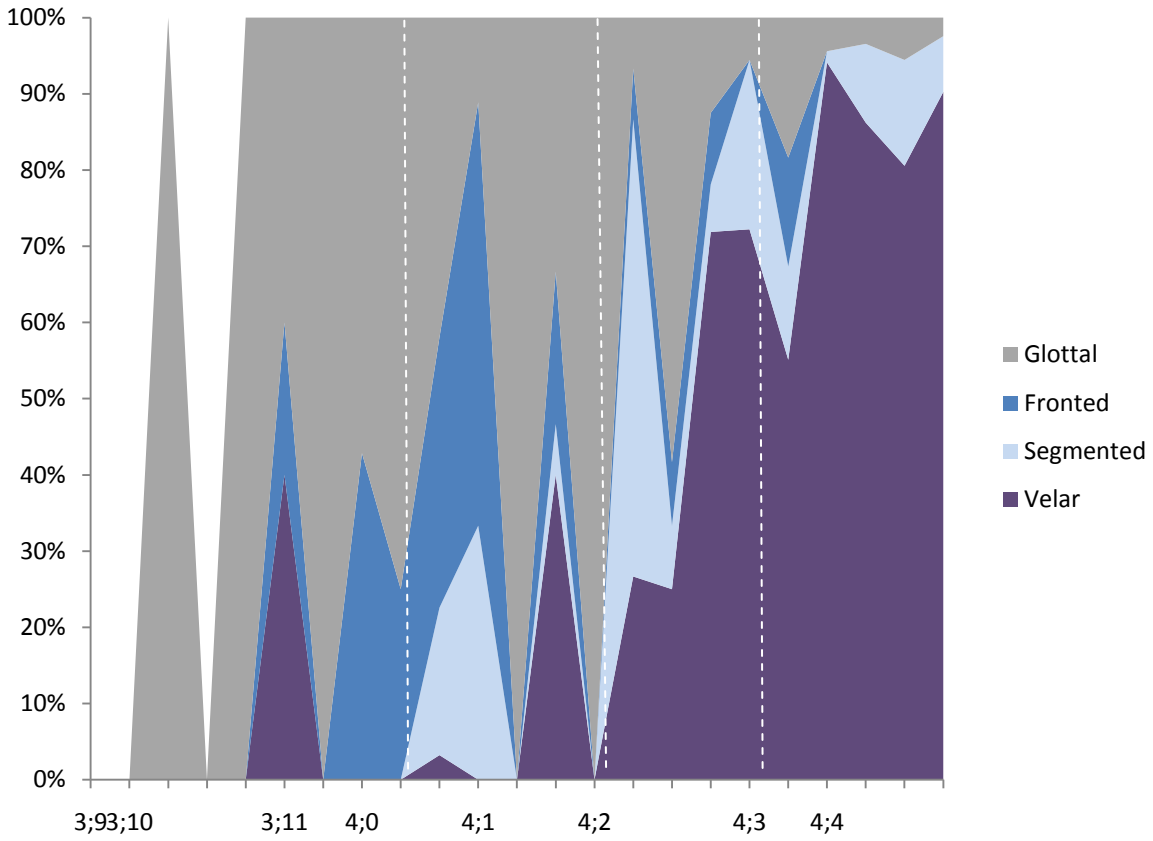
Figure 7. Percentage of tokens transcribed in four response categories, medial pretonic position



Lastly, Figure 8 represents the frequency of four processes in word-medial posttonic contexts. Here, in addition to fronted, segmented, and faithful velars, we see an additional category of glottal replacement, which was not an active repair for either of the two previous contexts. In the earliest stage, glottal replacement (e.g. [daʔ oʊ] for *tiger*) constituted the most favored repair. Fronted production was also attested from an early stage. A transition in B's production of medial posttonic velars can be identified between 4;0 and 4;1, with the emergence of a pattern of segmented velar production in weak word-medial contexts. Apart from one anomalous session early in the recorded period, this was his first replicable use of velar place, although in this early stage it was realized with pre- or post-glottalization. Adding a boundary at this point, we have now divided B's development of velar production into four rough stages. Note that the boundary demarcating the third stage, which was originally added based on a pattern in the pretonic word-medial context, also coincides approximately with changes in the posttonic context (i.e. a rapid increase in accurate velar production).

In his second and third stages of development, B's realization of medial posttonic velars was divided by the voicing specification of the adult target. Voiceless velars were realized with either segmented manner or glottal replacement throughout this interval. Voiced velars were generally fronted during B's Stage 2, whereas in Stage 3 they tended to be produced with faithful velar place. The role of voicing in conditioning B's realization of velar targets will be addressed in Section 6.

Figure 8. Percentage of tokens transcribed in four response categories, medial posttonic position



Thus, inspection of changes in B's application of repair strategies in velar target production has identified four rough stages in his acquisition of velar place, summarized in Table 1. The stages are not of equal length, becoming shorter in later stages of development as changes in B's velar production unfolded at an increasingly rapid pace. In a subsequent section, these developmental stages will serve as one independent variable in an analysis undertaken to provide a more detailed characterization of phonetic factors influencing B's production of velar targets.

Table 1. Summary of stages in B's acquisition of velar place

Stage	**Dates**	**Word-Initial Velar**	**Word-Medial Pretonic Velar**	**Word-Medial Posttonic Velar**	**Word-Final**
1	3;10 – 4;0.21	Fronted.	Fronted.	Generally debuccalized.	Generally debuccalized.
2	4;0.28 – 4;2.12	Fronted.	Fronted.	*Voiced*: Predominantly fronted. *Voiceless*: Debuccalized or segmented.	Mostly faithful with some ongoing debuccalization.
3	4;2.19 –	Fronted.	Predominantly	*Voiced*:	Faithful.

	4;3.6		fronted or segmented.	Predominantly faithful. *Voiceless*: Debuccalized or segmented.	
4	4;4 +	*Voiced*: Faithful. *Voiceless*: Segmented.	Limited data available.	Faithful.	Faithful.

5.3 Factors conditioning the accuracy of velar production

The previous section offered a qualitative overview of B's patterns of velar production as they changed over time. This section will offer statistical analysis of specific factors influencing his accuracy in velar production. The factors of prosodic context (initial, medial pretonic, or medial posttonic)[16] and developmental stage (Stages 1-4, identified above) will be included as independent variables in this analysis. Each token was additionally coded for the place of the following vowel (back or nonback). Vowel context was regarded as a factor of potential significance based on evidence that some child speakers produce velar place more accurately in the environment of a back vowel. Williams & Dinnsen (1987) described a child with phonological delay who produced velars and coronals in complementary distribution, such that coronal place occurred with front vowels and velar place with back vowels. Likewise, in an analysis of the frequency of consonant place errors across vowel contexts, White (2001) reported that errors for /t/ occurred with greater frequency in the context of a back vowel (/tu/), while errors affecting /k/ were most frequent in the context of a front vowel. Two additional factors were included in the analysis of velar production accuracy. First, each velar was coded for voicing specification, which in B's case had two components. Because B exhibited robust processes of prevocalic voicing and final devoicing over most of the recorded period, the consonants he produced were often transcribed with a voicing specification that differed from the adult target (e.g. [bok] for *pig*). Thus, transcribed and target voicing features were recorded separately for each velar token. In adult phonologies, voiceless velars are favored over voiced velars, such that many languages feature a gap in the phonemic inventory at *[g]; this has been attributed to aerodynamic factors that will be reviewed in detail below (Ferguson, 1975; Locke, 1983). Based on this evidence, it was predicted that voiceless velars would be produced with greater accuracy than voiced velars in B's output. Lastly, each word containing a velar target was coded for the presence or absence of another velar elsewhere in the word, which could potentially create an environment for consonant harmony. Harmony was predicted to have a potentially facilitative impact on the accuracy of B's velar production. The presence/absence of other velars was based on B's transcribed production rather than the form of the adult target word.

[16] Recall that word-final velars, which were realized with a high level of accuracy from an early stage, were not coded for this analysis.

Table 2 summarizes the factors that were taken into consideration in the analysis of B's acquisition of velar place. The hypotheses associated with each proposed conditioning factor will be discussed in greater detail throughout the following section.

Table 2. Summary of factors coded in analysis of velar productions

Independent Variable	**Levels**	**Null Hypothesis**	**Experimental Hypothesis**
Prosodic Context	Onset Medial Pretonic Medial Posttonic	Velar place is produced equally well in weak and strong contexts.	Velar place is produced with greater accuracy in a weak context (medial posttonic) than a strong context (initial/medial pretonic).
Developmental Stage	1 2 3 4	Velar place is produced with constant accuracy over time.	Velar place is produced with increasing accuracy over time.
Vowel Context	Back Nonback	Velar place is produced equally well in back and nonback vowel contexts.	Velar place is produced with greater accuracy in the context of back vowels.
Voicing: Adult Target	Voiced-A Voiceless-A	Velar place is produced equally well in the context of [+voice] or [-voice] targets.	Velar place is produced with greater accuracy in the context of [-voice] targets.
Voicing: B's Output (Transcribed)	Voiced-B Voiceless-B	Velar place is produced equally well in the context of [+voice] or [-voice] production.	Velar place is produced with greater accuracy in the context of [-voice] production.
Harmony (Presence of other velars)	Present Absent	Velar place is produced equally well in harmonizing and non-harmonizing environments.	Velar place is produced more accurately in the context of another velar than in isolation.

To determine which factors served as significant predictors of accuracy in velar production, the coded corpus of attempted velar productions was analyzed using logistic regression. The independent variables were the six parameters identified in Table 2.The dependent variable was accuracy in velar production. For purposes of the regression analysis, only fully correct velar productions were assigned a score of 1. All other response categories, including fronted, segmented, and glottal replacement forms, were assigned a score of 0. Note that even though pre- and post-glottalized forms were realized with velar place, they were perceptually anomalous and thus were not included among faithful velar productions.

Table 3 presents the results of the logistic regression analysis. The significance of each factor was determined using the likelihood ratio test on the residual deviance statistic, with terms added

sequentially to the model in the order indicated. Factors for which an effect was strongly predicted were added to the model before factors whose predicted effect was less extensively supported by previous research. Results significant at the $p < .05$ level are marked in bold. Significant effects were observed in connection with several of the experimental variables set out in Table 2, including developmental stage, prosodic context, voicing as specified by the adult target, and presence of another velar (harmony context). In addition, the logistic regression revealed significant or near-significant interactions between a number of experimental variables, also reported in Table 3. All factors participated in a significant interaction with developmental stage, indicating that no production variable applied in a completely uniform fashion across the period of study. Both main effects and interaction effects will be discussed in detail in the section to follow.

Table 3.Results of logistic regression analysis, first-order effects

Factor	Df	Deviance	Residual Df	Residual Deviance	p < |Chi|
Stage	3	366.6	1692	1549.5	**<.000**
Position (Prosodic Context)	2	248.3	1690	1301.3	**<.000**
Voicing (Adult Target)	1	169.6	1689	1131.7	**<.000**
Voicing (Transcribed)	1	0.0	1688	1131.7	0.92
Vowel Context	1	1.1	1687	1130.6	0.29
Harmony (Other velar)	1	7.4	1686	1123.2	**.01**
Stage : Position	6	50.5	1680	1072.7	**<.000**
Stage : Voicing (Adult)	3	29.7	1677	1043.1	**<.000**
Stage : Voicing (Trans.)	3	11.5	1674	1031.6	**0.01**
Stage : Vowel Context	3	10.3	1671	1021.3	**0.02**
Stage : Harmony	3	14.9	1668	1006.4	**<.000**
Position : Voicing (Adult)	2	19.1	1666	987.2	**<.000**
Position : Voicing (Trans.)	2	1.1	1664	986.1	0.57
Position : Vowel Context	2	0.6	1662	985.5	0.76
Position : Harmony	2	2.5	1660	983.1	0.29
Voicing (Adult) : Voicing (Trans.)	1	2.9	1659	980.2	0.09
Voicing (Adult) : Vowel Context	1	1.9	1658	978.3	0.17
Voicing (Adult) : Harmony	1	0.8	1657	977.5	0.37
Voicing (Trans.) : Vowel Context	1	0.1	1656	977.4	0.73
Voicing (Trans.): Harmony	1	0.7	1655	976.7	0.4
Vowel Context : Harmony	1	5.6	1654	971.1	**0.02**

6. Discussion of factors conditioning the accuracy of velar production

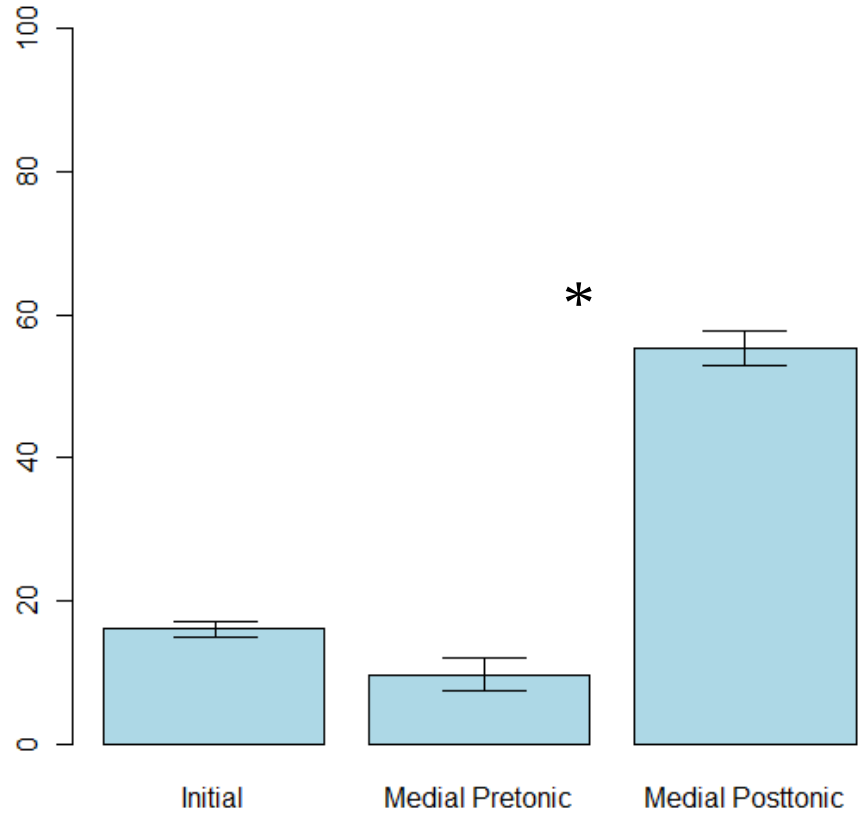
Having identified several factors that served as significant predictors of accuracy in B's velar productions, here we will examine each of these factors in detail. However, the factor of developmental stage was already explored in Section 5.2 and will not be reconsidered here. On the other hand, an additional factor that was not included in the logistic regression will be incorporated into this discussion. This is the presence of glottalization in the environment of a

velar target, which appeared to facilitate the realization of velar place in B's output. It will be argued that each of these facilitating factors can be understood to reduce the level of intraoral pressure during velar articulation, permitting a less forceful articulatory gesture and thus diminishing the likelihood of undifferentiated gesture production in connection with the constraint MOVE-AS-UNIT.

6.1 The role of prosodic context

From previous accounts of positionally conditioned patterns of velar fronting (e.g. Chiat, 1983; Bills & Golston, 2002; Inkelas & Rose, 2008), it was predicted that B's production of velar targets would be more accurate in prosodically weak relative to prosodically strong contexts. This prediction was supported by the results of the present analysis, as depicted in Figure 9. Collapsed over time, the word-medial posttonic context was associated with significantly greater accuracy than either of the two strong positions, word-initial or word-medial pretonic. The difference between initial and medial pretonic targets did not reach significance. It should be kept in mind that the highest accuracy was in fact associated with velar targets in word-final position, but specific percent accuracy data were not recorded for coda velars due to the large number of tokens and low incidence of fronting in this data set.

Figure 9. Percent correct velar production across prosodic contexts



In addition to comparing accuracy collapsed over time, we can comment on the role of prosodic environment in B's acquisition of velar place by comparing the chronological order in which faithful production emerged across different contexts. Although word-initial and word-

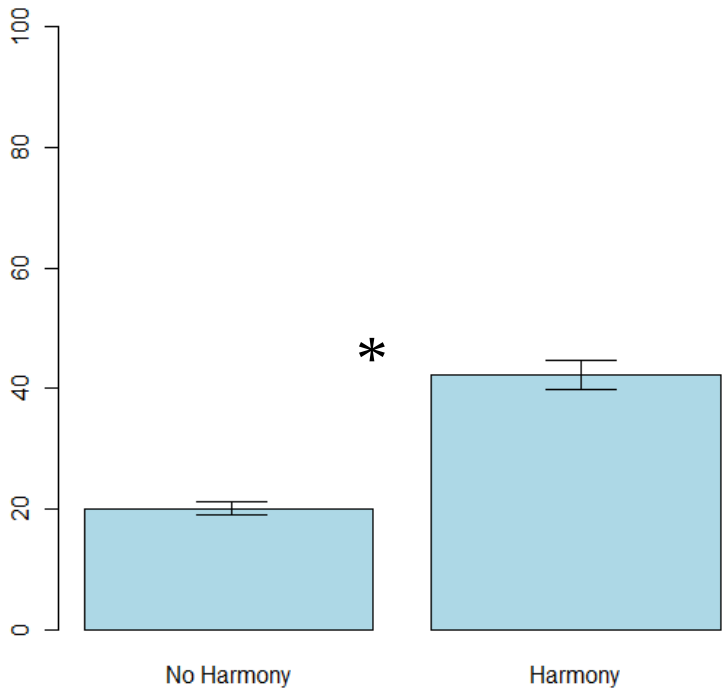
medial pretonic positions were associated with similarly low overall percent accuracies, B began to approximate appropriate velar production at an earlier stage in the word-medial context. Previously, Figure 7 showed that B began to produce word-medial pretonic velars with a segmented manner at around four years, two months of age, with appropriate velar production emerging shortly thereafter. However, Figure 6 revealed that in the word-initial context, velar place with either segmented or appropriate manner of production did not appear until more than six sessions later, when B was around four years, four months old. This finding is of some interest in that previous studies of positional velar fronting have not differentiated between initial and word-medial pretonic contexts as environments for velar fronting. In Section 7, it will be proposed that this distinction can be attributed to gradient differences in the strength of articulatory contact in word-initial versus word-medial pretonic contexts.

The significant stage by position interaction reported in Table 3 reflects fluctuations in the relative accuracy of initial and medial pretonic velars over time: medial pretonic velars were produced more accurately in the first and the third stages, initial velars in the second and final stages. Given the small number of tokens recorded for the medial pretonic context, it was hypothesized that this interaction was largely the consequence of accidental fluctuations across sessions and stages.

6.2 The role of harmonizing environments

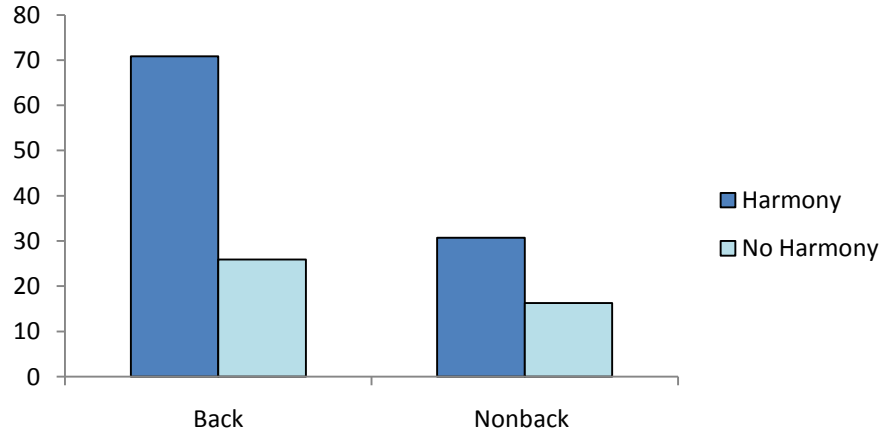
Each velar target analyzed in the present investigation was coded for the presence or absence of additional velar consonants in the word. For example, B's production [deik] for *cake* contains a coda velar in addition to the velar coded in word-initial position. If an additional velar was present in the adult form but not realized in B's output (e.g. [deiʔ] for *cake*), no velar context was coded. It was hypothesized that the presence of additional velars could facilitate faithful velar place through a type of harmonizing interaction. This is in keeping with the proposal that consonant harmony reflects a child-specific articulatory preference for repeated production of identical gestures over alternating realization of different places of articulation (e.g. Pater, 1997). Figure 10 shows that this hypothesis was supported, such that velar targets in the context of one or more other velars were realized with significantly greater accuracy than velars in isolation. Because the consonant harmony phenomenon will be described in detail in Chapter 6, complete discussion of this result will be deferred until then. It will be proposed that successive realizations of identical consonant gestures can give rise to coarticulatory undershoot, with the consequence that two velars in succession are realized with a slightly lower articulatory target than a velar followed by a consonant with a different place of articulation. This is in keeping with the proposal, put forward in full in Section 7 of this chapter, that a low articulatory target played a crucial role in permitting faithful realization of velar place in B's output.

Figure 10. Percent correct velar production by presence of other velars



It was additionally noted that the factor of consonant harmony participated in significant interactions with the factors of developmental stage and vowel context. The interaction of harmony with developmental stage reflected the fact that velar targets in harmony contexts were realized with enhanced accuracy in B's Stages 1, 2, and 4, whereas in Stage 3 isolated velars were realized with greater accuracy than velars in an environment for harmony. The cause of this reversal was not clear. The interaction of consonant harmony with vowel context, depicted in Figure 11, reveals that the influence of harmonizing context on velar production accuracy was greater in the context of a back vowel than a nonback vowel. This is consistent with the claim that repetitive sequences of tongue body gestures are associated with a lower height of the articulatory target, facilitating faithful velar production. This interaction will also be addressed in Chapter 6.

Figure 11. Interaction of vowel context with harmony environment (presence of other velar)



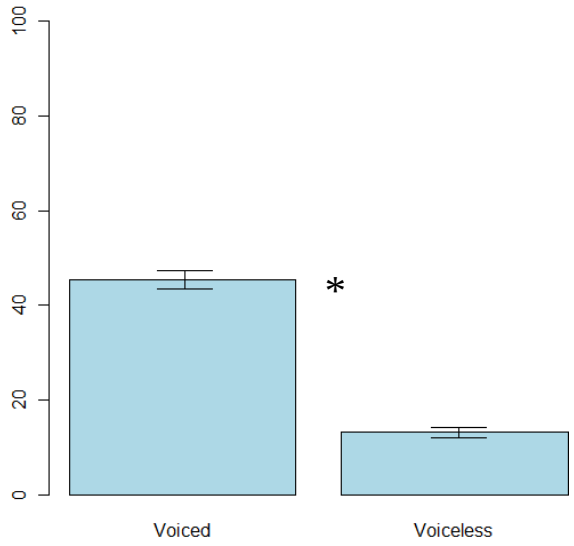
6.3 The role of voicing

Voicing was included as an independent variable in the regression model due to evidence that voiced and voiceless velars are associated with different degrees of articulatory difficulty. This difference is rooted in aerodynamic considerations that influencing the possibility of sustained vocal fold vibration. As discussed by Ohala (1983) and Westbury & Keating (1986), the availability of ongoing voicing depends on the existence of a pressure differential between subglottic and supraglottic spaces, with lower pressure above the level of the vocal folds. When a complete closure is created in the vocal tract, as in stop consonant articulation, pressure builds up in the space between the glottis and the point of constriction and inhibits voicing. This accumulation of pressure is more rapid in the smaller space that is created when the point of constriction is close to the glottis, as in velar consonant articulation. For this reason, voiceless velars tend to be favored over voiced velars cross-linguistically, with numerous phonemic inventories exhibiting gaps at *[g] (Ferguson, 1975; Locke, 1983). Based on the evidence from adult phonologies, it was predicted that B would produce voiceless velars with greater accuracy than voiced velars. Recall, however, that B exhibited a pattern of contextual voicing, whereby word-initial consonants tended to be voiced and word-final consonants voiceless. Thus, separate factors of target and transcribed voicing were included in the regression analysis.

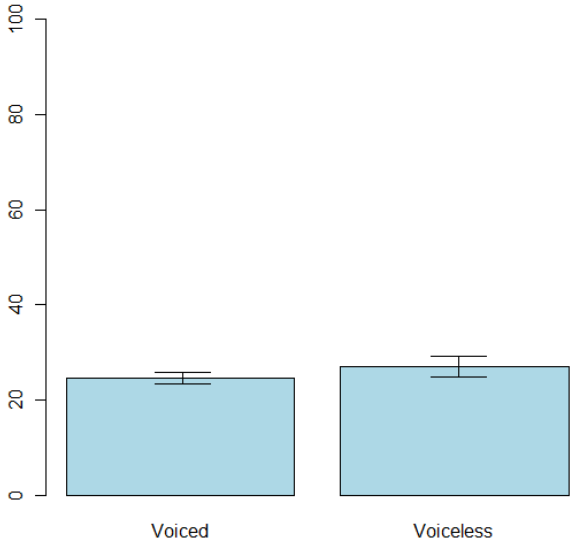
While voicing did emerge as a significant predictor of velar production accuracy in the logistic regression model, the observed effect was unexpected in two respects. First, even though there was frequent divergence between B's transcribed voicing and the voicing specification of the adult target, it was the adult target voicing rather than the transcribed voicing that had a significant effect on velar production accuracy. This result can be confirmed visually in Figure 12, where (12a) shows a clear difference in accuracy between velars specified as voiced and voiceless, but (12b) reveals no difference between velars transcribed as voiced and voiceless in B's output. Second, (12a) shows that B's voicing preference operated in the reverse of the direction that was predicted based on adult phonology: he produced voiced velar targets with greater accuracy than voiceless velars.

Figure 12. Percent correct velar production by voicing

a. Voicing specification of adult target



b. Voicing as transcribed in B's output



Looking at changes in B's patterns of velar production over time, we see three points of divergence in the realization of voiced and voiceless velars. In Stage 2, medial posttonic voiced velar targets were typically produced with fronting, whereas medial posttonic voiceless targets were debuccalized or realized with pre- or post-glottalization. Because fronted, segmented, and glottalized outputs all were scored as incorrect in the logistic regression, this particular point of divergence did not contribute to the contrast seen in Figure 9a. However, in Stage 3, B's medial posttonic voiced velars were transcribed as fully faithful, whereas voiceless targets in this context continued to show glottal epenthesis or debuccalization. Finally, in Stage 4 the equivalent contrast affected word-initial velar targets: voiced initial velar targets were fully faithful, while voiceless initial velars were produced with postglottalized manner. These contrasts are illustrated in (12)-(16).

(12) Stages 2-3: Voiceless medial posttonic velar targets are debuccalized or segmented.
a. [mʌʔi] 'making'
b. [maʔki]/[makʔi] 'monkey'

(13) Stage 2: Voiced medial posttonic velar targets are fronted.
a. [dadoʊ] 'tiger'
b. [wadi] 'froggie'

(14) Stage 3: Voiced medial posttonic velar targets are fully faithful.
a. [bʌgo] 'bagel'
b. [dagoʊ] 'tiger'

(15) Stage 4: Voiceless initial velar targets are segmented.
a. [kʔip] 'keep'
b. [kʔandoʊ] 'candle'

(16) Stage 4: Voiced initial velar targets are fully faithful.
a. [gœː] 'girl'
b. [gabaʃ] 'garbage'

These findings suggest that the effect of voicing on the accuracy of velar production was closely tied to B's use of a segmented manner of production for some voiceless velar targets. In fact, it remains to be demonstrated that the effect of voicing on velar production accuracy was not an accidental consequence of an unusual means of realizing voicing contrasts. Recall that neutralization of voicing contrasts was widespread in the transcribed record of B's speech. However, the realization of an oral stop with accompanying glottal closure gave rise to forms that, lacking transglottal airflow, were reliably perceived as voiceless. In the record of B's production of nonfinal velar targets, 61% of all productions transcribed as voiceless were also recorded as having glottal epenthesis or glottal replacement. By Stage 4, although B did produce a small number of forms with unfaithful voicing (e.g. [gij] for *key*), the majority of his productions reflected the voicing specification of the adult target. Thus far, it seems that glottal epenthesis may simply have been B's means of representing the voiced-voiceless contrast in a prevocalic context, and by failing to include pre- or post-glottalized velars in the category of

faithful velar place, this analysis artificially imposes an effect of voicing on velar production accuracy. However, there are several pieces of evidence indicating that segmented manner was specifically related to the realization of velar place, which will be reviewed in the remainder of this section. In the analysis to follow, it will be argued that glottal closure in the immediate environment of a velar target served to limit the level of intraoral pressure pushing on the velar constriction. With lower pressure, the velar target can be realized with lighter articulatory contact, which in the MOVE-AS-UNIT analysis pursued here plays a crucial role in dictating the availability of faithful velar production.

To pursue this proposal, our immediate task is to determine the extent to which preglottalization was a specific correlate of velar production, rather than a general attribute of B's production of voiceless prevocalic consonants. In fact, preglottalization was sometimes transcribed for non-velar consonants in word-medial posttonic positions, as illustrated in (17).

(17) Examples of preglottalization of non-velar consonants

(a) [iʔ tiŋ]	'eating'
(b) [baʔ pij]	'puppy'

However, the incidence of preglottalization was qualitatively observed to be lower in the context of nonvelar relative to velar targets. To test the significance of this difference, the percent application of preglottalization was calculated for both velar and nonvelar targets in a portion of the transcribed record of B's productions. Stage 2 (ages 4;1 – 4;2), which was associated with the highest incidence of preglottalization in velar target production, was selected for this computation. For each session in this stage, all coronal, labial, and velar stops in word-medial posttonic contexts were identified and coded for the presence or absence of glottal closure. As in the analysis of velar consonants alone, tokens were categorized as preglottalized only if the first-pass transcription made note of glottal closure preceding the oral consonant constriction. This analysis revealed that 8.5% of B's non-velar medial consonants in this stage were transcribed with preglottalization, whereas 25% of medial velars were perceived to be preglottalized during this same stage. Student's *t*-test revealed this to be a significant difference ($p < .01$). This finding might be questioned on the grounds that a lower incidence of segmented production could be expected for coronal consonants in medial posttonic contexts, since in the adult model, these would typically be voiced due to flapping. However, an influence of flapping on the relative frequency of voicing would not influence the behavior of word-medial labials. In the sample analyzed here, word-medial labials were evenly divided between voiced and voiceless specifications, but they were almost never transcribed with preglottalization.

In word-initial position, postglottalized manner was originally observed only for velar stops. It subsequently spread to affect some initial labial stops, although the frequency of attestation was lower for labial than for velar contexts. This manner of production was never transcribed in connection with initial coronal stops. Instead, at the stage when initial voiceless velars were transcribed with postglottalization, B continued to exhibit prevocalic voicing of voiceless coronal targets. Examples 18-19, drawn from a single session in B's Stage 4, illustrate the contrasting behavior of voiceless coronal and velar stops in word-initial position.

(18) Stage 4: Voiceless coronal targets are produced with prevocalic voicing.

a. [dakiŋ] ‘talking’
b. [dʊkij] ‘turkey’

(19) Stage 4: Voiceless velar targets are produced with postglottalization.
a. [kʔʌt] ‘cut’
b. [kʔɔf] ‘cough’

Finally, it is worth noting that postglottalized production of initial voiceless velars appeared as something of an idiosyncratic strategy in B’s phonology; it is not a process one might observe in typically developing children emerging from a process of neutralization of voicing contrasts. The pause between the velar release and the glottalized onset of the vowel was of high perceptual salience, giving B’s speech in this stage an unusual quality. It was speculated that B’s use of this rather drastic strategy was in part a response to his participation in speech therapy targeting velar production. While he had not yet emerged from under the motor constraints limiting his production of typical word-initial velars, he was highly aware of the adult target form and was trying mightily to reproduce it. Postglottalized production thus appeared as something of a last-ditch effort to preserve velar place.

The sum of the evidence presented here suggests that preglottalization in medial posttonic contexts was specifically linked to the realization of velar place in B’s output. The postglottalized pattern of production for initial voiceless velars, shown in (19), is of particular interest in that it coincided with faithful realization of voiced initial velars. Thus, a satisfactory account of B’s acquisition of velars will need to explain why the postglottalized velar is easier to produce than a voiceless velar but more difficult to produce than a voiced velar. This challenge can be met by an analysis in which the application of velar fronting is conditioned by differences in intraoral pressure, to be proposed in the following section.

7. A unified account of conditioning factors as minimization of articulatory force

B’s acquisition of velars differs from the pattern reported for Inkelas & Rose's subject E, who exhibited velar fronting uniformly across strong positions, then abruptly eliminated the process from all positions. The gradual and variable acquisition of velar place described here can be compared to Berg’s (1995) description of his daughter’s protracted acquisition of velars in German. However, while Berg posited that his daughter’s velar acquisition was lexically governed, in B’s case it is possible to isolate a number of phonetic conditioning factors. The statistical analysis in the preceding section demonstrated that B’s accuracy in velar place production was conditioned by prosodic context, voicing, and the presence of other velar targets. The presence of pre- or post-glottalization was related to the realization of the voiced-voiceless contrast but also appeared to play a role in faithful production of velar place.

This section will demonstrate that the conditioning factors of prosodic context, voicing, and glottalization can be unified under a single analysis reflecting differences in articulatory strength and intraoral pressure. It will be shown that each of the environments found to facilitate faithful velar production in B’s speech is associated with a relatively low level of intraoral pressure. Evidence will also be presented demonstrating that a stop consonant gesture is produced with greater force in the context of an elevated level of intraoral pressure. In Chapter 2

it was argued that children have difficulty executing discrete lingual gestures, and this difficulty increases as the tongue moves further from its source of support, the jaw. This difficulty will be formally encoded with the constraint MOVE-AS-UNIT, whose violations increase in magnitude with increasing height of the articulatory target. Lastly, it will be argued that when MOVE-AS-UNIT is satisfied, the typical pattern of linguopalatal contact associated with jaw-dominated movement begins at a posterior point and spreads into the coronal region, resulting in the percept of a coronal stop. The combination of speech-motor and aerodynamic factors proposed here can explain all of the major patterns that characterize B's acquisition of velars, including the preference for weak over strong contexts, the advantage for voiced over voiceless targets, and the use of glottalization as a repair strategy in the environment of velar targets.

7.1 Intraoral pressure and articulatory strength

This section will review evidence that different prosodic contexts and laryngeal specifications are associated with differing levels of intraoral pressure. When intraoral pressure is high, a stronger consonant gesture is required to offset the force of the air pressing on the point of oral constriction. Crucially, it will be seen that the contexts associated with the lowest intraoral pressure, permitting smaller, less forceful gestures, are precisely the contexts in which B produced velars with greatest accuracy.

7.1.1 Prosodic context and articulatory strength

Stop consonants, produced with a complete closure at some point in the vocal tract, involve a buildup of pressure behind the point of the constriction. It has been demonstrated that consonants in word-initial and stressed positions are associated with higher intraoral pressure than final or posttonic consonants. Malécot (1955) reported that word-initial consonants were associated with higher peak pressures and impulse values than word-final consonants. Ladefoged (1967) and Ladefoged & Loeb (2002) found that stressed syllables are produced with additional respiratory effort, including increased recruitment of the internal intercostal muscles, which actively force air out of the lungs. The elevated subglottal pressure associated with this expiratory force is passed on to create higher intraoral pressure during stop closure.

When high levels of intraoral pressure impinge on the point of constriction in the vocal tract, more forceful contact must be exerted to maintain a seal (Stetson, 1928; Leeper, 1969). Accordingly, positional differences in intraoral pressure can be seen to correlate with positional differences in articulatory strength. For instance, Browman & Goldstein (1995) reported significantly greater displacement for both lingual and labial consonants in syllable-initial relative to syllable-final contexts in a single-subject x-ray microbeam study. Keating (1995) used electropalatography to investigate the extent of consonant constriction in coronal stop production in word-initial and word-final positions in two subjects, where contexts for target consonants could be stressed (**t**imid, emi**t**) or unstressed (**t**imidity, limi**t**). Both of Keating's subjects exhibited more extensive linguopalatal contact in word-initial position relative to word-final position; the difference reached significance in one subject, while the second subject showed a significant initial-final distinction in stressed but not unstressed syllables. Additional evidence from studies by Keating & Fougeron (1997) and Fougeron (1999) was briefly reviewed in Section 4.2 of this chapter. The sum of the evidence from these studies supports the conclusion that "constrictions are generally tighter syllable-initially than -finally" (Krakow, 1999, p. 34). B's preferential realization of velar place in non-initial and unstressed contexts supports the

hypothesis that low intraoral pressure and correspondingly small articulatory gestures are facilitative of faithful velar production.

7.1.2 Voicing and articulatory strength

It has been demonstrated that voiceless consonants are produced with greater mean and peak intraoral pressure than voiced stops (e.g. Ladefoged & Maddieson, 1996). This pressure difference reflects the fact that voiceless consonants are produced with greater airflow than voiced consonants (Isshiki & Ringel, 1964), a contrast which in turn can be attributed to the impedance introduced by the vibrating vocal folds in the latter case (McGlone and Shipp, 1972).

Voiced and voiceless stops have also been associated with a number of articulatory differences, recently summarized by Hamann & Fuchs (2008). Voiceless stops are produced with more extensive linguopalatal contact (Moen & Simonsen, 1997). Wakumoto, Masaki, Honda & Ohue (1998) demonstrated that voiceless /t/ was produced with greater linguopalatal pressure than voiced /d/, which they inferred to indicate higher tongue position in /t/. Other studies have demonstrated that /t/ is produced with a higher jaw position than /d/ (Fujimura & Miller, 1979; Mooshammer et al., 2006, 2007). Ladefoged & Maddieson (1996) posited that these articulatory differences can be attributed to the need for a firmer seal at the place of articulation in voiceless stops relative to their voiced counterparts. Thus, differences in the strength of closure for voiced and voiceless consonants can be attributed to the differences in subglottal pressure associated with these two laryngeal states. Again, B's velar production was more accurate in the context associated with lower articulatory force, namely for voiced over voiceless targets.

7.1.3 Glottalized production and articulatory strength

Finally, we can consider the influence that glottal closure exerts on levels of intraoral pressure and thereby articulatory strength. The introduction of glottal constriction in the vicinity of the consonant target has the effect of valving the pressure from the lungs below the level of the articulatory constriction. This limits the magnitude of any buildup in intraoral pressure behind the consonant closure. Clements & Osu (2002) defined a class of "non-explosive" consonants in which they included implosive stops, both voiced and voiceless, as well as laryngealized, glottalized, and preglottalized stops. They posited that the feature defining this class was "the absence of air pressure buildup in the oral cavity." B's preglottalized productions can be characterized as members of the class of non-explosive consonants. The postglottalized manner of production, observed in some word-initial and medial posttonic contexts, appears as a slightly different means of limiting intraoral pressure. In B's postglottalized consonants, the oral constriction was released with a small amount of aspiration, followed by a pause and then the glottalized onset of the vowel. Because the accumulation of pressure for the vowel occurs behind the glottal closure, not the oral consonant constriction, the postglottalized manner also serves to limit the level of intraoral pressure impinging on the consonant constriction in the oral cavity.

Based on strong evidence of a relationship between intraoral pressure and articulatory force, as described above, it can be inferred that the pressure-limiting effect of pre- or post-glottalized production allows for particularly light articulatory contact. B's use of glottalization in the context of velar production can thus be understood as a means of averting a buildup of intraoral pressure that could interfere with faithful realization of velar place. This is consistent with the finding that, while glottalized production could be observed for voiceless stops with other places of articulation, it was most robustly attested in the context of a velar target.

In summary, this section demonstrated that B was consistently seen to produce velar consonants with greater accuracy in contexts that are associated with reduced levels of intraoral pressure and hence with potentially lower levels of articulatory strength. The following section will present the relation between the height of the articulatory target, the magnitude of the violation of MOVE-AS-UNIT, and the execution of undifferentiated gestures perceived to be fronted.

7.2 Velar fronting as a reflection of coordinated tongue-jaw movement

As reviewed in Chapter 2, investigations of articulatory maturation have converged on the finding that children are significantly limited in their ability to isolate the movement of an individual articulator, with control of the tongue posing a particular challenge for young speakers (Kent, 1992; Fletcher, 1992). This gives rise to the phenomenon of mandibular dominance in early articulation, whereby lingual consonants are realized through movements of the entire tongue-jaw complex instead of discrete tongue-tip or tongue-blade gestures. It was posited that this articulatory pressure asserts itself in child grammar through the action of the constraint MOVE-AS-UNIT, repeated in (20). The influence of MOVE-AS-UNIT is most prominent in young infants, as reported in studies of babbling conducted by MacNeilage, Davis, and colleagues. However, the preference for jaw-dominated movement can still be discerned after children begin to exhibit the capacity for independent tongue and jaw movement, as demonstrated by their production of consonant-vowel strings with separately specified places of articulation. In the work by Edwards et al. (1999) reviewed in Section 3 of this chapter, both typically developing and phonologically delayed four-year-old children studied by were found to produce lingual stops with a more ballistic manner than an adult comparison group.

(20) MOVE-AS-UNIT: Lingual targets are produced with movements of the tongue-jaw complex.

The relation between the height of the articulatory target and the pressure to move the tongue-jaw complex as a single unit was discussed in Chapter 2. It was noted that even children with a highly active MOVE-AS-UNIT constraint can be seen to exercise some degree of independent control over lingual movements. Because the tongue depends on the jaw for stability, however, the magnitude of the violation of MOVE-AS-UNIT increases as successively higher targets move the tongue increasing distances away from the jaw. A proposal that children might satisfy MOVE-AS-UNIT without producing an undifferentiated gesture by moving the jaw partway to the palate and then executing a discrete lingual gesture of the acceptable magnitude was rejected, since this controlled coordination of distance-crossing and homing gestures is unavailable to speakers with limited speech-motor control.

When a child moves the entire tongue-jaw complex in accordance with MOVE-AS-UNIT, both tip/blade and body regions of the tongue are tensed and contact the palate in a pattern dictated by the movement of the mandible. As a consequence, gestures that satisfy MOVE-AS-UNIT typically result in undifferentiated patterns of linguopalatal contact, as described by Gibbon (1999). In the following section it will be seen that the undifferentiated closures produced in conformity with MOVE-AS-UNIT effects are habitually perceived as coronal, giving rise to the velar fronting phenomenon.

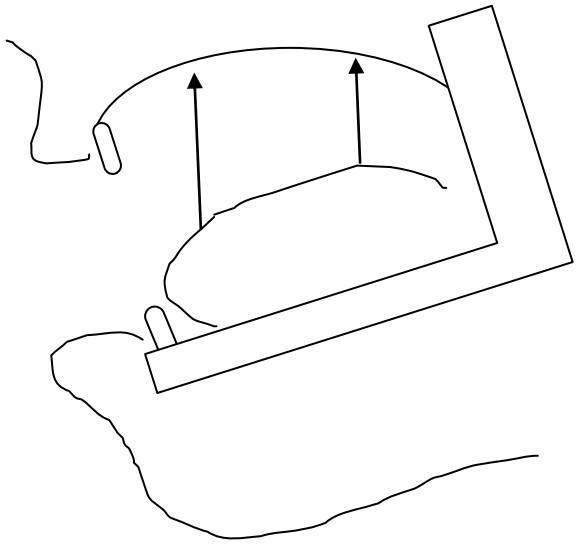
7.3 The coronal percept in jaw-dominated production

Gibbon (1999) noted that children's undifferentiated gestures were sometimes transcribed as coronal and sometimes as velar by adult listeners. She noted that listeners' judgment of consonant place could be seen to correlate with the sequencing of the release gestures for coronal and velar components of the undifferentiated closure, such that the later release tends to predominate in perception. Thus, a pattern of velar fronting is predicted in a child who produces undifferentiated closures and also tends to phase the release of the velar closure in advance of the coronal release. In fact, there are independent articulatory grounds for believing that this phasing should be the default sequence in children who produce undifferentiated gestures as a consequence of an active MOVE-AS-UNIT constraint.

In adult articulation, if tongue-tip and tongue-body gestures are initiated roughly simultaneously, we expect tongue-tip contact to be achieved first. This is because tongue tip gestures are more rapid than tongue body gestures, a consequence of the smaller mass and greater mobility of the anterior portion the tongue (Pouplier & Goldstein, 2005). By contrast, electropalatographic studies of child articulation have reported numerous instances of children whose undifferentiated gestures begin with a component of velar closure and end with contact in the coronal region (Gibbon, 1990, 1999; Gibbon, Dent, & Hardcastle, 1993). This reversal of the typical phasing of tongue-tip and tongue-body release gestures can be understood as a consequence of mandibular dominance in child articulation. Because jaw displacement has a rotational component, changes in jaw height produce a larger movement of the tongue tip than the tongue body. The anterior portion of the tongue crosses a larger distance than the posterior tongue, with the result that the tongue tip tends to be later to achieve contact with the palate. Figure 13 offers a schematic depiction of the differing distances between the palate and the anterior and posterior tongue. With linguopalatal contact thus initiated in a posterior region and spreading in an anterior direction, velar release habitually precedes coronal release in lingual gestures produced in accordance with MOVE-AS-UNIT. This gives rise to the percept of coronal place that is reported in children with velar fronting.[17]

Figure 13. Schematic representation of tongue-palate distances

[17] In their "frames, then content" hypothesis, MacNeilage & Davis (1990) posited that coronal place should co-occur with front vowels in jaw-dominated babbling, whereas velar place should co-occur with back vowels. This contrasts with the present proposal, where all lingual consonants in children with active MOVE-AS-UNIT are predicted to be perceived as coronal. In fact, the predicted cooccurrence of back vowels and velar place was supported weakly or not at all in several studies (Davis & MacNeilage, 1994; MacNeilage & Davis, 1995). The authors speculated that this weakened result reflected the absence of true velar place from some infants' productions. This is consistent with the present proposal that jaw-dominated gestures are realized with undifferentiated contact, typically perceived as coronal.



A separate but related factor further increases the likelihood that children's undifferentiated gestures will be perceived as coronal, especially in the context of forceful articulation. Inkelas & Rose (2008) proposed that strong contact between the tongue dorsum and the palate can cause the area of closure to extend anteriorly, extending into the coronal region. This hypothesis takes independent support from articulographic studies of adult speech, where stronger articulatory gestures have been associated with more anterior closure in the *velar loop* phenomenon. In the velar loop, the tongue body follows an elliptical path to and from the point of consonant closure, moving in an anterior direction at the same time it approaches the palate (Houde, 1967; Perkell, 1969; Kent & Moll, 1972; Mooshammer, Hoole, & Kuhnert, 1995). In their study of velar articulation using electromagnetic articulography (EMMA), Mooshammer et al. (1995) offered several indications that the velar loop effect is greater in the context of more forceful articulatory closure. Comparing the magnitude of horizontal displacement in voiced and voiceless velar stops, velar fricatives, and velar nasals in German, Mooshammer et al. found that anterior movement was greatest in the voiceless velar context and least in the context of velar nasals and fricatives. The voiceless stop is typically produced with the strongest linguopalatal contact, while the latter two are associated with weaker gestures. Mooshammer et al. proposed that the velar loop may reflect the translation of vertical movement into horizontal movement as the tongue dorsum contacts the palate. On this account, the anterior movement in velar articulation is a passive process, "the effect of tissue displacement as the tongue is pressed against the hard and soft palates" (p. 17). The more forceful the lingual gesture, the more pronounced this spreading should be.

Other analyses of the velar loop phenomenon in adults have explored the role of differences in intraoral pressure in predicting velar movements. As noted above, Mooshammer et al. (1995) observed the greatest magnitude of anterior displacement in the context of voiceless velars, associated with the greatest intraoral pressure, and little displacement in velar nasals, where intraoral pressure is minimal. In addition, Munhall, Ostry, & Flanagan (1991) reported greater anterior movement in velar closures in loud speech, where pressure is assumed to be higher. Hoole, Munhall, & Mooshammer (1998) found that forward movement of the tongue body was substantially diminished in the context of velar nasals relative to oral stops. However, because the anterior movement was not entirely eliminated in the context of velar nasals, which

do not involve an increase in intraoral pressure, the authors concluded that the velar loop should not be analyzed as a purely aerodynamic phenomenon. Instead, the role of intraoral pressure is best understood as indirect, a consequence of the correlation between elevated intraoral pressure and forceful articulatory contact that was set forth in the previous section.

Inkelas & Rose (2008) offered several reasons to believe that the anterior displacement of the tongue in a context for forceful articulation should be especially pronounced in child speech. Contributing factors include the comparatively large size and more anterior placement of the child's tongue, as well as the shorter length of the immature palate (Fletcher, 1973; Kent, 1981; Crelin, 1987). Inkelas & Rose posited that in the context of the child's articulatory anatomy, a gesture that is produced with relatively anterior closure in an adult speaker can be exaggerated into an undifferentiated gesture spanning velar and coronal regions of the palate. Furthermore, the jaw is habitually held higher in child articulation than in adult speech, reflecting the proportionately greater contribution of the jaw-raising gesture in a child speaker's production of a lingual stop (Howard, 1998). This higher jaw position should further enhance the anterior compression of the tongue body in children's productions of velar targets. In total, a number of anatomical and speech-motor factors converge on the conclusion that children's jaw-dominated gestures should involve undifferentiated linguopalatal contact with a perceptually prominent coronal component, giving rise to the velar fronting phenomenon.

8. Modeling velar production patterns with MOVE-AS-UNIT

8.1 MOVE-AS-UNIT and scales of articulatory effort

In the previous section, it was argued that MOVE-AS-UNIT could cause some child speakers to produce velar targets with an undifferentiated pattern of linguopalatal contact that is characteristically perceived as coronal. As it was introduced in Chapter 2, the constraint MOVE-AS-UNIT is sensitive to gradient differences in articulatory target height. This claim receives support from evidence that B consistently produced velar targets more accurately in contexts associated with limited intraoral pressure and hence a low level of articulatory force. In this section, B's pattern of velar production will be modeled with weighted constraints in a Harmonic Grammar framework. This section will spell out the MOVE-AS-UNIT violations incurred by discrete lingual targets across a variety of contexts and introduce other constraints that will be necessary to capture the processes attested in B's output. A subsequent section will demonstrate that the proposed set of constraints can successfully model B's output across various contexts and stages.

We have seen evidence that violations of MOVE-AS-UNIT are scaled to different levels of gestural strength, which in turn are closely tied to different levels of intraoral pressure. The correlation between intraoral pressure and force of articulation can be enforced by the interaction of faithfulness constraints and effort-minimization constraints. Pressure for a strong articulatory closure is derived from IDENT-manner constraints, which militate against leniting processes such as spirantization. At the same time, a general-purpose effort-minimization constraint (*EFFORT) will assign increasing penalties in the context of increasing levels of articulatory force.[18] The

[18] Note that *EFFORT, which militates against the expenditure of biomechanical energy, is playing a role distinct from that of MOVE-AS-UNIT, which specifically penalizes discrete lingual gestures. The role of MOVE-AS-UNIT will be elaborated below.

interaction of these two constraint scales ensures that the gestural force applied in a given context will be sufficiently strong to offset the level of intraoral pressure associated with that context, but no stronger than necessary. Table 4 schematizes the interaction between *EFFORT and IDENT-manner constraints. The number of violations of *EFFORT schematizes the level of articulatory effort used to produce the closure, represented as a subscript on the consonant in the candidate form. Candidate (a) in Table 4 represents a closure that is insufficiently strong, resulting in spirantization. Candidates (c) and (d) are produced with articulatory force exceeding the level required to offset intraoral pressure in this (hypothetical) context, and they are thus eliminated due to violations of *EFFORT.

Table 4. Sample schematization of weighted *EFFORT and IDENT-manner constraints

/dɔ gij/, "doggie"	IDENT-manner	*EFFORT	**TOTAL**
	2	1	
a. dɔ ɣ$_1$ij	1	1	**3**
b. ☞ dɔ g$_2$ij	0	2	**2**
c. dɔ g$_3$ij	0	3	**3**
d. dɔ g$_4$ij	0	4	**4**

While the four levels of articulatory strength represented in Table 4 are strictly hypothetical, it is desirable to be more systematic in positing a scale of articulatory target heights to be used in comparing candidates for a velar target. Table 5 lays out various factors posited to influence intraoral pressure and thereby the height of the articulatory target. The sum in the final column of Table 5 acts as an index of the articulatory height associated with a candidate of a given shape. On the hypothesis that the constraint MOVE-AS-UNIT is sensitive to gradient differences in articulatory target height, the sums in Table 5 will be encoded directly in the tableaux to follow, representing the magnitude of the MOVE-AS-UNIT violation incurred by a given candidate. Consequently, "height" and "violation" have equivalent meanings in the discussion to follow.

Each candidate produced with supraglottic constriction of the vocal tract receives a base height/violation of magnitude 1. On the assumption that intraoral pressure and articulatory force decline over the course of a word, targets occurring in non-final contexts receive one unit of height in excess of that assigned to a word-final target. A further violation of magnitude 1 is added to a candidate in a pretonic context, and likewise for a candidate with a voiceless (aspirated) laryngeal specification. Articulographic studies of adults have returned mixed results as to whether initial position, independent of stress placement, makes a significant contribution to articulatory force (Keating, 1995). However, in the longitudinal data from B, faithful production of velar place tended to emerge in medial pretonic before word-initial pretonic contexts. Thus, an additional violation of magnitude .5 was added to candidates in initial position. Finally, candidates with glottal closure have special status in the calculation of articulatory target height and MOVE-AS-UNIT violations. No violation is incurred by an isolated glottal stop. In B's productions where oral closure was accompanied by immediately preceding or following glottal closure, a single violation is incurred by the oral place gesture. However, other factors posited to influence intraoral pressure are not included in the calculation of

violations for these candidates, since closure of the glottis creates a barrier insulating the oral constriction from the influence of changes in pressure. All forms with pre- or post-glottalization are thus assigned a violation of magnitude 1.

Table 5. Calculation of MOVE-AS-UNIT violations from with articulatory strength levels

Context	Example	Oral Place	Non-Final	Pre-tonic	Voiceless	Initial	SUM
Initial pretonic voiceless	[kiŋ], *king*	+1	+1	+1	+1	+.5	**4.5**
Pretonic voiceless	[bukaj], *bouquet*	+1	+1	+1	+1		**4**
Initial pretonic voiced	[gam], gum	+1	+1	+1		+.5	**3.5**
Pretonic voiced	[ə gɛ n], *again*	+1	+1	+1			**3**
Posttonic voiceless	[maki], *monkey*	+1	+1		+1		**3**
Posttonic voiced	[dɔ gi], *doggie*	+1	+1				**2**
Final	[dak], *duck*	+1					**1**
Pre-/Post-glottalized	[mʌ ʔ kiŋ], *making* [dakʔ oʊ], *tiger* [kʔ ajn], *cane*	+1					**1**
Glottal stop	[toʔ onat], *coconut*						**0**

8.2 Other constraints

This section lays out additional constraints that will be necessary to model B's patterns of velar production. It is of particular interest to identify the faithfulness constraint or constraints that will penalize productions involving velar fronting. In contrast with traditional analyses, here velar fronting is not interpreted as a categorical phonological substitution of the feature [coronal] for the feature [velar]. Instead, fronting is hypothesized to reflect the production of undifferentiated lingual gestures in response to articulatory limitations. In the tableaux to follow, undifferentiated lingual gestures will be represented with the mid-palatal stops [c] and [ɟ], but this is strictly for notational convenience. In the present analysis, the child speaker with velar fronting actually specifies appropriate velar place for a target /k/ or /g/. However, he does so with the knowledge that if he produces such a target while satisfying the articulatory constraint MOVE-AS-UNIT, he will generate linguopalatal contact spanning both velar and coronal regions, with deviant perceptual consequences. Accordingly, here listener-oriented faithfulness constraints (Boersma, 1998) will be invoked to penalize fronted forms. The perceptually oriented constraint IDENT-Place(percept) is presented in (21).

(21) IDENT-Place(percept): A segment specified as [α place] in the input is realized

with the perceptual correlates of [α place].

In the previous section, several arguments were advanced in support of the claim that listeners will typically transcribe undifferentiated lingual gestures with coronal place. However, there is also evidence that adult listeners regard undifferentiated forms as somewhat anomalous or ambiguous in their perceptual characteristics. To reflect this slightly deviant nature of undifferentiated forms, in the analysis below an undifferentiated candidate will be penalized with an IDENT-Place(percept) violation of slightly greater magnitude than what would be assigned for a true coronal substitution. It is worth noting that, although no coronal targets will be considered in the tableaux below, the constraint MOVE-AS-UNIT militates for undifferentiated production of coronal as well as velar targets. It is thus posited that during a stage of active velar fronting, B also produced coronal targets with undifferentiated lingual gestures. Since undifferentiated gestures are transcribed with coronal place, the substitution of an undifferentiated gesture for a coronal target would not incur a violation of IDENT-Place(percept) on the order of that associated with velar fronting. However, in light of the present claim that undifferentiated gestures involve some degree of perceptual deviance from a true coronal target, a small-magnitude violation of IDENT-Place(percept) should in fact be incurred.

Other candidates to be considered below are not only deviant in their perceptual consequences, but in fact involve true processes of featural deletion or substitution. In particular, debuccalization of oral stops was frequently attested in early stages of B's development. In this process, oral stops with all places of articulation were replaced with glottal stop in a word-final or medial posttonic context. At this same stage of development, B could be seen to realize coda fricatives with faithful alveolar or postalveolar place; this asymmetry will be given detailed consideration in the following chapter. Chapter 5 will also adduce evidence that B's control of laryngeal function was advanced relative to his capacity for controlled movements of the oral articulators. For the moment, B's avoidance of consonants produced with complete constriction of the oral articulators will be encoded with a constraint *ORAL-STOP, presented in (22). If an oral stop is debuccalized in accordance with the preference expressed by *ORAL-STOP, a violation of the featural constraint MAX-Place, seen in (23), is incurred. To capture the observation that debuccalization was attested in coda but never in onset position in B's phonology, we can use a high-weighted positional faithfulness constraint banning the deletion of place features from a segment in onset position, MAX-Place-ONS (24).[19]

(22) *ORAL-STOP: Do not produce complete closure of the oral articulators.

(23) MAX-Place: For every place feature in the input, there is a corresponding place feature in the output.

(24) MAX-Place-ONS: For every place feature in an onset position in the input, there is a corresponding place feature in the output.

[19] The reader may recall that in Chapter 1, some time was dedicated to demonstrating that positional faithfulness constraints are unsuitable for modeling child phonological processes. However, this argument was particular to child-specific processes of neutralization in strong position. In the present case, where the child conforms to the adult pattern of greater contrast in strong position, it is unproblematic to invoke positional faithfulness.

Several additional faithfulness constraints will be necessary to complete the model. Because it is possible in principle to reduce the magnitude of the MOVE-AS-UNIT violation incurred by a consonant target by producing a voiced rather than a voiceless segment (see Table 5 above), an IDENT-voice constraint will be needed to deal with candidates with unfaithful voicing.

(25) IDENT-voice: A segment specified as [α voice] in the input is [α voice] in the output.

A DEP-glottal constraint will be required to contend with repairs involving glottal epenthesis, including both pre- and post-glottalization. Both general and positional DEP-glottal constraints, seen in (26) and (27), will be invoked in the analyses to follow. Note that no violation of DEP-Glottal will be incurred by candidates with debuccalization, since the glottal stop in these forms represents the target consonant with its place node deleted.

(26) DEP-glottal: For every glottal segment in the output, there is a corresponding glottal in the input.

(27) DEP-glottal-ONS: For every glottal segment in onset position in the output, there is a corresponding glottal in the input.

9. Implementation of constraints

9.1 B's Stage 1

In this and following chapters, analyses will be presented using weighted constraints in a Harmonic Grammar framework. The transition from one stage to the next can thus be represented by adjusting the weights assigned to key constraints. It will be demonstrated that the set of weighted constraints proposed here can capture the differing behavior of velar targets across the various prosodic contexts and stages of B's development.

Table 6 lays out the weights that will be used to model this first stage of B's development. In the earliest stage for which data are available, B was consistently perceived to front both voiced and voiceless velar targets in strong positions, namely word-initial and word-medial pretonic contexts. At the same time, word-final and word-medial posttonic velars were most typically replaced with glottal stop. The top-weighted constraint in this stage is the positional faithfulness constraint MAX-Place-ONSET, followed by the markedness constraints MOVE-AS-UNIT and *ORAL-STOP. An intermediate weight is assigned to the perceptually-oriented faithfulness constraint IDENT-Place, to IDENT-Voice, and to DEP-[ʔ]-ONSET, the positional constraint banning glottal stop epenthesis. Finally, a weight of 1 is assigned to MAX-Place and DEP-[ʔ], the general counterparts of the positional constraints noted previously.

Table 6. Specification of constraint weightings for B's Stage 1

Constraint Name	Weight
MAX-PLACE-ONS	4

MOVE-AS-UNIT	3
*ORAL-STOP	3
IDENT-Place	2
IDENT-Voice	2
DEP-[□]-ONS	2
MAX-PLACE	1
DEP-[□]	1

Table 7 shows that for a velar target in word-initial position, the candidate with undifferentiated place (perceived as coronal) will emerge as most harmonic. Candidates (a) and (b), with faithful velar place, are ruled out due to their large number of violations of high-weighted MOVE-AS-UNIT. Candidate (c) shows that fronting to true coronal place does not facilitate articulation, since it too calls for production of a discrete lingual gesture. Since this candidate additionally violates IDENT-Place, it is harmonically bounded by the fully faithful candidate; accordingly, candidates involving fronting to true coronal place will be excluded from future tableaux. Candidates involving glottal epenthesis (e) and glottal replacement (f) incur fewer violations of MOVE-AS-UNIT than candidates (a)-(c), but they are ruled out by the weight of their faithfulness violations. Undifferentiated candidate (d) thus emerges as most harmonic, in spite of the violation of perceptually-oriented IDENT-Place incurred by the undifferentiated lingual gesture. Table 8 shows a similar computation for a velar target in a word-medial pretonic context, giving rise to the same preference for undifferentiated production. Substituting a voiced velar target in either Table 7 or Table 8 would not change the outcome in this stage of B's development.

Table 7. Stage 1. An initial velar is fronted.

/kaʊ/, "cow"	MAX-Place-ONS	MOVE-AS-UNIT	*ORAL STOP	IDENT-Place	IDENT-Voice	DEP-[□]-ONS	MAX-Place	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. kaʊ	0	4.5	1	0	0	0	0	0	**16.5**
b. gaʊ	0	3.5	1	0	1	0	0	0	**15.5**
c. taʊ	1	4.5	1	1	0	0	0	0	**22.5**
d. ☞ caʊ	0	0	1	1.5	0	0	0	0	**6**
e. kʔ aʊ	0	1	1	0	0	1	0	1	**9**
f. ʔ aʊ	1	0	0	1	0	0	1	0	**7**

Table 8. Stage 1. A word-medial pretonic velar is fronted.

/okej/, "ok"	MAX-Place-ONS	MOVE-AS-UNIT	*ORAL STOP	IDENT-Place	IDENT-Voice	DEP-[□]-ONS	MAX-Place	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. okaj	0	4	1	0	0	0	0	0	**15**
b. ogaj	0	3	1	0	1	0	0	0	**14**
c. ☞ ocaj	0	0	1	1.5	0	0	0	0	**6**
d. oʔ kaj	0	1	1	0	0	1	0	1	**9**
e. oʔ aj	1	0	0	1	0	0	1	0	**7**

Tables 9 and 10 illustrate the contrasting behavior of velar targets in weak positions, namely word-final and word-medial posttonic contexts. The faithful candidates in these positions incur a smaller number of violations of MOVE-AS-UNIT than their counterparts in strong contexts; this is particularly true in the case of the word-final velar. However, at this stage a faithful candidate is less harmonic than a candidate with glottal replacement. Because debuccalization in B's phonology affected labial and coronal as well as velar targets, the process is modeled as the consequence of not MOVE-AS-UNIT but *ORAL-STOP, which disfavors any consonant produced with complete constriction in the oral cavity. While the high-weighted positional faithfulness constraint MAX-Place-ONSET blocks debuccalization in strong positions, a consonant in a weak context is subject only to the lower-weighted general faithfulness constraint MAX-Place. (Without taking a stand as to whether a medial posttonic consonant occupies a true coda position or possesses ambisyllabic status, it will be assumed that glottal stops in medial posttonic contexts do not incur a violation of MAX-gesture-ONS.) Thus, the constraints and weightings proposed for B's Stage 1 succeed in modeling debuccalization in weak contexts as well as fronting of velars in prosodically strong contexts.

Table 9. A word-final velar is debuccalized.

/bæ k/, "back"	MAX-Place-ONS	MOVE-AS-UNIT	*ORAL STOP	IDENT-Place	IDENT-Voice	DEP-[□]-ONS	MAX-Place	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. bak	0	1	2	0	0	0	0	0	**9**
b. bag	0	1	2	0	1	0	0	0	**11**
c. bac	0	0	2	1.5	0	0	0	0	**9**
d. ☞ baʔ	0	0	1	1	0	0	1	0	**6**

In Table 10 and in other representations of medial posttonic targets to follow, only a single candidate with glottal epenthesis has been represented in the tableau. Because pre-and post-glottalized forms ([jʌ ʔ ki] versus [jʌ kʔ i]) incur identical violations of the constraint set

used here, a single form with glottal epenthesis will stand for both pre- and postglottalization in the tableaux to follow. This is consistent with the observation that, in stages where forms with glottal epenthesis were favored for posttonic velar targets, pre- and post-glottalized versions appeared to be in free variation with one another in B's output.

Table 10. Stage 1: A medial posttonic voiceless velar is debuccalized

/jʌ ki/, "yucky"	MAX-Place-ONS	MOVE-AS-UNIT	*ORAL STOP	IDENT-Place	IDENT-Voice	DEP-[□]-ONS	MAX-Place	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. jʌ ki	0	3	1	0	0	0	0	0	**12**
b. jʌ gi	0	2	1	0	1	0	0	0	**11**
c. jʌ ci	0	0	1	1.5	0	0	0	0	**6**
d. jʌ ʔ ki	0	1	1	0	0	0	0	1	**7**
e. ☞ jʌ ʔ i	0	0	0	1	0	0	1	0	**3**

9.2 B's Stage 2

The only systematic change occurring between B's Stages 1 and 2 was observed to affect word-final and medial posttonic velars. While previously they were subject to debuccalization, in Stage 2 word-final velars came to be realized with mostly faithful velar place. Word-medial posttonic velars were divided according to voicing in this stage, such that voiced velar targets underwent fronting, while voiceless velars were realized with glottal epenthesis or debuccalization. The changes from Stage 1 to Stage 2 can be captured simply by adjusting the relative weights of *ORAL-STOP (decreased by 2) and the faithfulness constraints IDENT-Place and MAX-Place (each increased by 1). Table 11 depicts the updated constraint weights for Stage 2.

Table 11. Specification of constraint weightings for B's Stage 2

Constraint Name	**Weight**
MAX-Place-ONS	4
MOVE-AS-UNIT	3
IDENT-Place	3
IDENT-Voice	2
DEP-[□]-ONS	2
MAX-Place	2
*ORAL-STOP	1
DEP-[□]	1

Because the behavior of word-initial and medial pretonic targets remains unchanged under the new set of constraint weightings, these candidates will not be represented explicitly in this section. On the other hand, Table 12 shows that with the updated constraint weightings, faithful velar place emerges as most harmonic for a word-final velar target.

Table 12. Stage 2: A word-final velar is realized faithfully.

/bæ k/, "back"	MAX-Place-ONS	MOVE-AS-UNIT	IDENT-Place	DEP-[□]-ONS	IDENT-Voice	MAX-Place	*ORAL STOP	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. ☞ bak	0	1	0	0	0	0	2	0	**5**
b. bac	0	0	1.5	0	0	0	2	0	**6.5**
c. baʔ	0	0	1	0	0	1	1	0	**6**

Table 13 shows that glottalization continues to represent a favored repair for a voiceless velar in a medial posttonic context, but now the glottal epenthesis candidate is equally harmonic.

Table 13. Stage 2: A medial posttonic voiceless velar is glottalized/debuccalized.

/jʌ ki/, "yucky"	MAX-Place-ONS	MOVE-AS-UNIT	IDENT-Place	DEP-[□]-ONS	IDENT-Voice	MAX-Place	*ORAL STOP	DEP-[□]	**SUM**
	4	3	3	2	2	2	1	1	
a. jʌ ki	0	3	0	0	0	0	1	0	**10**
b. jʌ gi	0	2	0	0	1	0	1	0	**9**
c. jʌ ci	0	0	1.5	0	0	0	1	0	**5.5**
d. ☞ jʌ ʔ ki	0	1	0	0	0	0	1	1	**5**
e. ☞ jʌ ʔ i	0	0	1	0	0	1	0	0	**5**

Table 14 represents the behavior of a voiced velar target in medial posttonic position. As noted above, B's application of glottal replacement and glottal epenthesis was sensitive to the adult voicing specification of a velar target. In B's output, forms with epenthetic glottal stop were overwhelmingly associated with voiceless targets, and they were uniformly transcribed as voiceless. This suggests that for a medial posttonic voiced velar target, an additional constraint will be needed to eliminate candidates such as [bʌ ʔ go] or [bʌ gʔ o], with glottal epenthesis adjacent to a voiced consonant. This constraint, seen in (28), has a clear phonetic basis in the

aerodynamic incompatibility of voicing and glottal closure; it is assigned a correspondingly high weight.

(28) *GLOTTAL-VOICE: Glottal closure does not occur adjacent to a voiced obstruent.

Note that the divided behavior of voiced and voiceless velar targets in medial posttonic position would be difficult to encode using strictly ranked constraints: if IDENT- Place >> IDENT-Voice, we could expect the glottal epenthesis candidate to prevail over the fronted form in spite of its unfaithful voicing. In the Harmonic Grammar framework used here, violations of lower-weighted IDENT-Voice and MAX-Place or DEP-[ʔ] can gang up to make glottalized forms less harmonic than the fronted form, in keeping with B's attested output.

Table 14. Stage 2: A medial posttonic voiced velar is fronted.

/bejgəl/, "bagel"	*GLOT VOICE	MAX Place ONS	MOVE AS UNIT	IDENT Place	DEP [□] ONS	IDENT Voice	MAX Place	*ORAL STOP	DEP-[□]	**SUM**
	10	4	3	3	2	2	2	1	1	
a. bʌ go	0	0	2	0	0	0	0	2	0	**8**
b. ☞ bʌ ɟ o	0	0	0	1.5	0	0	0	2	0	**6.5**
c. bʌ ʔ ko	0	0	1	0	0	1	0	2	1	**8**
d. bʌ ʔ go	1	0	1	0	0	0	0	2	1	**16**
e. bʌ ʔ o	0	0	0	1	0	1	1	1	0	**8**

9.3 B's Stage 3

In Stage 3, B's pattern of production for word-initial and word-final targets remained unchanged, such that the former were consistently fronted and the latter consistently faithful. The modified weightings adopted in this section will not affect the outcome of the comparison of candidates for these forms, which accordingly will not be represented explicitly here. The behavior of medial velars in B's Stage 3 was highly variable. The most reliable change relative to the previous stage affected voiced velar targets in medial posttonic position, which ceased to undergo fronting and emerged preferentially with faithful velar place. This transition can be captured by reducing the weight of MOVE-AS-UNIT from 3 to 2. Updated constraint weightings reflecting this single change are depicted in Table 15.

Table 15. Specification of constraint weightings for B's Stage 3

Constraint Name	**Weight**
MAX-PLACE-ONS	4
IDENT-Place	3
MOVE-AS-UNIT	2

IDENT-Voice	2
DEP-[□]-ONS	2
MAX-PLACE	2
*ORAL-STOP	1
DEP-[□]	1

Table 16 shows that with the decreased weight of MOVE-AS-UNIT, faithful velar place emerges as more harmonic than fronted place for a voiced medial posttonic target. Meanwhile, Table 17 shows that segmented place is the single most harmonic output for a voiceless velar target in the medial posttonic context. Two factors contribute to the split in the behavior of voiced and voiceless medial posttonic velars in this stage. First, the voiced medial posttonic velar incurs a smaller violation of MOVE-AS-UNIT than its voiceless counterpart. Second, the violation of IDENT-Voice makes the glottal epenthesis candidate a dispreferred repair in the voiced medial posttonic context. For a voiceless target, where IDENT-Voice is not at issue, the use of glottal epenthesis is favored as a means of further lowering the magnitude of the MOVE-AS-UNIT violation.

Table 16. Stage 3: A medial posttonic voiced velar is realized faithfully.

/bejgəl/, "bagel"	*GLOT VOICE	MAX Place ONS	IDENT Place	MOVE AS UNIT	DEP [□] ONS	IDENT Voice	MAX Place	*ORAL STOP	DEP [□]	**SUM**
	10	3	3	2	2	2	2	1	1	
a. ☞bʌ go	0	0	0	2	0	0	0	2	0	**6**
b. bʌ ʄ o	0	0	1.5	0	0	0	0	2	0	**6.5**
c. bʌ ʔ ko	0	0	0	1	0	1	0	2	1	**7**
d. bʌ ʔ go	1	0	0	1	0	0	0	2	1	**15**
e. bʌ ʔ o	0	0	1	0	0	1	1	1	0	**8**

Table 17. Stage 3: A medial posttonic voiceless velar is segmented.

/jʌ ki/, "yucky"	MAX-Place-ONS	IDENT-Place	MOVE-AS-UNIT	DEP-[□]-ONS	IDENT-Voice	MAX-Place	*ORAL-STOP	DEP-[□]	**SUM**
	3	3	2	2	2	2	1	1	
a. jʌ ki	0	0	3	0	0	0	1	0	**7**
b. jʌ gi	0	0	2	0	1	0	1	0	**7**
c.	0	1.5	0	0	0	0	1	0	**5.5**

jʌ ci									
d. ☞ jʌ ʔ ki	0	0	1	0	0	0	1	1	**4**
e. jʌ ʔ i	0	1	0	0	0	1	0	0	**5**

9.4 B's Stage 4

The last stage of development documented in the present study featured a division in the behavior of voiced and voiceless targets in word-initial position. Voiced targets were produced faithfully, while voiceless targets emerged with a postglottalized manner of production. Both voiced and voiceless targets in word-medial posttonic contexts were typically realized with faithful velar place in this stage. These changes can be effected by increasing the weight of IDENT-place from 3 to 4 while decreasing the weight of MOVE-AS-UNIT from 2 to 1. The adjusted constraint weightings are listed in Table 18.

Table 18. Specification of constraint weightings for B's Stage 3

Constraint Name	Weight
IDENT-Place	4
MAX-Place-ONS	4
IDENT-Voice	2
DEP-[□]-ONS	2
MAX-Place	2
*ORAL-STOP	1
DEP-[□]	1
MOVE-AS-UNIT	1

Table 19 shows that this combination of the lower weight of MOVE-AS-UNIT and the increased weight of perceptually-oriented faithfulness permits fully faithful production to emerge as the most harmonic candidate for a word-initial voiced velar target. Table 20 shows that at this stage, fronting finally ceases to apply to a voiceless velar in initial position. However, here fully faithful production is less harmonic than a postglottalized manner of production. The smaller magnitude of the MOVE-AS-UNIT violation in the postglottalized candidate is sufficient to offset the violations of faithfulness incurred by this form, even though the relatively high-weighted positional faithfulness constraint DEP-[□]-ONS is violated. The lack of an IDENT-Voice violation is crucial in predicting the preference for glottal epenthesis in the context of an initial voiceless velar.

Table 19. Stage 4: An initial voiced velar is realized faithfully.

/goʊ/, "go"	*GLOT VOICE	IDENT Place	MAX Place ONS	DEP [□] ONS	IDENT Voice	MAX Place	*ORAL STOP	DEP [□]	MOVE AS UNIT	**SUM**
	10	4	4	2	2	2	1	1	1	

a. ☞ goʊ	0	0	0	0	0	0	1	0	3.5	**4.5**
b. ɟ oʊ	0	1.5	0	0	0	0	1	0	0	**7**
c. kʔ oʊ	0	0	0	1	1	0	1	1	2.5	**8.5**
d. gʔ oʊ	1	0	0	1	0	0	0	2	1	**15**
e. ʔ oʊ	0	1	1	0	1	1	0	0	0	**12**

Table 20. Stage 4: An initial voiceless velar is segmented.

/kaʊ/, "cow"	IDENT-Place	MAX-Place-ONS	DEP-[□]-ONS	IDENT-Voice	MAX-Place	*ORAL-STOP	DEP-[□]	MOVE-AS-UNIT	**SUM**
	4	4	2	2	2	1	1	1	
a. kaʊ	0	0	0	0	0	1	0	4.5	**5.5**
b. gaʊ	0	0	0	1	0	1	0	3.5	**6.5**
c. caʊ	1.5	0	0	0	0	1	0	0	**7**
d. ☞ kʔ aʊ	0	0	1	0	0	1	1	1	**5**
e. ʔ aʊ	1	1	0	0	1	0	0	0	**10**

The tableaux presented throughout this section have captured the positional nature of velar fronting, which is exclusive to contexts that are associated with a limited strength of articulatory contact. The divided behavior of voiced versus voiceless targets was also fully accounted for in the constraint system adopted here. Finally, the present model provides an explanation for B's use of glottal epenthesis in the environment of a velar: here it was argued that by valving subglottal pressure below the point of oral constriction, B was able to use lighter articulatory contact and thereby avoid producing undifferentiated lingual gestures.

10. Conclusion

The child-specific process of velar fronting is a well-known example of the puzzling child tendency to neutralize phonemic contrasts in strong position. In addition to purely phonological accounts modeling the distribution of velars and coronals in positional velar fronting, several studies have pointed to speech-motor factors that might give rise to velar-coronal neutralizations in child speech. Edwards et al. (1999) argued that children with phonological disorders produce lingual stops using a ballistic gesture of the entire tongue-jaw complex rather than a discrete raising of either tongue tip or tongue body. Gibbon (1999) showed that EPG imaging of lingual consonants produced by children who neutralize the coronal-velar

contrast frequently reveal undifferentiated lingual gestures in which linguopalatal contact spanning coronal through velar regions. Inkelas & Rose (2008) offered new insight into the velar fronting phenomenon by incorporating anatomical and motor-control differences between child and adult speakers into their phonological analysis. They proposed that velar fronting occurs when some children make a phonologically appropriate effort to strengthen consonants in prosodically strong positions, yet are unable to do so without altering the perceived place of articulation of the target.

Here, Inkelas & Rose's account was extended and formalized based on evidence from a longitudinal study of velar place acquisition in case study subject B. While B showed the typical preference to neutralize coronal and velar place in prosodically strong positions, other conditioning factors were also evident in his velar production accuracy. Of particular interest was the effect of voicing on the accuracy of velar place, whereby voiced velar targets were realized with significantly greater accurately than voiceless targets. B also exhibited a tendency to produce velar targets with glottal stop epenthesis immediately preceding or following the velar closure. Based on these preferences, it was posited that B produced velars with greater accuracy in a context with low intraoral pressure, while elevated levels of pressure appeared to induce fronting. This effect can be understood as the consequence of more forceful articulatory contact in the context of elevated intraoral pressure, which in turn predisposes the child speaker to an undifferentiated pattern of lingual contact. This reflects our claim from Chapter 2 that the constraint MOVE-AS-UNIT is sensitive to the height of the articulatory target, such that larger violations are assigned to higher/more forceful targets. It was demonstrated that this constraint can be used to account for both positional and laryngeal conditioning factors influencing B's acquisition of velars over several stages. This analysis shares the basic insights of Inkelas & Rose's account of velar fronting but fleshes out the phonetic motivation of the process, also specifying constraint formalism for the analysis. In keeping with the theme of this dissertation, it is argued that consideration of child-specific phonetic factors, most notably articulatory limitations, permits us to offer an explanatory account of an otherwise problematic phenomenon in child speech.

Chapter 5. Fricative Neutralization in Strong Position in Child Phonology

1. Introduction

Studies of both typically developing and phonologically disordered children have documented an interesting pattern in which fricatives in word-final contexts emerge in advance of word-initial fricatives. Like the velar fronting pattern described in the previous chapter, this poses a challenge for modeling with constraints from adult phonology, which are ill-equipped to deal with instances of neutralization in a perceptually strong position together with preservation of contrast in a weak position. This chapter will demonstrate that children's asymmetric acquisition of fricatives emerges as a consequence of constraints militating for minimization of articulatory effort. These constraints are active in adult phonology, where they drive patterns of coarticulation. However, the greater weight of this constraint in child speakers, in combination with the influence of certain child-specific motor-control limitations, will be shown to give rise to the asymmetric pattern observed in acquisition.

This chapter will present a longitudinal study of fricative acquisition in our four-year-old case study subject, B. While B produced postvocalic fricatives appropriately from the earliest recorded stage, at the outset of the study he consistently replaced all word-initial fricatives with glides. As word-initial fricatives began to emerge in subsequent stages, they were specific to the context of a [+high] segment, either a high vowel or an epenthetic palatal glide. Fricatives preceding a nonhigh vowel were the last to appear with faithful fricative manner.

Here it will be argued that B's pattern of fricative acquisition reflects the action of effort-minimization constraints that penalize rapid movements of the mandible (*$\text{EFFORT}_{\text{mand}}$). The advantage for fricative production in [+high] over [-high] vowel contexts reflects the preference to minimize effort costs by making small articulatory transitions. Alternatively, it is possible to cross a relatively large articulatory distance without incurring excessive violations of *$\text{EFFORT}_{\text{MAND}}$ if the transition is held to a sufficiently slow rate. This will play a crucial role in accounting for the onset-coda asymmetry in fricative acquisition. It will be shown that, at least in B's speech, the closing gesture from vowel to fricative habitually extended over a longer time interval than the fricative-vowel gesture, reducing the magnitude of the *$\text{EFFORT}_{\text{mand}}$ violation and permitting faithful fricative production. While a somewhat elongated transition is additionally attempted in the word-initial context, here it will be demonstrated that the child speaker's slow transition has anomalous perceptual consequences. In a skilled speaker, a coarticulated transition from a fricative to a vowel is achieved by means of anticipatory lowering of the jaw, while the tongue is held in a high position to sustain frication. This dissociation is dispreferred in a child speaker with an active MOVE-AS-UNIT constraint banning discrete lingual gestures. It will be argued that the epenthetic glide in B's fricative-vowel transitions is the perceptual consequence of an extended opening gesture characterized by simultaneous lowering of the tongue and jaw. Thus, by invoking a combination of general and child-specific articulatory factors, it is possible to account for all of the perplexing properties of the positional fricative distribution exhibited by a child like B.

2. On the acquisition of fricatives

2.1 Fricatives in typical phonological development

The fricative class ([+continuant]) is regarded as relatively marked in the course of typical phonological development. The generalization that stops emerge before fricatives was included among Jakobson's (1968) implicational universals, and the tendency for fricatives to emerge later in development than stops, nasals, or glides has been documented repeatedly since then (Sander, 1972; Smith, 1973; Ferguson, 1978; Stoel-Gammon, 1985; Dinnsen, Chin, Elbert, & Powell, 1990; Smit, Hand, Freilinger, Bernthal, & Bird, 1990; Kent, 1992). In their large-scale articulatory norming study, Smit et al. (1990) reported that word-initial coronal stops were produced appropriately by 90% of three-year-old children sampled; by contrast, the 90% mastery criterion for the coronal fricative /s/ was not reached until subjects were more than seven years of age. Ferguson (1978) suggested that the late emergence of fricatives in development can been attributed to the sustained, precise nature of the gesture needed to create a high-velocity airstream for the creation of frication noise. In Chapter 2, it was noted that fricatives are included in the more articulatorily demanding category of controlled gestures, which tend to emerge later in the course of development (Kent, 1992). The marked status of fricative articulation is also evident in cross-linguistic typology: while nearly forty languages are reported to have no fricative phonemes in their inventories, there are no languages that possess fricatives but no stops (Maddieson & Precoda, 1990, cited in Li, Beckman, & Edwards, 2009).

While fricatives do have a relatively marked status in development and cross-linguistic typology, it is not the case that they are completely absent from the inventories of young children. Stoel-Gammon (1985) reported that more than half of a group of 33 two-year-old subjects exhibited spontaneous use of /s/ and/or /f/ fricatives. Likewise, in a study of two groups of ten children between two years and three years, three months of age, Dyson (1988) reported that spontaneous use of /f/ and /s/ could be observed in at least half of the subjects throughout the recorded interval.

Having established that fricative manner is marked but by no means unattested in the early stages of phonological development, we now will focus on a striking distribution commonly observed in young children's acquisition of fricatives. The literature provides numerous instances of young speakers for whom fricative production is attested in coda before onset position (Menn, 1971; Edwards, 1979, 1996; Dinnsen, 1996; Rvachew & Andrews, 2002; Marshall & Chiat, 2003; Stites, Demuth & Kirk, 2004; Dinnsen & Farris-Trimble, 2008). This is a surprising finding in that coda consonants also have a marked status in phonological acquisition, emerging later than onset consonants. Given their doubly-marked status, fricative codas might be expected to be particularly late-emerging in the course of development. Furthermore, the child pattern represents a surprising reversal of preferences evident in adult phonological typologies. Korean is an example of a language that permits fricatives, stops, and affricates in onset position, but neutralizes manner contrasts in codas (Ahn, 1988). The child pattern, where more extensive manner contrasts are permitted in coda position, is not attested in adult typology. The remainder of this section will review results from the literature to substantiate the claim that fricatives can be seen to emerge in final before initial position in the course of phonological development.

2.2 Fricative production in babbling

Studies of babbling in typically developing infants have revealed what appears to be a consistent preference to produce fricatives in coda position. Analyses of transcribed corpora of babbled speech have revealed that fricatives outnumber stops in coda position, while initial stops are more common than initial fricatives. This result was obtained by Oller, Wieman, Doyle, & Ross (1976) in a study of nine infants between six and eight months of age, as well as by Kent & Bauer (1985) in a similar study of five 13-month-old infants. Likewise, comparisons across onset and coda contexts have revealed that fricative manner is more frequently attested in coda position. Oller & Eilers (1982) demonstrated that the onset-coda asymmetry in fricative production has cross-linguistic attestation, reporting that both a group of infants learning Spanish and an age-matched group of English-acquiring infants exhibited a similar preference to produce fricatives in coda position. In a study of approximately 148 transcribed hours of babbled speech collected from six typically developing infants between six months and one year of age, Redford, MacNeilage, & Davis (1997) reported that 7% of nonfinal consonants were produced with fricative manner, whereas 24% of final consonants were fricatives. This difference was statistically significant. Finally, in a study of four infants between roughly the seventh and the eighteenth month of life, Gildersleeve-Neumann, Davis, & MacNeilage (2000) reported that throughout the duration of the study, all four infants produced fricatives and affricates with significantly greater frequency in utterance-final relative to non-final positions.

2.3 Fricative production beyond babbling

The preference for coda fricatives is not unique to babbling; the literature also reports numerous cases of older children who produced fricatives faithfully in coda position while neutralizing them with other categories in onset. The most frequently attested pattern involves neutralization of onset stops and fricatives (Edwards, 1996; Dinnsen, 1996; Rvachew & Andrews, 2002; Marshall & Chiat, 2003; Stites, Demuth & Kirk, 2004; Dinnsen & Farris-Trimble, 2008). However, neutralization of fricatives and glides is also attested (Rvachew & Andrews, 2002) and will constitute the focus of the case study reported here. Finally, Menn (1971) reported a case in which fricatives were deleted in prevocalic position only.

Edwards (1979) suggested that reports by Ferguson (1975) and Farwell (1977) had given rise to a conventionally accepted notion that word-final fricatives have a favored status in acquisition. She investigated this claim in a seven-month longitudinal study of six children with starting ages between 1;5 and 2;3. When data were pooled across all subjects, she did observe a small advantage for final over initial position in the accuracy of fricative production. However, individual subjects failed to show a clear pattern of positional preference, and there was variation in preferred position across fricatives with different places of articulation. Edwards did note a significant preference to replace word-initial fricatives with consonants with a tighter constriction, while no such preference was noted in word-final position.

In a subsequent study, Edwards (1996) investigated the behavior of fricatives in the productions of one four-year, eight-month-old child with a developmental phonological disorder. In a spontaneous speech sample and a picture-naming battery, this child produced no accurate word-initial fricatives. By contrast, he generally produced word-final f/v and s/z targets correctly, and when he produced a final fricative incorrectly, his errors effectively always preserved the [+continuant] feature of the target. Fricative targets in word-medial contexts also tended to be produced with faithful manner; pretonic and posttonic targets were produced with

comparable accuracy. It was thus posited that initial versus non-initial status was the crucial factor conditioning fricative production accuracy in this child. In this case, then, Edwards concluded that her findings supported the conventional notion of an advantage for coda fricatives in phonological acquisition.

In an investigation of the syllabification of intervocalic consonants, Marshall & Chiat (2003) reported data from a child who exhibited stopping of fricatives in word-initial but not word-final contexts. This child was also noted to produce word-medial posttonic fricatives with faithful manner, while medial fricatives before a primary stress were subject to stopping. These data are reminiscent of the distribution of faithful velar place in children with positional velar fronting (Chiat, 1983; Bills & Golston, 2002; Inkelas & Rose, 2003, 2008). Marshall & Chiat suggested that these patterns can be described with reference to foot structure rather than position in the syllable, similar to the analysis for velar fronting posited by Bills & Golston.

Rvachew & Andrews (2002) reported mixed results in a study of three children with position-dependent patterns of fricative production. One of their subjects exhibited a pattern of positional fricative gliding, replacing target fricatives with glides before a syllable with primary or secondary stress in either initial or medial contexts. This child also deleted word-final fricatives, with the result that correct fricative production was exclusive to the word-medial context before a stressless syllable. A second child also produced fricatives with notably lower accuracy in initial and medial pretonic contexts, although she replaced fricatives in these contexts with stops rather than glides. However, the third participating child exhibited the opposite pattern, producing fricatives with significantly greater accuracy in word-initial than word-final position. The variability observed among Rvachew & Andrews' subjects indicates that a preference for coda position is not universally attested in the acquisition of fricatives. This is unsurprising in light of the generally extensive between-child variation in the order of acquisition of phoneme targets, both within and across positions. Other instances of children acquiring onset fricatives before codas have been reported by Stoel-Gammon & Dunn (1985), Stoel-Gammon (1998), and Stites, Demuth & Kirk (2004).

It is worth noting that, for the most part, the studies reviewed above have aimed primarily to describe rather than to explain the child-particular phenomenon of fricative neutralization in strong position. While the child-specific processes of consonant harmony and velar fronting have received more extensive attention in the theoretical literature, there have been relatively few attempts to provide an explanatory account of the fricative distribution described here. The phenomenon of fricative gliding is especially understudied. In an effort to arrive at a more in-depth understanding of the factors motivating fricative gliding processes, this chapter will present detailed information regarding the emergence of fricative manner in B, the four-year-old child with apraxia of speech who has been discussed in previous chapters. At the start of this period, B exhibited quite a striking avoidance of fricatives in prevocalic contexts while simultaneously producing faithful fricatives in coda position. Over the course of a six-month period, he gradually acquired fricative manner in onsets, but the course of this development was not uniform, involving several repair strategies and differences across vowel contexts. The section to follow will provide descriptive and quantitative data regarding B's production of fricatives over the course of a six-month period of study.

3. Fricative gliding: A case study

3.1 Methods

The reader is referred to Chapter 2 for general information regarding case study subject B and his patterns of speech development. This portion of the investigation focuses on B's patterns of fricative production over a period of approximately six months between the ages of 3;9 and 4;3. Over this interval, the author saw B for one-hour speech therapy sessions on a roughly biweekly basis. All of B's interactions with the clinician and with his mother were recorded using a Sony ICD-SX57 portable recorder. From these recordings, all of B's utterances were narrowly transcribed and glossed as completely as possible. Items for which a definitive gloss could not be established were excluded from consideration. One drawback of collecting data in the therapy setting is that the fricative targets analyzed here are rather heterogeneous in the manner and context of elicitation. Some reflect immediate imitation of an adult model, while others occurred in the context of spontaneous connected speech. In the discussion to follow, an effort will be made to identify situations in which elicitation context may have influenced B's accuracy in fricative production.

The glossed transcription was used to identify all words for which the adult target form contained a prevocalic fricative from the set /s, ʃ, f/. Because /h/ did not pattern together with the supraglottal fricatives, it will be omitted from the analysis. Interdental fricatives were also omitted from the present study due to their sparse attestation in B's output.[20] For the remaining fricative targets, each token that B produced was coded for several properties. The adult target fricative was recorded, and B's output was classified in one of four production categories, illustrated in Section 3.2. Vowel context was also noted. If the vowel produced by B differed from the adult target vowel—a relatively common occurrence—the surface form of the vowel in B's production was treated as the primary conditioning context. Finally, deviations from target place, such as [s] for /f/, were noted, but place substitution data were not systematically analyzed as part of the present investigation. A total of 813 prevocalic fricative targets were catalogued using this system. Postvocalic fricatives were not tracked separately because B produced them with near-ceiling accuracy throughout the recorded period.

3.2 Fricative production categories

B's attempts at prevocalic fricative targets were coded into three major production categories: glide replacement, glide epenthesis, and faithful production of fricative manner (which included instances of fricative production with deviations in place). Less common patterns, including stopping and deletion of prevocalic fricatives, were classed as "Other." The "Other" category typically accounted for less than 10% of attempted fricative productions in a given session. Examples illustrating B's three major patterns are provided below. Examples (a), (b), and (c) in each item represent alveolar, postalveolar, and labial places of articulation, respectively. The bulk of the analysis to follow will focus on the sibilant fricatives, which were most robustly attested.

[20] During the stage under consideration, B tended to replace function words with "filler syllables" (Pepinsky, Demuth, & Roark, 2001), which were typically vocalic in nature. The absence of unambiguous attestations of *the, than,* etc., significantly diminished the number of opportunities to observe interdental fricative targets in B's productions.

(1) Gliding: Word-initial fricatives are realized as glides.

a.	[jak]	'sock'
b.	[jip]	'sheep'
c.	[waf]	'five'

(2) Glide epenthesis: Word-initial fricatives are separated from the following vowel by an epenthetic glide.

a.	[sjɔ]	'saw'
b.	[ʃ jao]	'shell'
c.	[fwat]	'[ele]phant'

An additional repair strategy was evident in B's productions in word-medial position. In this context, fricative manner was generally preserved, but the fricative was separated from the following vowel by an epenthetic glottal stop, as seen in (3).

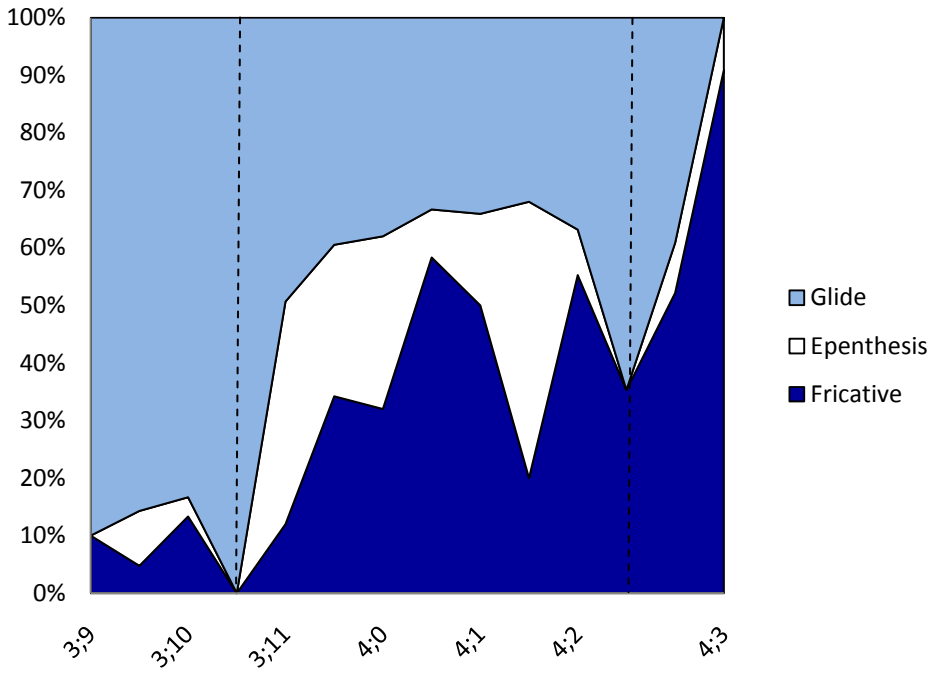
(3) Glottal stop epenthesis: Medial fricatives are followed by an epenthetic glottal stop.

a.	[mʌ sʔ ij]	'messy'
b.	[dojʊ ʃ ʔ ɛ s]	'delicious'
c.	[wasʔ oʊ]	'waffle'

3.3 Identifying developmental stages in B's acquisition of fricatives

The previous section provided examples of the various repair strategies that B used in the production of prevocalic fricatives over the time period investigated. However, these processes did not apply uniformly across the course of B's development. Figure 1 summarizes the prevalence of B's three major patterns of fricative production (gliding, glide epenthesis, and faithful fricative manner) over time. Only word-initial fricatives are represented in Figure 1 and in the statistical analyses to follow. While there is a great deal of variability in these data, the graph does show that faithful fricative production (in dark blue) increases over time. On the other hand, the frequency of gliding does not fall off as rapidly as might be expected, remaining a prominent process throughout all but the very end of the period investigated. This variability can be attributed in part to the collapsed presentation of spontaneous productions with elicited single-word utterances. As B's speech grew more intelligible over time, spontaneous connected speech came to represent a greater proportion of his utterances in the transcript. The greater frequency of gliding in these connected utterances can account for the continuing high occurrence of gliding processes over time.

Figure 1. Percentage of word-initial tokens with gliding, epenthesis, and accurate production



In the discussion to follow, B's patterns of fricative production are described across three chronologically ordered stages. In the first stage (ages 3;9 to 3;10), B's avoidance of prevocalic fricatives was fairly uniform. In the following stage (ages 3;11 to 4;2), B displayed an emerging ability to produce fricatives in prevocalic contexts. His production of fricatives was quite variable and proved to be conditioned by the segmental context in an interesting manner that will be described below. Finally, B's third stage of development was marked by increasingly consistent fricative production across all contexts.

3.3.1 Stage 1 (Ages 3;9 – 3;10.22)

The data in (4-7) exemplify the distribution of fricatives in B's speech at the earliest stage recorded, from ages 3;9 to roughly 3;11. The examples in (4) illustrate the process of fricative gliding, which was robustly present in B's word-initial fricatives in this stage. At the same time, fricative targets were produced with faithful manner in coda position, as seen in (5). Strikingly, (6) shows that B exhibited a reversed pattern of positional preference for stops in Stage 1: while stops were realized faithfully in prevocalic contexts, coda stops were consistently debuccalized. Finally, (7) illustrates that fricatives in word-medial positions did not undergo gliding. However, this was not an exception to the ban on prevocalic fricatives: in B's speech, word-medial fricatives were consistently separated from the following vowel by an epenthetic glottal stop. In many cases, there was also a distinct pause between the two syllables. This suggested that the syllables were separate at a higher level of the prosodic hierarchy, namely at the level of the Prosodic Word or even the Intonational Phrase. This property of B's prosodification will play a role in the analysis of the onset-coda asymmetry to be offered below.

(4) Supraglottal fricative onsets are realized as glides.

a. [jɔ s] ‘swords’
b. [jaʔ] ‘shark’
c. [wɔ dɛ ʔ] ‘forget’

(5) Fricative codas are realized faithfully. Note faithful realization of prevocalic stops.
a. [kaʊ s] ‘cows’
b. [mas] ‘mouse’
c. [babajis] ‘strawberries’

(6) Non-fricative codas are debuccalized or deleted.
a. [daʔ] ‘cake’
b. [jʌ ʔ] ‘up’
c. [waʔ] ‘what’

(7) Medial fricatives are followed by an epenthetic glottal stop.
a. [wasʔ o] ‘waffle’
b. [bʌʃ ʔ o] ‘shovel’
c. [wesʔ as] ‘raisins’

3.3.2 Stage 2 (Ages 3;11.13 – 4;2.5)

Items (8-10) illustrate an intermediate period in which B’s fricative productions were variable and context-conditioned. The examples in (8) show that gliding continued to represent the default outcome in B’s efforts to produce prevocalic fricative targets in spontaneous, unmonitored speech. Likewise, glottal stop epenthesis continued as the most common outcome for word-medial fricatives, as seen in (9).

(8) Running speech: Continued gliding in word-initial position.
a. [jio] ‘seal’
b. [jak] ‘sock’
c. [japĩ] ‘shopping’

(9) Running speech: Continued glottal stop epenthesis in word-medial position.
a. [pisʔ ɛ s] ‘pieces’
b. [sjʊ sʔ ɔ] ‘sister’
c. [dojʊ ʃ ʔ ɛ s] ‘delicious’

However, new options for fricative production emerged in this stage when B used closely monitored speech, often in the context of elicited production of individual words containing fricative targets. (10) shows that many word-initial fricatives in this stage were produced with a following epenthetic glide, typically /j/. This is a surprising repair pattern, appearing paradoxically to increase the articulatory complexity of the utterance by creating a consonant cluster. Other initial consonant clusters were effectively unattested at this stage, suggesting high-

ranked *COMPLEX. The glide epenthesis process suggests that B's difficulty in producing initial fricatives lay specifically in the transition from the fricative to the following vowel.

(10) Monitored speech: Some word-initial fricatives followed by epenthetic glide.

a.	[sjʌ]	'sun'
b.	[sjut]	'suit'
c.	[ʃ jɛ po]	'shepherd'

During this same stage, B began to produce his first faithful prevocalic fricatives in a highly constrained context. Besides occurring only in monitored speech, these faithful fricatives were observed only in the environment preceding a [+high] vowel. Examples of B's faithful fricative productions are provided in (11).

(11) Monitored speech: Some initial fricatives realized faithfully before high vowels.

a.	[sʊ p]	'sip'
b.	[sio]	'seal'
c.	[ʃ uw]	'shoe'

3.3.3 Stage 3 (Age 4;2 +)

In the final stage documented in the present study, B was in the process of eliminating the fricative-neutralizing processes described previously. The examples in (12) show that glide epenthesis was effectively eliminated from B's productions in this stage. Instead, prevocalic fricatives in all vowel contexts were realized with faithful fricative manner in monitored speech. (13) shows that word-medial fricatives came to be realized without glottal stop epenthesis in both monitored and running speech. Finally, (14) shows that some initial fricative gliding continued to be attested in this stage, notably in the context of rapid or unmonitored speech.

(12) Monitored speech: Faithful production replaces epenthesis across vowel contexts.

a.	[sij]	'see'
b.	[sʌ n]	'sun'
c.	[ʃ ʊ do]	'sugar'

(13) Monitored and running speech: Faithful production in word-medial position.

a.	[jʊ ʃ ɛ s]	'wishes'
b.	[jiso]	'lizard'
c.	[dʊ sɛ t]	'different'

(14) Running speech: Initial gliding continues to be attested.

a.	[jʌ n]	'fun'
b.	[jamo]	'summer'
c.	[jæʔ ədas]	'Santa Claus'

3.4 Preliminary phonological modeling of B's fricative production

Let us briefly consider how B's grammar might be modeled across the three stages described above. For the purpose of exposition, we will temporarily adopt constraints that describe the data without necessarily going into a deeper level of explanation for the observed pattern. In particular, for the moment it will be assumed that B's grammar includes a constraint banning prevocalic fricatives, *SV, shown in (15). Following a more detailed investigation of the factors conditioning B's fricative production accuracy, *SV and the other preliminary formulations adopted here will be replaced with more explanatory constraints.

(15) *SV: A fricative does not immediately precede a vowel.

3.4.1 Modeling B's Stage 1

Table 1 illustrates the behavior of fricatives in word-final postvocalic position. As elsewhere in this dissertation, the analysis makes use of weighted constraints in a Harmonic Grammar framework. Due to the asymmetric nature of *SV, all unfaithful candidates are harmonically bounded by the faithful candidate. This causes fricatives in word-final coda contexts to be realized with consistently faithful fricative manner.

Table 1. Stage 1: A word-final fricative is realized faithfully.

Input: /bʌ s/ 'bus'	*SV	FAITH	**SUM**
	1	1	
a. ☞ bʌ s	0	0	**0**
b. […others]	0	≥1	**≥1**

Table 2 depicts the behavior of word-medial fricatives in B's Stage 1.[21] This case is of interest because a variety of repairs, such as gliding, glide epenthesis, and glottal stop epenthesis, should in principle be available to B in this context. B showed a preference to remain faithful to fricative manner when he had the option to do so, namely by syllabifying the fricative target in coda position. Other repairs, including gliding and stopping, were not attested, suggesting that IDENT-continuant and IDENT- consonantal are high-weighted constraints in B's grammar.[22] B consistently used glottal stop epenthesis rather than glide epenthesis to accomplish resyllabification, suggesting that DEP-IO (glide) >> DEP-IO (ʔ). This preference would not necessarily have been predicted from the typology of adult languages, where both glides and glottal have been reported as preferred epenthetic segments (Lombardi, 1999; Steriade, 1999). However, the preference is sensible in the context of B's particular articulatory difficulties. While B exhibited substantial difficulty in controlling the oral articulators as well as velopharyngeal function, his capacity for laryngeal control appeared to be relatively age-appropriate. For example, while B's prosody was substantially disrupted with respect to the

[21] Only medial posttonic fricatives are represented in the record of B's productions in this stage of development.
[22] B's strong preference to preserve the [+continuant] feature has a somewhat idiosyncratic character, as many children with seemingly comparable articulatory abilities clearly do use stopping as a repair strategy. The factors that might lead a child to prefer gliding over stopping as a repair strategy will be briefly considered in Section 8.3.

duration and rhythm of syllables, his intonation contours were quite appropriate and often helped to convey a message that was not interpretable from segmental content alone. B also used glottal stops as replacements for oral stops in word-final position or in final affricates and clusters. Thus, B's preference for glottal stop epenthesis is consistent with his tendency to use laryngeal gestures to compensate for diminished control of oral articulation.

Table 2. Stage 1: A word-medial fricative is followed by an epenthetic glottal stop.

Input:/mɛ sij/ 'messy'	IDENT-continuant	*SV	DEP-IO (glide)	IDENT-consonantal	DEP-IO (ʔ)	**SUM**
	1	1	1	1	.5	
a. mʌ sij	0	1	0	0	0	**1**
b. ☞ mʌ sʔ ij	0	0	0	0	1	**.5**
c. mʌ sjij	0	0	1	0	0	**1**
d. mʌ jij	0	0	0	1	0	**1**
e. mʌ dij	1	0	0	0	0	**1**

Table 3 shows that glottal stop epenthesis is not available for a fricative in word-initial position, where it is banned by a high-weighted constraint banning fricative-glottal clusters in initial contexts. The winning candidate replaces the fricative with a glide, which satisfies high-weighted IDENT-continuant while also avoiding a violation of *SV.

Table 3. Stage 1: A word-initial fricative undergoes gliding.

Input: /soʊ/ 'sew'	IDENT-continuant	*$_{\sigma}$[S	*SV	DEP-IO (glide)	IDENT-consonantal	DEP-IO (ʔ)	**SUM**
	1	1	1	1	.5	.5	
a. soʊ	0	0	1	0	0	0	**1**
b. sʔ oʊ	0	1	0	0	0	1	**1.5**
c. sjoʊ	0	0	0	1	0	0	**1**
d. ☞ joʊ	0	0	0	0	1	0	**.5**
e. toʊ	1	0	0	0	0	0	**1**

3.4.2 Modeling B's Stage 2

B's transition from Stage 1 to Stage 2 was characterized by the emergence of several new processes, including glide epenthesis following a word-initial fricative. Because glide epenthesis and glide replacement coexisted in this stage of development, the constraints DEP-IO(glide) and IDENT-consonantal are modeled with the same weight. This allows the candidates [jak] and [sjak] to emerge as equally harmonic in Table 4.

Table 4. Stage 2: A word-initial fricative is realized with gliding or glide epenthesis.

Input:/sak/ ‘sock’	IDENT-continuant	*σ[S□	*SV	DEP-IO (glide)	IDENT-consonantal	DEP-IO (□)	**SUM**
	2	2	2	1	1	.5	
a. sak	0	0	1	0	0	0	**2**
b. ☞ jak	0	0	0	0	1	0	**1**
c. ☞ sjak	0	0	0	1	0	0	**1**
d. sʔ ak	0	1	0	0	0	1	**2.5**

Table 5 shows that the new constraint weighting captures B’s continuing preference for glottal stop insertion over glide epenthesis or glide replacement in word-medial contexts.

Table 5. Stage 2: A word-medial fricative is realized with glottal stop epenthesis.

Input:/pisəz / ‘pieces’	IDENT-continuant	*σ[S□	*SV	DEP-IO (glide)	IDENT-consonantal	DEP-IO (ʔ)	**SUM**
	2	2	2	1	1	.5	
a. pisɛ s	0	0	1	0	0	0	**2**
b.☞ pisʔ ɛ s	0	0	0	0	0	1	**.5**
c. pijɛ s	0	0	0	0	1	0	**1**
d. pisjɛ s	0	0	0	1	0	0	**1**

Finally, B’s Stage 2 was characterized by the first emergence of faithful prevocalic fricatives, which were limited to the context of [+high] vowels. This possibility is provisionally represented by splitting *SV into two positional constraints, $*SV_{[+HIGH]}$ and $*SV_{[-HIGH]}$, as in (16).

(16) a. $*SV_{[+HIGH]}$: A fricative does not immediately precede a [+high] vowel.
b. $*SV_{[-HIGH]}$: A fricative does not immediately precede a [-high] vowel.

Table 6 shows that assigning a relatively low weight to $*SV_{[+HIGH]}$ allows for faithful fricative production in the [+high] context. $*SV_{[+HIGH]}$ receives the same weight as DEP-IO (glide) and IDENT-consonantal, making it possible to model the simultaneous attestation of gliding, glide epenthesis, and faithful manner for initial fricative targets in B’s Stage 2.

Table 6. Stage 2: Emerging faithful production of fricatives before [+high] vowels

Input:/ʃuw / ‘shoe’	IDENT-continuant	*σ[S□	*SV [-HIGH]	DEP-IO (glide)	IDENT-consonantal	*SV [+HIGH]	DEP-IO (□)	**SUM**
	2	2	2	1	1	1	.5	
a. ☞ ʃuw	0	0	0	0	0	1	0	**1**
b. ☞ juw	0	0	0	0	1	0	0	**1**
c. ☞ ʃjuw	0	0	0	1	0	0	0	**1**

4. Factors conditioning the accuracy of fricative production

4.1 Testing the significance of factors contributing to fricative production accuracy

The previous section offered a descriptive characterization of stages in B's acquisition of fricative manner. This qualitative overview suggested that B's fricative production accuracy was conditioned by the height of the following vowel as well as by position in the syllable. This section will present statistical measures demonstrating the significance of these apparent conditioning factors. All of B's productions containing word-initial fricative targets were coded for analysis; non-initial fricatives were excluded in order to maintain a manageable level of complexity. First, fricative targets were coded for the height of the following vowel context (high or nonhigh). Here, the classification of vowel height was based on the experimenter's transcription of B's output, although Section 3.2 will explore different schemes for classifying his vowels. B's outputs were additionally coded for the place of articulation of the fricative target (labial, alveolar, or postalveolar); this factor was included to test a qualitative impression that postalveolar place was realized with greater accuracy than labial or alveolar place. The adult target was used to code fricative place in order to avoid the complication posed by gliding, which neutralized alveolar and postalveolar fricatives to palatal place. Finally, each token was coded for the stage of development in which it occurred, using Stages 1-3 detailed above.

To determine the significance of each factor in predicting the accuracy of B's fricative production, the coded corpus of fricative targets was analyzed using logistic regression. Accuracy in fricative production served as the dependent variable: productions with correct fricative manner, independent of any substitutions in the place of the fricative, were assigned a score of 1. All other response categories, including glide epenthesis, gliding, and other deviations, were assigned a score of 0. Tokens with glottal stop epenthesis did not appear in this data set because only word-initial fricatives were considered. Independent variables were the three parameters identified above, namely developmental stage, vowel context, and target fricative place. Table 7 summarizes the factors included in this analysis, along with hypotheses regarding the effect each conditioning factor might have on B's fricative production.

Table 7. Summary of factors coded in analysis of fricative productions

Independent Variable	**Levels**	**Null Hypothesis**	**Experimental Hypothesis**
Developmental Stage	One	Fricative manner is produced with constant accuracy over time.	Fricative manner is produced with increasing accuracy over time.
	Two		
	Three		
Fricative Target Place	/s/	Fricative manner is produced equally well across target places.	Fricative manner is produced with greater accuracy in the context of postalveolar target place.
	/ʃ/		
	/f/		
Height of Transcribed Vowel	[+high]	Fricative manner is produced equally well	Fricative manner is produced with greater

	[-high]	in the context of [+high] or [-high] vowel production.	accuracy in the context of [+high] vowel production.

The results of the logistic regression are presented in Table 8. The significance of each factor was determined using the likelihood ratio test on the residual deviance statistic, with terms added sequentially to the model in the order indicated. Results significant at the $p < .05$ level are marked in bold, while trends approaching significance ($p < .1$) are italicized. On this analysis, all three main effects (vowel context, target fricative place, and developmental stage) emerged as significant predictors of accuracy in fricative production. There was also a significant interaction of vowel context and fricative target place.

Table 8. Analysis of deviance for fricative production accuracy

Parameter	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	***p* >|Chi|**
Vowel Context (Transcribed)	1	225.5	632	553.7	**< .000**
Target Fricative Place	2	51.0	630	502.7	**< .000**
Developmental Stage	2	31.8	628	471.0	**< .000**
Vowel Context x Fricative Place	2	8.7	626	462.3	**0.01**
Vowel Context x Stage	2	4.80	624	457.45	*.09*
Fricative Place x Stage	4	1.03	620	456.42	.91

The significant effect of developmental stage corresponds with the observation that B's accuracy in fricative production increased over time. This is an intuitively straightforward result that will not be discussed in greater detail. The other factors found to make a significant contribution to B's fricative prodution accuracy will be examined more fully in following sections.

4.2 Influence of fricative target place

To begin, we will consider the effect of fricative target place on B's accuracy in fricative production. The logistic regression analysis revealed that B produced fricatives with significantly different levels of accuracy across different places of articulation. Figure 2 shows that B produced labial fricatives with very low accuracy (3.9%), coronal fricatives with somewhat greater accuracy (25.4%), and postalveolar fricatives with a much higher accuracy (62.9%). Post hoc comparison using Student's *t*-test with a Bonferroni correction for multiple comparisons revealed that pairwise differences between places of articulation were significant.

The percent accuracy scores reported here are based on different numbers of attempted targets across places of articulation. Alveolar fricatives were by far the most commonly attested, followed by postalveolar fricatives, whereas labial fricatives were relatively infrequent in this dataset. The number of tokens for each place of articulation is represented in Table 9; the relative frequency with which each target occurred across high and nonhigh vowel contexts is also represented.

Figure 2. Percent correct fricative production by target place of articulation

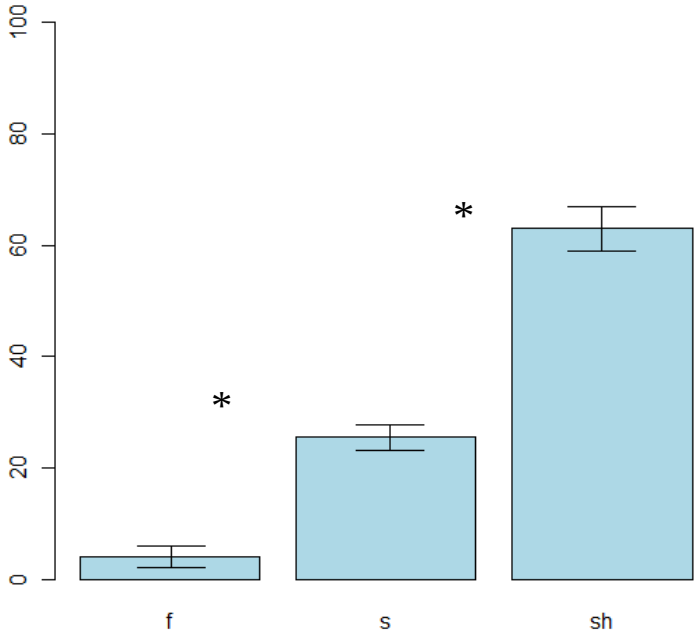


Table 9. Fricative place: Number of tokens across vowel contexts

Fricative Target	Total	High Vowel (% of Total)	Nonhigh Vowel (% of Total)
/f/	102	19 (18.6)	83 (81.4)
/s/	389	172 (44.2)	217 (55.8)
/ʃ/	143	105 (73.4)	38 (26.6)

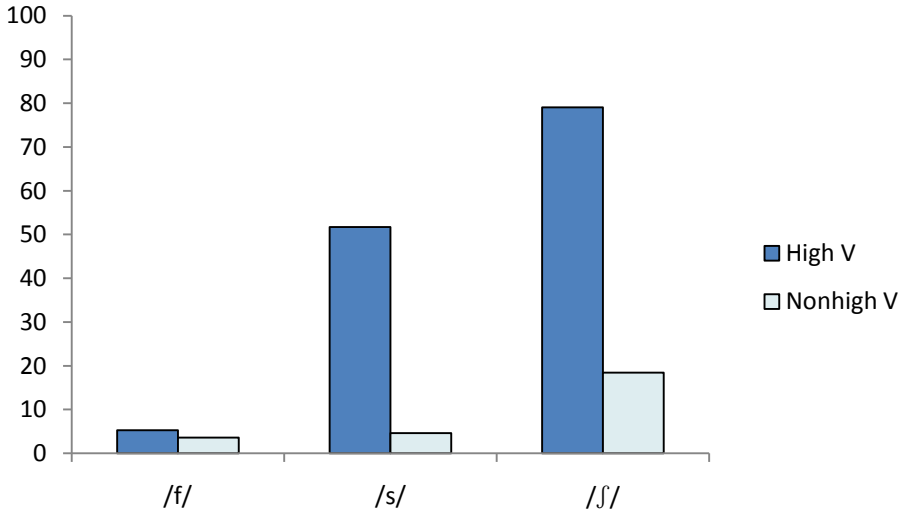
Table 9 shows that /ʃ/ occurred in [+high] vowel contexts with proportionally greater frequency than the other two targets. It is possible that the asymmetric distribution of fricative place across vowel contexts reflects conditioning of vowel place by the fricative. It is known that consonant place can wield coarticulatory influence over the placement of the constriction for an adjacent vowel, most notably in the context of vowel fronting in the environment of coronal consonants (Flemming, 2003). Along the same lines, the high position of the tongue body in postalveolar fricative production could condition raising of the following vowel. Such conditioning was observed in a subset of B's productions, as illustrated in example (17a). However, the majority of B's postalveolar fricative productions were not characterized by perceptually detectable conditioning of vowel place; (17b) is included as one representative example. The remainder of the elevated coocurrence of /ʃ/ with high vowels may reflect the fact that among the relatively small number of /ʃ/-initial words in the English-speaking child's lexicon, a disproportionate number of targets have a high vowel (e.g. *she, sheep, shoe, ship*).

(17) The postalveolar fricative may or may not condition raising of a following vowel.
a. [ʃ io] 'shell'

b. [ʃ aʔ s] ‘shapes’

The logistic regression also revealed a significant interaction of fricative place with vowel height. This effect is illustrated in Figure 3, which depicts the percentage of correct productions for each place of articulation in both high and nonhigh vowel contexts. The interaction effect reflects the fact that while /s/ and /ʃ/ were produced with significantly greater accuracy in high relative to nonhigh vowel contexts, labial fricatives were produced with nearly identical accuracy in both contexts. Figure 3 also shows that /ʃ/ was produced with notably greater accuracy than /s/ or /f/ in the context as of nonhigh as well as high vowels, providing visual confirmation of a significant effect of fricative place, independent of vowel context.

Figure 3. Percent correct production for high and nonhigh vowel contexts, by fricative place



Due to the sparse attestation of labial fricatives in the present data set, the analysis to be offered below will focus on the sibilants /s/ and /ʃ/. However, B’s production of labial fricatives does warrant mention here on account of an interesting opacity. In most prevocalic contexts, /f/ emerged as /w/, as seen in (18). There was a single lexical exception, *fish*, which was consistently realized with a palatal glide and also happened to be B’s most frequently occurring /f/-initial word. On the other hand, (19) shows that /f/ and /v/ in word-final position were generally neutralized with /s/. An analysis of the factors influencing faithful versus unfaithful realization of fricative place will be left as a topic for future investigation.

(18) Prevocalic /f/ is realized as [w] with the single lexical exception ‘fish’

a. [wæ s] ‘fast’
b. [wodaʔ] ‘forgot’
c. [jʊ ʃ] ‘fish’

(19) Postvocalic /f/ or /v/ is realized as [s]

a. [was] ‘five’
b. [wasʔ o] ‘waffle’
c. [jɛ s] ‘chef’

4.3 Influence of vowel context

The logistic regression analysis indicated that the height of the following vowel served as a significant factor conditioning the accuracy of fricative production. The interaction of fricative place with vowel height, depicted in Figure 3 above, revealed that only the sibilants /s/ and /ʃ/ were significantly impacted by the height of the following vowel. Accordingly, labial fricative data have been excluded from the figures and calculations that follow.

Figure 4 confirms the qualitative impression that B realized fricative manner with substantially greater accuracy in [+high] vocalic contexts. Figure 5 depicts the relative accuracy of fricatives in high and nonhigh contexts over time, revealing that this difference was robustly present throughout the recorded period of development.

Figure 4. Percent accurate sibilant production by vowel context, collapsed over time

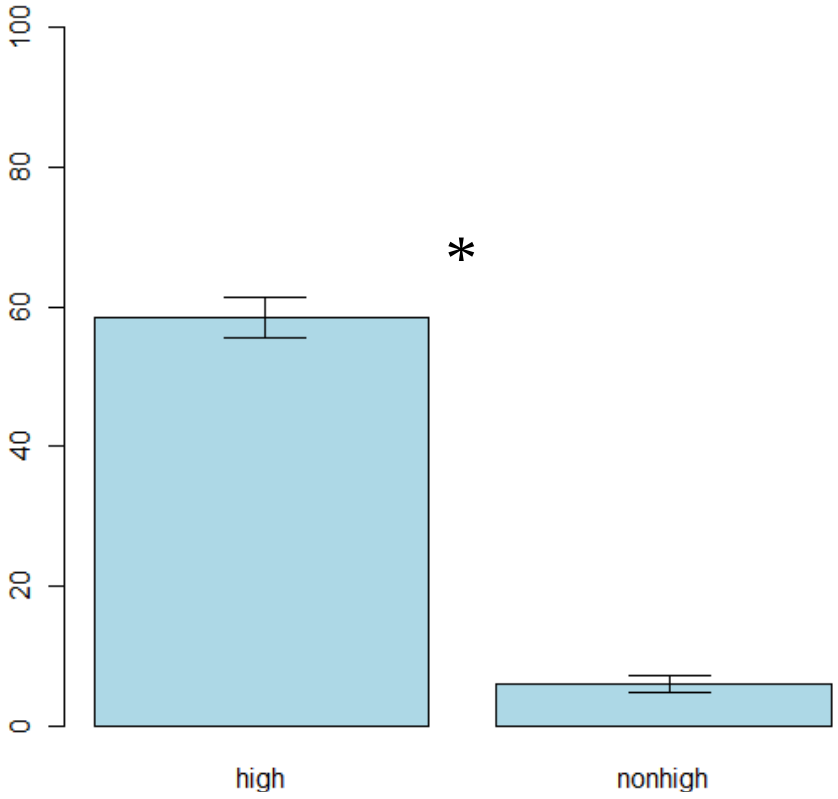
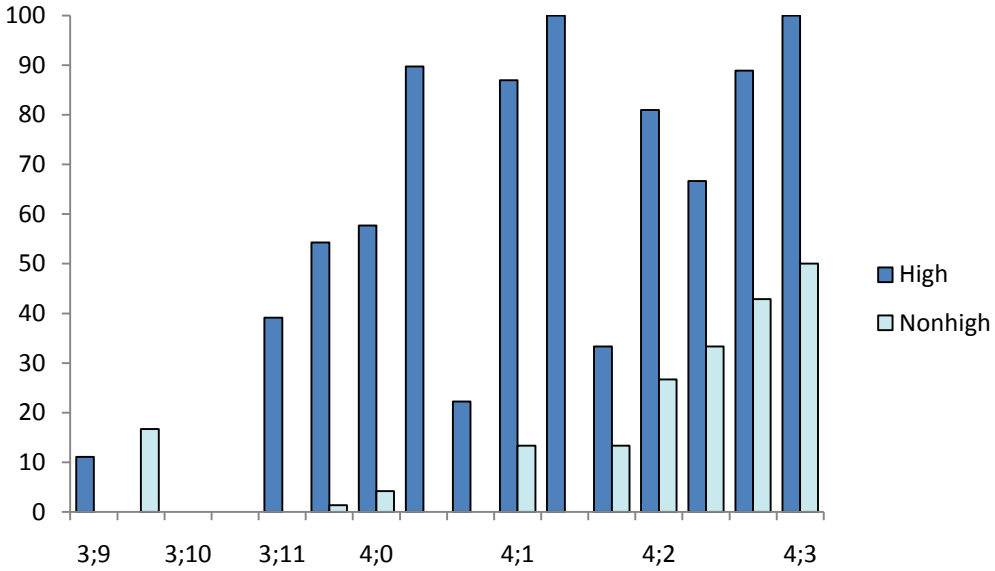
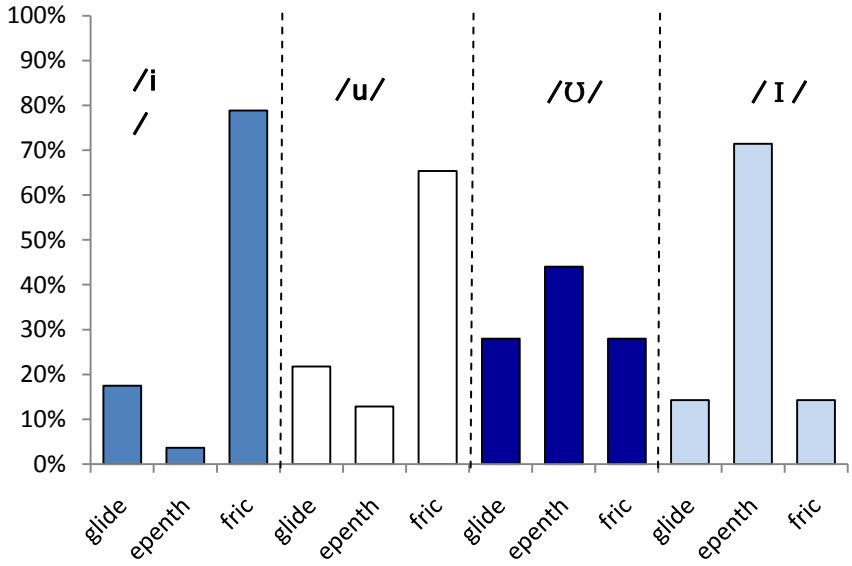


Figure 5. Percent accurate sibilant production by vowel context over time



Although the vowel context entered into the logistic regression was only specified as [+/- high], there were indications that the factor of vowel context conditioning B's fricative production accuracy did not map precisely onto the [+/- high] feature contrast. Within the category of [+high] vowels, the behavior of the tense vowels /i, u/ was distinct from that of the lax vowels /ɪ , ʊ/. Figure 6 depicts the accuracy of fricative production across tense and lax high vowel contexts,as transcribed by the experimenter, collapsed over time. B's overall accuracy of fricative production was quite high in the context of the tense high vowels, particularly /i/, while glide epenthesis was rarely used in this environment. The lax vowels show quite a different pattern, with little faithful fricative production and a strong tendency for glide epenthesis.

Figure 6. Percent substitution type by vowel context within [+high] feature specification



These data suggest that B's pattern of fricative production was conditioned by some factor other than a simple high-nonhigh contrast. For a better understanding of the conditioning effect of vowel context, acoustic analyses were carried out for a subset of B's productions of fricative targets. The results of the acoustic investigation are presented in Section 4.4.

4.4 Acoustic analysis of the effect of vowel context

4.4.1 Data collection

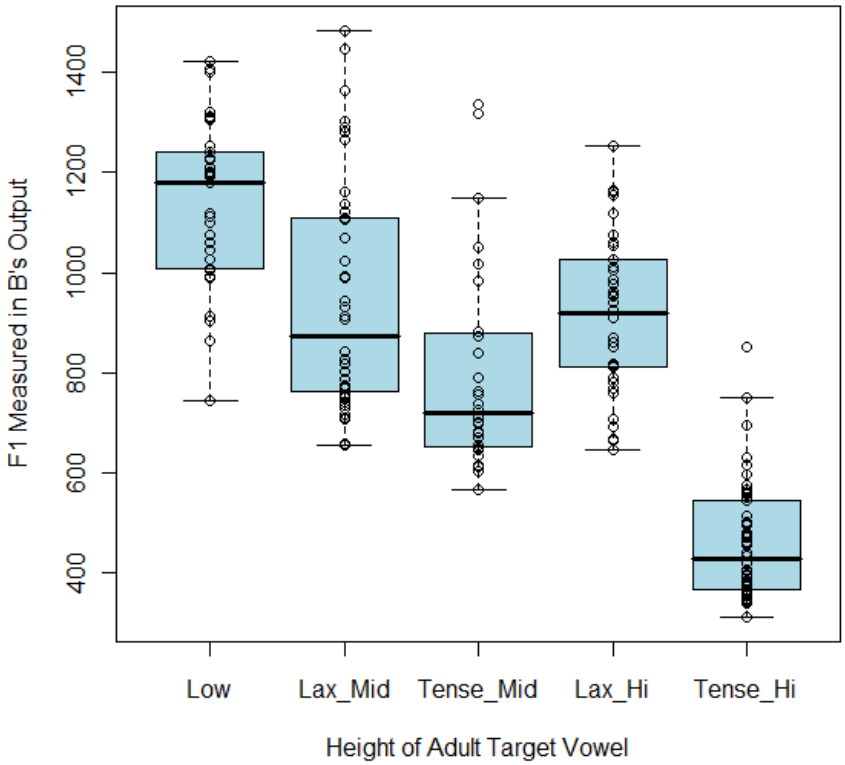
For the purpose of acoustic analysis, all sibilant-initial tokens were extracted from three sessions early in B's Stage 2, when he was 3;10 to 3;11 years old. These sessions were selected because they contained a large number of fricative targets (75, 125, and 47, respectively), and because the full range of possible outputs (gliding, glide epenthesis, and accurate fricative production) was attested in B's productions during this stage. Gliding was the most commonly occurring output category in this period, accounting for 41% of B's initial sibilants. 33% of targets were transcribed with glide epenthesis, 19% with faithful fricative manner, and 7% with other error type.

After all sibilant-initial targets were identified in the transcribed record of these three sessions, each token was isolated from the audio recording for analysis in Praat. F1 and F2 were extracted from the midpoint of the steady-state portion of the vowel. If a vowel had a diphthongal quality, formant values were collected from the midpoint of the first portion. Formant tracking was set to a default of three formants in 5000-Hertz range, but the number and range could be adjusted to optimize formant tracking. Forty-four tokens were excluded from analysis due to background noise or poor formant resolution. In total, formant values were collected from 203 words with initial sibilants, of which 30 had initial /ʃ/.

4.4.2 B's vowel system

The discussion to follow will investigate the contribution of differing levels of vowel height in B's fricative accuracy. As a starting point for this comparison, it is important to know how closely B's production of vowel contrasts mapped onto the adult vowel system. Recall that B's speech was characterized by significant distortion of vowel quality, a hallmark of childhood apraxia of speech. Figure 7 depicts the range of F1 values attested in B's output for each of six levels of vowel height in the adult target. The categories used were low (/æ, a/), mid-lax (/ʌ, ə, ɛ/), mid-tense (/e, o, ɔ/), high-lax (/ɪ, ʊ/), and high-tense (/i, u/).

Figure 7. Correspondence between target height and F1 height in B's output



This graph confirms the impression that B's vowel height categories at the time of this recording did not conform to the typical system of adult contrasts. Particularly striking was his production of the lax high vowel targets /ɪ , ʊ/, which distributed around a median F1 value higher than that observed for either tense or lax mid vowel targets. Note that this F1 distribution is not a feature of the adult dialect of B's environment: the triplet *big, beg, bug* is perceptually distinct in B's home dialect, but it was habitually neutralized in his productions. The high F1 of B's lax high vowels is consistent with the observation that these targets conditioned different behavior of fricative targets relative to tense high vowels (see Figure 6).

To arrive at an estimate of the number of vowel height categories in B's system, the F1 values associated with each of the five height categories in the adult vowel system were compared using Student's *t*-test with a Bonferroni correction for multiple comparisons. The following height contrasts emerged as significant: low versus lax mid ($p < .001$), lax mid versus tense mid ($p = 0.03$), and lax high versus tense high ($p < .001$). The difference between tense mid and lax high vowels appeared as a trend approaching significance ($p = .05$), where the former was associated with lower F1 values. There was no significant difference in F1 height between lax mid and lax high vowel targets. Given the inconsistent behavior of vowels away from extreme high and extreme low targets, it was proposed that B's system of vowel height contrasts could best be modeled with a three-way (low, mid, high) distinction. This model deviates from the feature specifications of the adult categories, since lax high vowels pattern with mid vowels rather than tense high vowels. Table 10 depicts the proposed mapping from adult vowel categories to B's vowel system.

Table 10. Mapping from adult vowel categories to proposed three-way height distinction

Adult Vowel System	**B's Vowel System**

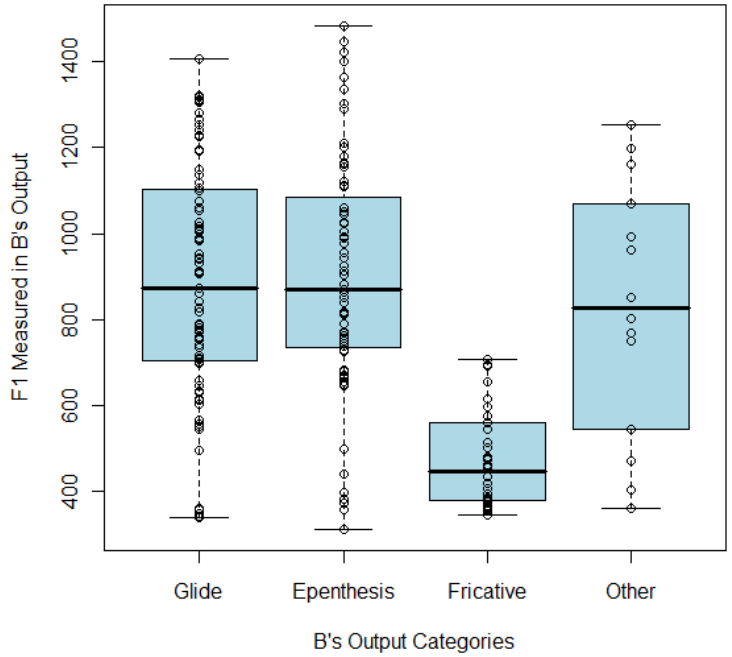
Low (/æ, a/)	Low
Mid-Lax (/ʌ, ə, ɛ/)	Mid
Mid-Tense (/e, o, ɔ/)	
High-Lax (/ɪ, ʊ/)	
High-Tense (/i, u/)	High

In calculations to follow, this mapping from adult vowels onto B's postulated vowel system will be adopted in place of the vowel height as transcribed by the experimenter. It is preferable not to use the experimenter's transcribed vowel height due to the significantly unreliable correspondence between perceived vowel height and measured F1 values for outputs in B's mid-range.

4.4.3 Vowel height and fricative production accuracy

Besides allowing visualization of B's system of height contrasts, the F1 data can be used to examine the association between vowel height and output categories in B's production. Figure 8 depicts the distribution of F1 values associated which each of the four categories recognized in this experiment (Glide, Epenthesis, Fricative, Other). While accurate fricative targets are clearly distinct, the F1 distributions associated with the three non-target categories are extremely similar. The similarity across the three non-target categories indicates that the influence of vowel context on B's fricative productions can be modeled with simple logistic regression, where outputs are categorized as 1 (= correct fricative manner) or 0 (= gliding, epenthesis, or other error).

Figure 8. F1 distribution associated with four categories of fricative production



Logistic regression can be used to address a question regarding the fine-grainedness of the influence of vowel context on B's fricative production accuracy. One possibility is that B's fricative production accuracy is conditioned exclusively by the categorical distinction among high, low, and mid vowels. An alternative is that gradient differences in vowel height have an

impact on fricative production accuracy. If B's fricative production accuracy is sensitive to fine-grained differences in F1 height, a model including gradient F1 values should account for significantly more variance than a model with vowel height categories alone. To compare these two possibilities, fricative production accuracy was modeled first in a logistic regression with height (low, mid, or high) as the sole predictive factor. In a subsequent regression, raw F1 values were included as a predictor. Table 11 presents the results of this modeling.

Table 11. Results of logistic regression for vowel heights

Parameter	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	***p* >|Chi|**
Vowel Height (3 levels)	2	87	200	109	**< .000**
F1	1	3	199	106	*0.077*

The likelihood ratio comparison reported in Table 10 reveals that vowel height in a three-level model was the sole significant predictor of variance in the logistic regression model. However, the contribution of ratio-level F1 values also approached the level of significance (p = .077). Thus, while the results from this limited data set remain inconclusive, a larger-scale analysis might be reveal that fine-grained differences in vowel height played a significant role in conditioning B's fricative production accuracy. This speculation will be incorporated into the analyses to follow, where it will be proposed that fricative production is conditioned by an effort-minimization constraint sensitive to gradient differences in jaw height.

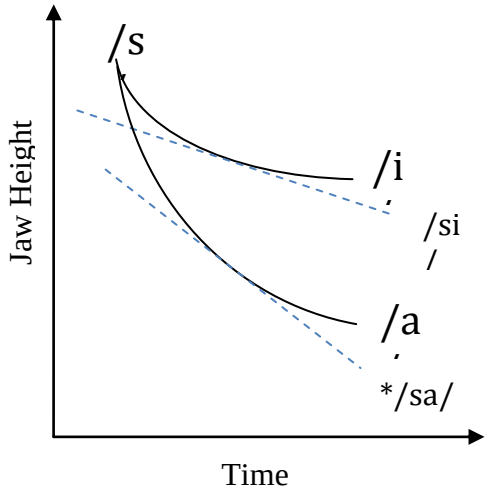
5. Articulatory factors conditioning fricative production accuracy

Having gathered both quantitative and qualitative data regarding B's acquisition of fricative manner, we can begin to model the process in phonetic and phonological terms, in keeping with our overarching aim of identifying phonetic factors that can be understood to motivate child speech processes lacking clear correspondents in adult phonologies. So far, it has been established that the unusual fricative gliding pattern in B's phonology was conditioned by the height of the following vowel as well as position in the syllable. It has not yet been explained why fricative production should be facilitated in coda position or in the context of high vowels. Here, it will be demonstrated that these asymmetries arise from constraints on the expenditure of articulatory effort, laid out in Chapter 2. This section will demonstrate that B's fricative distribution can be understood as a phonetically natural response to principles of effort-minimization, including articulatory limitations specific to immature speech-motor systems. The present discussion will be limited to a purely schematic review of articulatory limitations that interact with fricative articulation, with formal phonological analysis deferred until Section 6.

5.1 Vowel conditioning effects as minimization of articulatory distance

An effort-minimization strategy is evoked by the segmental conditioning effects evident in B's earliest prevocalic fricative productions. By making the transition from a fricative to a [+high] glide or vowel but not to a [-high] segment, B reveals a preference for transitions between articulatory targets that are close together in space. In particular, we can examine the magnitude of mandibular movements involved in making these transitions. Among English speech sounds, coronal consonants are produced with the highest jaw position (Keating, Lindblom, Lubker, & Kreiman, 1994). Jaw position is even higher for coronal fricatives than stops, a finding that has been related to the need to create a narrow channel to produce frication (Lindblom, 1983; Geumann, Kroos, & Tillman, 1999; Mooshammer, Hoole, & Geumann, 2006). Given this high starting point, the transition from a coronal fricative to a [-high] vowel requires a significantly larger jaw excursion than the transition to a [+high] vowel. Figure 9 is a schematization of the articulatory trajectory between a coronal fricative and a following vowel, either [+high] (/si/) or [-high] (/sa/). For the moment, the duration of the articulatory transition is held constant. Tangent lines to the curves in Figure 9 represent the velocity of the transition. The steeper slope of the tangent line to the /sa/ curve shows that the greater articulatory excursion required by the transition to the nonhigh vowel translates to greater articulatory velocity. This suggests that B's avoidance of fricatives in nonhigh vowel contexts can be understood as an indication that he is motivated to avoid large and therefore effortful articulatory transitions.

Figure 9. Comparison of articulatory distances, /si/ versus /sa/

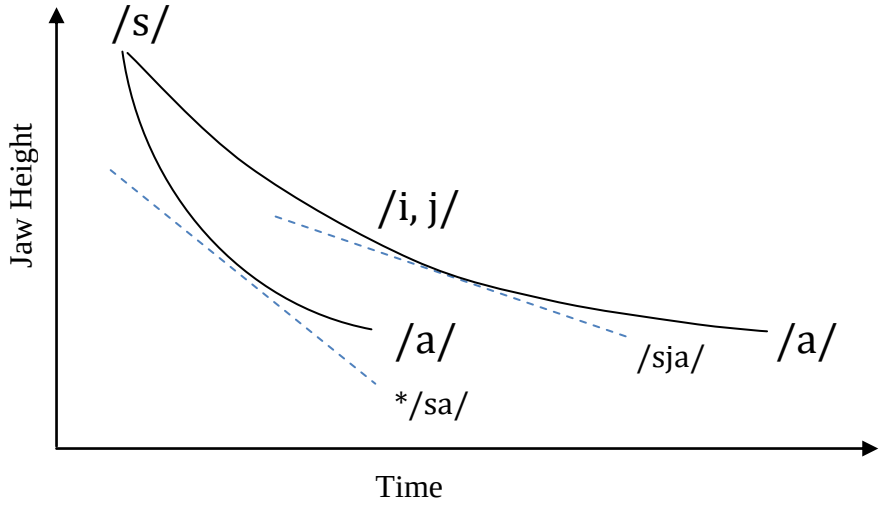


5.2 Glide epenthesis as minimization of articulatory velocity

In Figure 9, the temporal duration of the fricative-vowel transition was held constant across vowel contexts. However, effort is generally treated as a property of articulator velocity (Boersma, 1998; Flemming, 2001, 2008). Thus, the duration as well as the magnitude of an articulatory transition should be included in our analysis. It is possible to make a larger transition with constant velocity and therefore an equal degree of effort by extending the transition in the temporal domain. Figure 10 suggests that B exploits this possibility through his process of glide epenthesis. In the previous section, we saw that the sequence /sa/ was associated with a change in jaw height of a problematically large magnitude. However, Figure 10 shows that when the transition is stretched out through an intermediate configuration, the peak velocity of the

transition from /s/ to /a/ (as indicated by the slope of the tangent to the curve) is lower, comparable to that of the shorter transition from /s/ to /i/. It is posited that the adult listener perceives this extended fricative-vowel transition as an epenthetic glide. Note that on the account adopted here, glide epenthesis in B's speech is a phonetic-level phenomenon rather than a true process of segmental insertion.

Figure 10. Comparison of transition duration, /sa/ versus /sja/



At this point, it is reasonable to inquire whether and how this pattern of articulation differs from coarticulatory transitions in adults. In certain contexts, such as rapid or casual speech, adults also are highly motivated to minimize articulatory effort, yet we do not perceive epenthetic glides in the fricative-vowel transitions in even the most heavily coarticulated adult speech. Artificially slowing the rate of an adult fricative-vowel transition also fails to give rise to the percept of a glide. To understand this dissociation, we again look to child-specific speech-motor limitations. It will be seen that children's articulatory restrictions, as discussed in Chapter 2, prevent the realization of a normal coarticulated transition, instead forcing an atypical transition with anomalous perceptual consequences.

To understand the contrasting behavior of coarticulatory transitions in child and adult speech, we can look to studies of the relative timing of tongue and jaw gestures in adult fricative productions. Mooshammer, Hoole & Geumann (2006) used electromagnetic midsagittal articulography (EMMA) to investigate the temporal coordination of tongue tip and jaw gestures in VCV disyllables produced by adult speakers. In the transition from a fricative to a vowel, it was observed that subjects would first begin to lower the jaw to anticipate the more open configuration of the vowel, meanwhile keeping the tongue in a high position to maintain frication. While it would be difficult to perform a comparable study with very young children, it is easy to envision how this coarticulatory pattern might be affected in a young speaker with limited speech-motor control. Chapters 2 and 4 described young speakers' difficulty producing discrete movements of a single articulator, particularly movements of the tongue without the support of the jaw. If a child whose tongue movements are parasitic on mandibular gestures attempts to produce the anticipatory jaw-lowering described above, the movement of the jaw will also carry the tongue away from its point of constriction, causing frication to cease. To avoid truncating the fricative, the child might be expected to maintain a high jaw position until fricative

articulation is completed, then lower the jaw and tongue simultaneously to the position for the vowel target. In the absence of anticipatory lowering, however, the jaw will have to move particularly rapidly if the vowel target is to be reached on a normal time frame. This rapid, uncoarticulated transition will be ruled out by constraints on the expenditure of articulatory effort. A third alternative would be to complete the articulation of the fricative, then lower both tongue and jaw in a simultaneous transition of extended duration. This configuration serves to minimize articulatory effort, but the extended formant transitions associated with this slow, coordinated tongue and jaw movement causes the child's output to deviate in its perceptual properties from the adult model. It remains to be confirmed that the child speaker's atypical transition from a fricative to a nonhigh vowel should perceived as comparable in quality to a high vowel or a palatal glide. While it is indeed the case that the jaw target for a palatal glide has a height intermediate between that of a sibilant fricative and that of a nonhigh vowel, additional lingual adjustment would be necessary to transition from a canonical alveolar fricative to a canonical palatal glide. On the other hand, the palatal glide represents a natural intermediate stage in a child who produces all fricatives with the tongue body held relatively high. This claim will be substantiated for B, with more detailed discussion and acoustic data, in Section 7.

5.3 Gliding as minimization of articulatory velocity and coarticulatory undershoot

The same logic that motivates B's process of glide epenthesis can also offer insight into his use of gliding as a repair strategy for prevocalic fricative targets. Gliding can be understood as a more extreme version of the coarticulated transition depicted in Figure 10. In this case, in addition to the protracted intermediate stage between fricative and vowel targets, there is undershoot of the fricative target. Failure to attain articulatory targets due to coarticulatory pressures is a well-known phenomenon that especially occurs when adjacent targets are far apart in articulatory space (Lindblom, 1963; Flemming, 2001). While other targets might be able to tolerate considerable undershoot without major perceptual consequences, fricative production is highly sensitive to fine differences in articulatory configuration. If the degree of target undershoot in response to effort-minimizing pressures is too great, frication will not generated at all. While sacrificing the fricative has rather severe consequences for the perceptual correspondence between B's output and the adult target, the savings in terms of articulatory effort are extensive. First, by replacing the fricative with a glide, B is enabled to use a smaller mandibular gesture, since the palatal glide is produced with a lower jaw height than the class of coronal fricatives. Additional savings in articulatory effort are afforded by avoiding the precise gesture necessary for fricative production. While effort-minimizing constraints that penalize precise gestures have not played an active role in the models pursued in this dissertation, their existence has been thoroughly documented in other contexts. Kirchner (1998) has pointed out that precise gestures require additional muscle activation, since antagonist as well as agonist muscles must be recruited to achieve refined articulator placement. This is particularly relevant in the production of strident fricatives, where the speaker must hold the tongue close to the palate without overshooting and creating complete closure. Given these difficulties, it is easy to understand how considerations of articulatory effort could compel a speaker with significant speech-motor limitations to sacrifice faithfulness to fricative manner.

5.4 The onset-coda asymmetry as minimization of articulatory effort

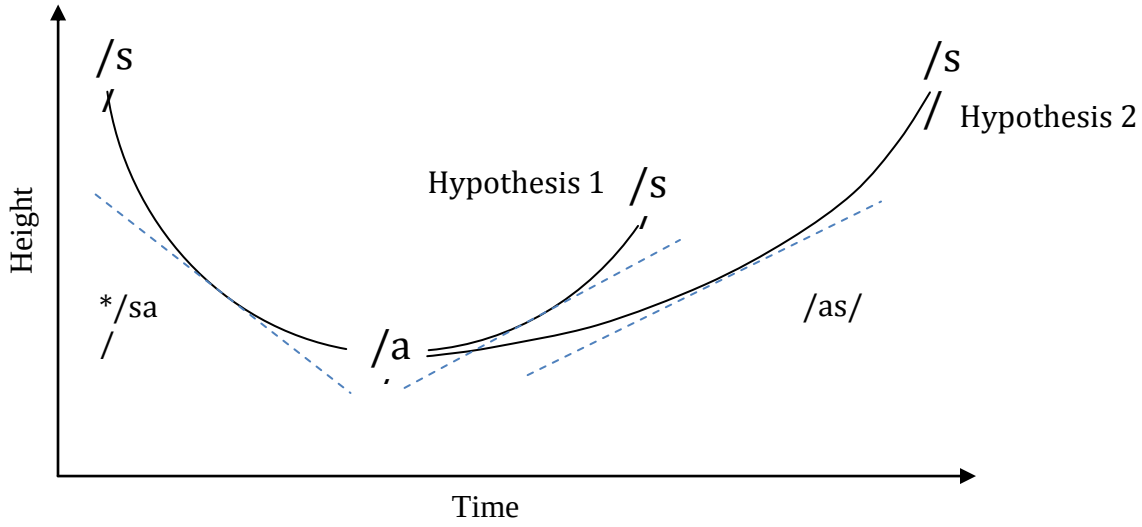
5.4.1 Possible sources of a positional asymmetry in effort expenditure

Sections 4.2 and 4.3 demonstrated that considerations of effort-minimization can account for B's use of gliding and glide epenthesis as alternatives to faithful fricative production, as well as the advantage for accurate fricative production in the context of a high vowel. However, the effort-minimization account has not yet explained the phenomenon of greatest interest to the present investigation, namely the asymmetric behavior of fricatives in prevocalic and postvocalic contexts. Given the success of effort factors in accounting for other aspects of B's pattern of fricative production, it will be assumed that the onset-coda asymmetry is also conditioned by considerations of articulatory effort. There are two major ways in which a vowel-fricative transition could require less effort than a fricative-vowel transition, in keeping with the notion of effort as proportional to articulatory velocity. These are stated in (20) and represented graphically in Figure 11.

(20) Possible sources of asymmetry in effort: fricative-vowel versus vowel-fricative transitions.

a. Hypothesis 1. The postvocalic fricative is produced with a weaker gesture, requiring a smaller degree of articulator displacement.
b. Hypothesis 2. The vowel-fricative transition unfolds over a longer period of time than the fricative-vowel transition.

Figure 11. Possible transition asymmetries, /sa/ versus /as/



5.4.2 The onset-coda asymmetry as difference in gestural magnitude

We begin by considering the first hypothesis, which posits that postvocalic fricatives might be associated with a lesser degree of constriction, with the reduced magnitude of the gesture incurring less effort than the larger prevocalic fricative. This possibility was raised by Inkelas & Rose (2008), who proposed that processes of neutralization in strong position, including positional stopping of fricatives, can be understood as a reflection of differences in the strength of articulatory gestures across prosodic contexts (Keating, 2006). On closer investigation, however, it is highly unlikely that a difference of sufficient magnitude could emerge in the case of the fricative asymmetry. While there is evidence that coronal stops are produced with slightly greater constriction in onset than coda contexts, the size of the effect at the word level is quite modest (Keating, 1995). More importantly, experimental evidence indicates that there is extremely little variation in the degree of constriction in sibilant production across prosodic positions (Fougeron, 1998, 2001). This is thought to reflect the limited range of deviation in articulatory placement that can be tolerated while still creating the precise aperture needed for sibilant production. Overall, while it remains possible that some small discrepancy in articulator height exists between fricatives in onset versus coda position, we can be confident that this difference is not large enough to account for the robustly distinct behaviors of pre- and postvocalic fricatives in B's productions.

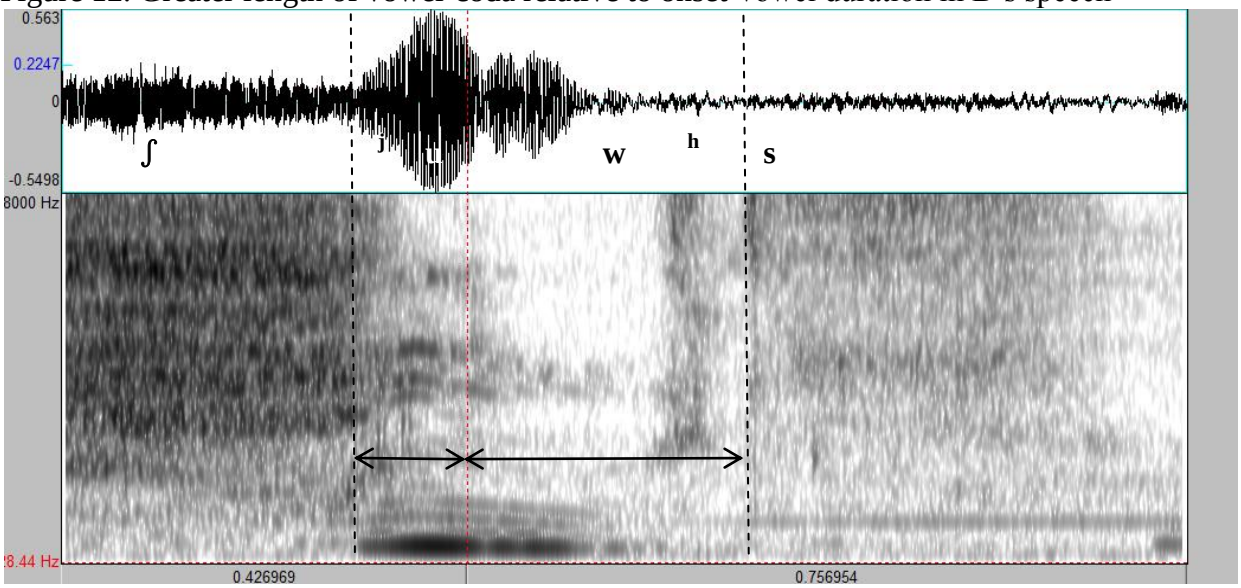
5.4.3 The onset-coda asymmetry as difference in transitional duration

A second possibility depicted in Figure 11 holds that fricative-vowel and vowel-fricative transitions can unfold at different rates. From the adult articulatory literature, it is not immediately predicted that CV transitions should be more rapid than VC transitions. Hertrich & Ackermann (1997) reported that the labial closing gesture in a /pVp/ syllable had a significantly shorter duration than the opening gesture, citing similar results from Adams, Weismer, & Kent (1993), Vatikiotis-Bateson & Kelso (1993), and Gracco (1994). However, Beckman, Edwards, & Fletcher (1991) reported a different pattern for /pVp/ syllables in a context for domain-final lengthening. They found that the longer duration of the syllable in the final lengthening context was attributable entirely to elongation of the jaw-closing gesture, while the duration of the jaw-opening gesture remained unchanged relative to non-lengthening contexts. While this study did not test /sVs/ syllables in final lengthening contexts, if a comparable effect were found, it would conform precisely to the prediction of Hypothesis 2, represented in Figure 11.

While in adults this difference in the relative durations of opening and closing gestures is specific to phrase-final contexts, there is reason to believe that a more pervasive lengthening effect characterized B's productions. Recall that B's speech was marked by atypical prosody, considered one of the hallmarks of childhood apraxia of speech. One of the most striking abnormalities was the presence of distinct pauses between adjacent syllables. Based on this and the behavior of other boundary phenomena such as glottal epenthesis and flapping, it was argued that B's syllable boundaries typically had the properties of word- or even phrase-level boundaries. This gives rise to the prediction that domain-final lengthening could apply in phrase-medial or even word-medial contexts in B's productions. This speculation was borne out through inspection of spectrograms of B's prevocalic and postvocalic fricative productions. Figure 12 illustrates the asymmetric nature of fricative-vowel and vowel-fricative transitions in a single word, *shoes*, collected from a phrase-medial context. The time from the offset of frication to the calculated midpoint of the steady-state vowel is noticeably shorter than the time interval from

vowel midpoint to the onset of the coda fricative. (The broad-spectrum noise preceding the onset of the final fricative is an interval of preaspiration, a pervasive phenomenon in B's speech that will be discussed in detail below.)

Figure 12. Greater length of vowel-coda relative to onset-vowel duration in B's speech



However, demonstrating the presence of final lengthening effects in B's phonology provides only a partial explanation for the onset-coda asymmetry in his production of fricatives. It is additionally necessary to demonstrate that a comparable lengthening process was unavailable in the context of consonant-vowel transitions. If B could extend the duration of the CV transition at will, he should have been able to slow the transition to the point where faithful fricatives would emerge in initial contexts as well. Instead, B appears to have been constrained in the CV context to produce a more rapid transition, with the higher associated effort costs accounting for the non-attestation of prevocalic fricatives in the earliest stage of the recorded period.

Precisely such an asymmetry has been formalized in the framework of articulatory phonology (Browman & Goldstein, 1986, 1995). The basic units of articulatory phonology are gestures, which are constrictions of the vocal tract that are defined in terms of their spatial and temporal properties. Here we will focus on the temporal dimension. Browman & Goldstein have argued that gestures stand in characteristic timing relations with respect to each other based on their position in the syllable. Gafos (2002) summarizes their proposal as follows (p. 279):

> [Browman & Goldstein's] work suggests that syllables are characteristic patterns of temporal cohesion among gestures. To say that a set of gestures belong to the same syllable is to say that these gestures enter into a characteristic pattern of temporal organization. Specifically, Browman and Goldstein (1988) have argued that consonants are coordinated with a vowel in a way that depends on their syllabic position.

Several temporal landmarks can be identified over the course of a gesture, including the gestural onset (the initiation of movement toward a target), the target (the point at which the gesture first attains its target position), the C-center (the midpoint of the period during which the

gesture is at its target), and the release (the beginning of movement away from the target position). These are depicted in Figure 13, as schematized by Gafos (2001). Gafos has proposed that the characteristic alignments of consonant and vowel gestures can be captured using Optimality-Theoretic alignment constraints. He maintains that the CV transition is subject to an alignment constraint requiring the c-center of the consonant to coincide with the onset of the vocalic gesture, which he terms ALIGN(C, C-Center, V, Onset), while the preferred relation between a vowel and a coda consonant aligns the release of the vowel with the target of the consonant (ALIGN(V, Release, C, Target)). Figure 14 depicts the preferred phasings for CV and VC sequences.

Figure 13. Landmarks in the articulatory gesture

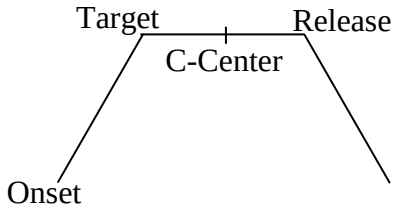
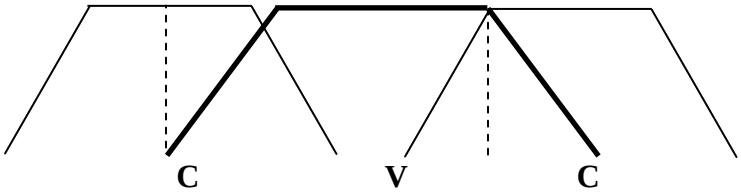


Figure 14. Preferred phasings for CV (C-Center, V-Onset) and VC (V-Release, C-Target)



There is evidence that consonant-vowel sequences are more tightly bound in their timing than vowel-consonant sequences. The differing flexibility of CV and VC transitions can be expressed using the phase-window framework advocated by Byrd (1996). Byrd observed that the degree of overlap between two gestures is subject to variation conditioned by a number of factors, including speech rate and the presence of word or phrase boundaries. She argued that a framework in which relationships of gestural coordination are defined by just two points is not sufficient to account for this range of phasing behaviors. To accommodate this variability, Byrd suggested that preferred coordination relationships are expressed not in terms of individual points, but by a range of overlap between two gestures, or phase window. A wide phase window allows for more variation in the timing of a transition, whereas a narrow phase window enforces a tight timing relationship. Cho (1998) suggested that the timing preferences expressed by a phase window can be encoded in a grammatical constraint, IDENT(timing): "The range of gestural phasings in the output must be identical to, or fall within the Phase Window in the input which specifies a permissible range of gestural overlap" (cited in Davidson, 2003, p. 15). Crucially, it has been posited that the phase window of an onset-coda transition is narrower, and the timing relationship thus more constrained, than the phase window for other components of the syllable (Davidson, 2003). This asymmetry is supported by the abovementioned finding that VC but not CV transitions appear with extended duration in a context for final lengthening

(Beckman, Edwards, & Fletcher, 1991; Byrd, 1995).[23] On the hypothesis that the phase window is larger for a VC than a CV transition, IDENT(timing) will limit changes in the duration of CV transitions more strictly than changes in the VC context. This provides an explanation for the absence of prevocalic fricatives from B's earliest stage of development. At this stage, slowing the fricative-vowel transition to the point of reaching an acceptable level of articulatory effort would require extending the duration of the transition beyond the interval permitted by the CV phase window, incurring a crucial violation of high-weighted IDENT(timing).

5.4.4 Perceptual asymmetries between fricative-vowel and vowel-fricative transitions

Having accounted for the difference in timing and hence in articulatory effort distinguishing vowel-fricative and fricative-vowel sequences in B's output, we still face an unexplained asymmetry in the transcribed record of these two transitions. In preceding discussion of B's process of glide epenthesis between a fricative and a nonhigh vowel, it was argued that the glide was the perceptual consequence of an elongated articulatory transition characterized by synchronous tongue and jaw movement. However, the transition from a vowel to a coda fricative is also posited to involve a slow transition with simultaneous tongue and jaw movement, a slightly extended mirror image of the transition associated with the epenthetic glide in the CV context. We might thus expect an epenthetic offglide to be perceived in this context. In actuality, around the same time that prevocalic fricatives in nonhigh vowel contexts were frequently transcribed with an epenthetic glide, offglides or changes in vowel quality were conspicuously absent from the transcribed record of B's vowel-to-fricative transitions. To maintain the analysis proposed thus far, it will be necessary to account for this asymmetry.

A first hypothesis looks back to the discussion of perceptual asymmetries in Chapter 1, where we reviewed evidence that CV transitions are of greater perceptual salience than VC transitions (Fujimura, Macchi, & Streeter, 1978). The lower salience of formant transitions in the VC context could prevent the percept of an epenthetic glide from arising in the context of a fricative-vowel transition. This hypothesis can be tested by reversing the direction of audio play for both types of transitions. It is predicted that the percept of the glide should be eliminated from a fricative-vowel transition played in the VC direction, whereas a glide percept should emerge from vowel-fricative transitions played in the CV direction. This prediction was substantiated in numerous tokens from B's speech. Figure 15 depicts a fricative-vowel transition that was perceived to contain a clear epenthetic glide in the forward direction, yet reversal to a vowel-fricative transition yielded the percept of a grossly monophthongal vowel. Figure 16 illustrates the opposite case, a vowel-fricative transition with no associated glide percept that was found to acquire an epenthetic glide when played backwards. The percept of a glide was not evident when adult vowel-fricative transitions in comparable contexts were played in the backwards direction.

[23] A different line of evidence suggesting that CV is more tightly bound than VC comes from phoneme segmentation tasks administered to preliterate child speakers. Geudens & Sandra (2003) reported that children treat CV as a unit to the exclusion of the coda consonant, whereas the rime does not behave as a cohesive unit.

Figure 15. Formant transition perceived as glide in forward direction only (target word “sit”)

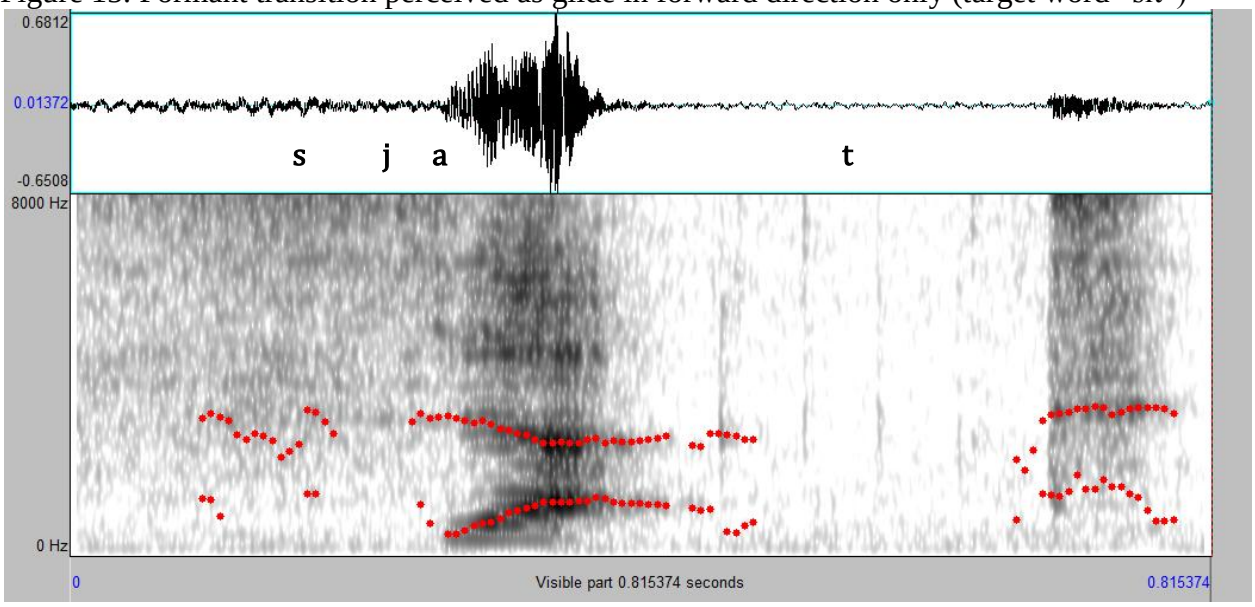
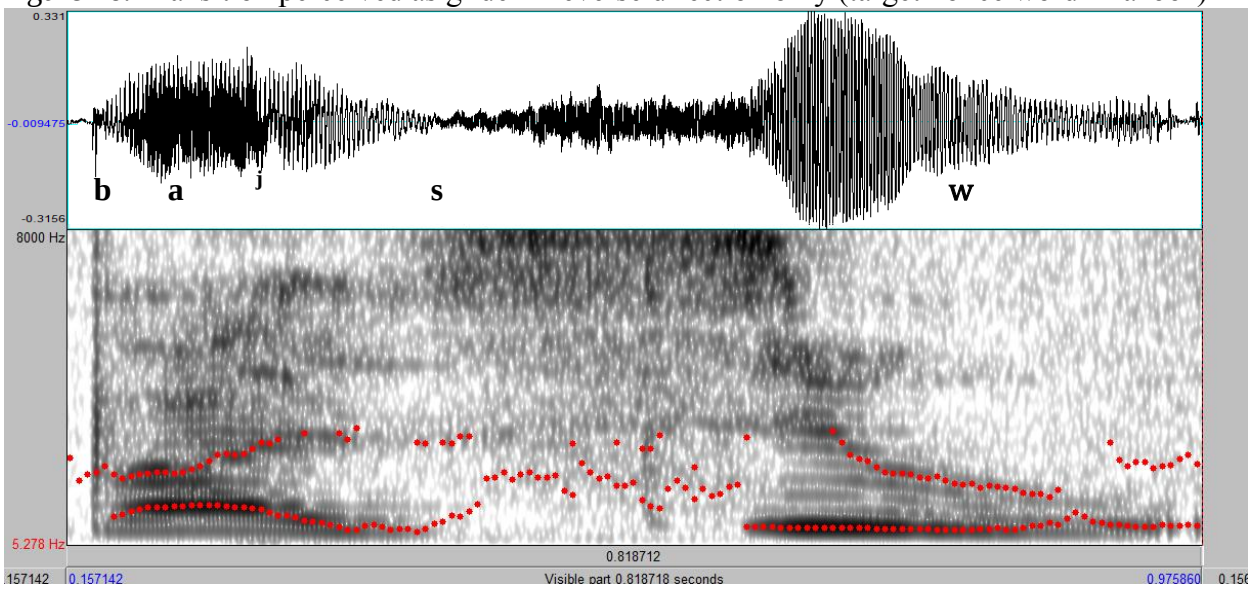


Figure 16. Transition perceived as glide in reverse direction only (target nonce word “Bazoo”)



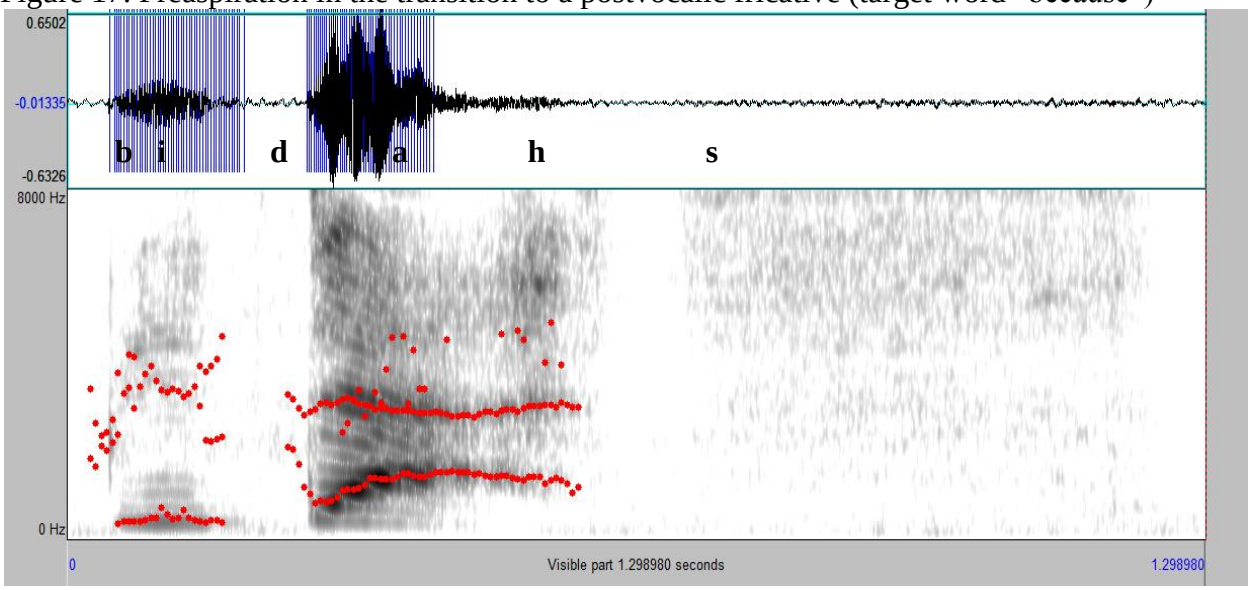
At the same time, though, this investigation identified a sizable number of tokens for which audio presentation in the reverse direction failed to generate or eliminate the percept of a glide in the hypothesized fashion. Thus, while the perceptual asymmetry between CV and VC contexts does play a role in the absence of transcribed glides in postvocalic contexts, differences in production must be making a contribution as well.

A potentially relevant difference in production has already been identified in the longer duration of vowel-fricative relative to fricative-vowel transitions, a consequence of B’s pervasive domain-final lengthening process. (Note that even the elongated fricative-vowel transitions perceived to have an epenthetic glide were habitually shorter than their VC counterparts;

compare the durations of the two transitions in Figures 15 and 16, where the two windows have nearly equivalent total durations.) This durational difference might have an influence on the listener's likelihood of perceiving a glide; for instance, transitions that exceed some durational threshold might lose their glidelike nature. In this case, however, perceptual consequences in the form of a change in vowel quality could still be expected. Indeed, preliminary investigation indicated that slowing the glide portion of a fricative-vowel transition did not eliminate the percept of a change in vowel quality, even when this segment was played in reverse. Thus, durational differences do not in and of themselves account for the absence of a perceived epenthetic glide in the context of the vowel-fricative transition. However, the perceptual asymmetry does find an explanation in another factor that was found to correlate with the final lengthening phenomenon in B's productions, namely preaspirated production of postvocalic fricatives.

While preaspirated production of coda fricatives was not noted in the transcribed record of B's speech, inspection of the acoustic data revealed that a preponderance of vowel-fricative transitions contained a period of aspiration preceding the onset of frication. Figure 17 offers a striking illustration of this preaspirated interval. In B's speech, preaspiration was just as pervasive as lengthening; it was not specific to phrase-final contexts or syllables of unusually long duration. In addition, in B's speech the preaspiration interval was not limited to the context of voiceless fricative targets, a consequence of his productive process of coda devoicing. These intervals of aspiration have the effect of obscuring formant transitions into the fricative. While the present investigation can offer no specific information regarding the activity of the articulators during this silent interval, it can be speculated that B executed a gradual transition in articulator height throughout the duration of the aspiration. Thus, the absence of the percept of a glide in the vowel-fricative transition can be understood as the consequence of the cessation of voicing during the prolonged period of articulator movement.

Figure 17. Preaspiration in the transition to a postvocalic fricative (target word "because")



It is not entirely clear whether the preaspirated interval in B's production of coda fricatives was a deliberate strategy for obscuring perceptually anomalous transitions or an accidental consequence of other phonetic factors. There is reason to believe that B might produce

preaspirated coda fricatives independent of any question of faithfulness to a perceptual target. Anticipatory opening of the glottis between a vowel and a voiceless fricative can be observed in adult articulation, where it is thought to be motivated by the aerodynamic pressure to insure adequate airflow for fricative production (Hoole, 1999; Gordeeva, 2007). In adult speakers, preaspiration of coda fricatives appears to be particularly pronounced in a context for final lengthening; given the pervasive nature of lengthening in B's speech, we could expect preaspiration to be correspondingly widespread. A second factor expected to enhance the occurrence of preaspiration in B's speech is his differential timing of laryngeal and oral gestures. In Section 3.4, it was noted that B appeared to exercise a greater degree of control over laryngeal function than he did over movements of the oral articulators. Thus, if he produced appropriately timed laryngeal adduction and abduction to mark the onset and offset of a vowel, the onset of oral closure could be expected to lag behind laryngeal abduction, creating an interval of aspiration. In sum, general aerodynamic principles appear to have conspired with B's disparate control of laryngeal and oral gestures to create a tendency for preaspirated fricative production.

While preaspiration may thus have originated as an accidental consequence of articulatory and aerodynamic factors, it offers an additional advantage in the assessment of perceptual faithfulness. If phonation were sustained during B's extended movements of the tongue and jaw during the vowel-fricative transition, a change in vowel quality and an associated faithfulness violation could be expected. On the other hand, an interval of aspiration noise preceding a coda consonant is known to have extremely low perceptual salience (Kingston, 1990; Silverman, 2003). Consistent with this claim, B's postvocalic fricatives with preaspiration were almost never perceived as atypical relative to adult models. In the analysis to follow, the lower perceptibility of preaspiration will be modeled by assigning a higher weight to the perceptually-oriented DEP-Glide constraint relative to DEP-Glottal. However, this perceptual asymmetry does not obtain in the CV context, where aspiration noise is perceptually salient. Because the introduction of an aspirated interval is no less anomalous than the offglide perceived when the fricative-vowel transition is produced with continuous voicing, postaspiration of prevocalic fricatives was rarely attested in B's output. This can be modeled by assigning the positional constraint DEP-Glottal-Onset an equal or greater weight than that assigned to DEP-Glide-Onset.

In summary, the segmental and prosodic factors found to condition B's acquisition of fricatives can be understood as the consequence of constraints on articulation. The pressure to minimize articulatory effort gives rise to a preference for transitions that are limited in magnitude or unfold over an extended period of time. The advantage for postvocalic over prevocalic fricative production can thus be understood as a consequence of slower transitions in the context of coda fricatives; this slowing was achieved through a pervasive pattern of domain-final lengthening that was blocked for onset fricatives due to the tighter timing of CV relative to VC gestural sequences. The phenomenon of glide epenthesis can be understood as the perceptual consequence of extended coarticulatory transitions involving simultaneous movement of the tongue and jaw, a reflection of B's limited capacity for discrete lingual gestures. In coda contexts, the perceptual consequences of the extended transition were obscured by a process of preaspiration. Additional investigation will be required to determine the generality with which these factors can be seen to apply across other children exhibiting positional asymmetries in the acquisition of fricative manner.

6. Formal phonological analysis

Section 5 laid out the phonetic underpinnings of the proposal that the onset-coda asymmetry in B's fricative production can be modeled as the consequence of limitations on articulatory effort. In this section, the analysis will be formalized using phonetically motivated constraints.

6.1 Review of constraints and weightings

As it was presented in Section 5, this account will require two separate constraints on articulatory effort. The first is a general effort-minimizing constraint of the type that is active not only in child productions, but also in adult speech, where it can be observed to motivate processes of coarticulation. The present analysis will invoke *EFFORT, a constraint that places a limit on rapid transitions between articulatory configurations (Flemming 2001, 2008). In light of differences in the weight and motor-control properties of various articulators, discussed in Chapter 2, it is likely that separate effort-minimizing constraints govern the behavior of the tongue, lips, and jaw, as well as the velum and glottis. Given the well-documented dominance of jaw movement in child speech production (MacNeilage & Davis, 1990; Nittrouer, 1993; Green, Moore, & Reilly, 2002) it is the * $\text{EFFORT}_{\text{mand}}$ constraint governing jaw movement that will be of relevance for the present analysis.

(21) *$\text{EFFORT}_{\text{mand}}$: Minimize the velocity of the mandibular articulator.

In principle, violations of *$\text{EFFORT}_{\text{mand}}$ are assessed based on the distance between two articulatory targets and the time taken to cross that distance. However, these measurements will not be available as part of the present discussion. Instead, *$\text{EFFORT}_{\text{mand}}$ violations will be estimated from the relative distances and hypothesized durations of different types of articulatory transitions. The analysis in Section 5 also invoked a child-specific constraint banning independent movements of the tongue and the jaw. This is the constraint MOVE-AS-UNIT, familiar from Chapter 4, which stipulates that the tongue moves together with the jaw as part of a single articulatory complex.

Lastly, we can consider the faithfulness constraints relevant to B's fricative production. IDENT-consonantal, which played a prominent role in our preliminary modeling in Section 3 of this chapter, will also be included in the articulatory-based constraint system. The constraint DEP-glide will also need to be carried over from the preliminary analysis. Unlike the earlier model, however, here glide epenthesis is viewed not as phonological insertion of a glide target, but as the perceptual consequence of the child's extended fricative-vowel transition. DEP-glide can accommodate this possibility if it is formulated as a perceptually oriented constraint that penalizes the presence of the acoustic correlates of a glide in the absence of an underlying glide segment.

(22) DEP-glide: The perceptual correlates of a glide in the output are associated with a corresponding glide in the input.

Weights for the constraints described here are proposed in Tables 12-14. For B's Stage 1, when prevocalic fricatives were uniformly replaced with glides, MOVE-AS-UNIT is assigned

weight 3; this is consistent the weight it received in the roughly contemporaneous Stage 1 of the analysis of B's acquisition of velar place. The faithfulness constraint IDENT-consonantal receives a weight slightly higher than that of DEP-glide. Finally, the effort-minimization constraint *EFFORT$_{mand}$ starts out with weight 1, but some candidates will incur multiple violations of this constraint based on the size and duration of the transition.

To model B's Stage 2, it is necessary to represent the availability of glide epenthesis as well as gliding as a repair strategy for prevocalic fricatives. In addition, faithful prevocalic fricatives began to be attested in the context of high vowels only. These changes can be accomplished with a minimal adjustment to the model, namely a slight increase in the weight of IDENT-Consonantal. B may have come to assign a higher weight to this faithfulness constraint following exposure to exaggerated adult models of fricative-initial words.

Finally, several changes in the scheme of weights make it possible to model the transition to fully faithful fricative production in B's Stage 3. The first involves ongoing increases in the weights accorded to the faithfulness constraints IDENT-consonantal and DEP-glide. In addition, it is proposed that repetitive practice of the motor plan for fricative articulation led to a decrease in the weight assigned to violations of MOVE-AS-UNIT and *EFFORT$_{mand}$. As a result, in Stage 3 the weights of the faithfulness constraints *EFFORT$_{mand}$ and DEP-glide exceed those assigned to MOVE-AS-UNIT and *EFFORT$_{mand}$, permitting faithful realization of prevocalic fricatives. Note that the weight assigned to MOVE-AS-UNIT is once again in keeping with the weight of that constraint in a contemporaneous stage in the model of B's development of velar place, seen in Chapter 4. B's Stage 3 of velar development (ages 4;2.19-4;3.6) coincides with Stage 3 of fricative development (age 4;2+), and in both cases the weight assigned to MOVE-AS-UNIT is 1.

Table 12. Specification of constraint weightings for B's Stage 1

Constraint Name	**Weight**
MOVE-AS-UNIT	3
IDENT-consonantal	1.5
*EFFORT$_{mand}$	1
DEP-glide	1

Table 13. Specification of constraint weightings for B's Stage 2

Constraint Name	**Weight**
MOVE-AS-UNIT	3
IDENT-consonantal	2
*EFFORT$_{mand}$	1
DEP-glide	1

Table 14. Specification of constraint weightings for B's Stage 3

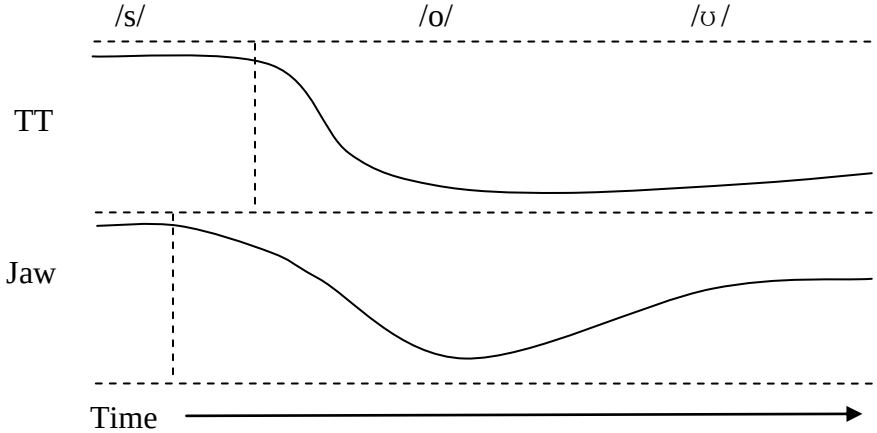
Constraint Name	**Weight**
IDENT-consonantal	3
DEP-glide	2
MOVE-AS-UNIT	1
*EFFORT$_{mand}$	.5

6.2 Implementation of constraints: Prevocalic fricatives in nonhigh vowel contexts

In the tableaux that follow, the proposed constraints are implemented to model prevocalic fricatives across different vowel contexts and stages of development. Because of the directly phonetic nature of the constraints used here, it will be necessary to enrich our representations of candidate forms to reflect differing articulatory configurations. However, to simplify the modeling task, the phase windows discussed in Section 5.4.3 will not be represented in these diagrams. Instead, while a variety of patterns of gestural coordination will be represented here, consideration will be limited to those candidates whose intergestural relations fall within the phase window dictated by the relevant position in the syllable. Candidates not satisfying this requirement are presumed to be ruled out by high-weighted IDENT(timing). In addition, unfaithful candidates with fricative stopping (e.g. [doʊ] for *sew*) will not be considered in these tableaux. In the preliminary analysis proposed in Section 3.4, stopping was ruled out by the high weight of the IDENT-continuant constraint.

We begin by modeling a target with a nonhigh vowel, *sew*. Figure 18 diagrams the articulatory movements that are posited to characterize a typical adult production of this target; this form will be represented as [s□oʊ] in the tableaux that follow, with the arc connecting /s/ and /o/ symbolizing typical adult coarticulation of the fricative and vowel. The upper portion of the score shows that the tongue tip (TT) starts out high and then makes a rapid transition to a low height for the nonhigh vowel. However, the jaw-lowering gesture depicted in the bottom half of the score begins in advance of the tongue-tip gesture and has a more gradual slope. The dissociated movement of tongue and jaw incurs a violation of MOVE-AS-UNIT. However, the early initiation of jaw movement permits a slow mandibular transition, and the violation of *EFFORT$_{mand}$ incurred by this form is equivalent to that incurred by the glide epenthesis candidate, depicted in Figure 21 below.

Figure 18. Fricative-vowel transition exhibiting anticipatory jaw-lowering ([s□oʊ])

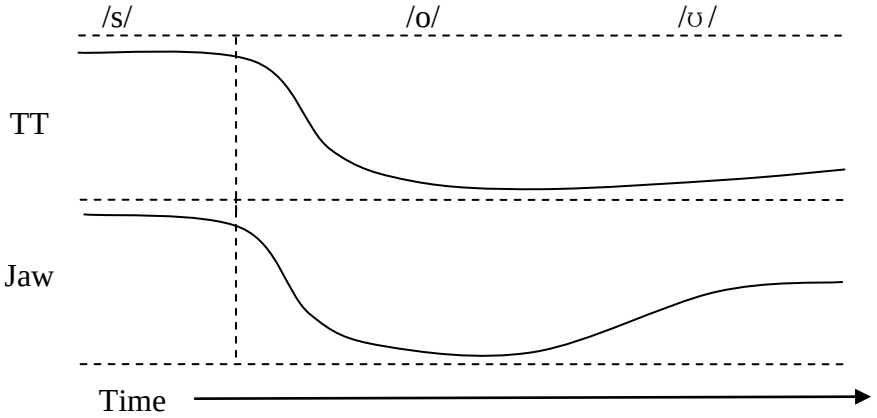


Number of violations: MOVE-AS-UNIT (1), *EFFORT$_{mand}$(2)

The second candidate eschews the anticipatory jaw-lowering described above. In Figure 19, both tongue and jaw are held high throughout fricative articulation, then rapidly lowered to the vowel target. This candidate does not require dissociated action of tongue and jaw and thus does not violate MOVE-AS-UNIT. Due to the rapid nature of the transition, it is also postulated to result in a perceptually typical fricative-vowel transition, with no violation of faithfulness.

However, the particularly rapid movement of the jaw in this candidate significantly violates the preferences of *EFFORT$_{mand}$, schematized below with four counts of violation of this constraint.

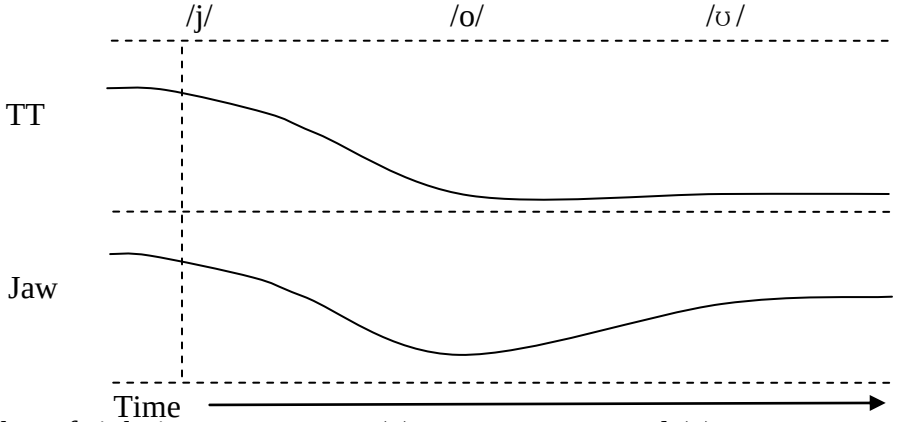
Figure 19. Fricative-vowel transition without anticipatory jaw-lowering



Number of violations: *EFFORT$_{mand}$(4)

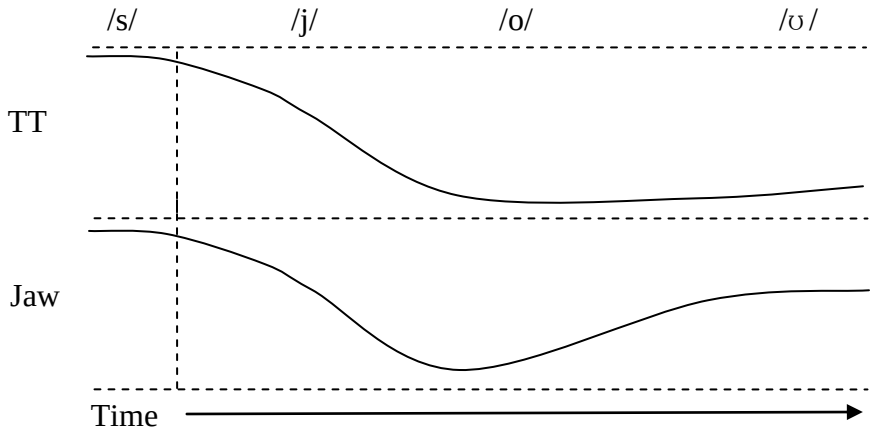
We now consider two unfaithful outcomes, gliding and glide epenthesis. The gliding candidate [joʊ] is depicted in Figure 20, the glide epenthesis candidate [sjoʊ] in Figure 21. Both of these forms are notable for their slow and gradual transition from a high jaw position to a more open configuration, which limits violations of *EFFORT$_{mand}$. Because there is no dissociation of tongue and jaw movement in these candidates, MOVE-AS-UNIT is satisfied as well. The two forms differ only in that the glide epenthesis candidate achieves a period of frication, while in the gliding candidate, coarticulatory undershoot eliminates the fricative target completely. Generation of sibilant frication requires a higher jaw position than production of a high glide, resulting in one violation of *EFFORT$_{mand}$ in excess of the single violation incurred by the gliding candidate. These two candidates also violate different faithfulness constraints: gliding is penalized for violating IDENT-consonantal, while glide epenthesis incurs a violation of DEP-glide due to the percept of a glide that emerges from the extended fricative-vowel transition.

Figure 20. Extended transition with coarticulatory undershoot, perceived as glide



Number of violations: EFFORT$_{mand}$ (1), IDENT-consonantal (1)

Figure 21. Fricative-vowel transition with extended duration, perceived as glide epenthesis



Number of violations: *EFFORT$_{mand}$ (2), DEP-glide (1)

Table 15 compares the violations incurred by the candidates laid out above. In Stage 1, the high weight assigned to MOVE-AS-UNIT and the relatively lower weight of IDENT-consonantal leads the least effortful candidate, [joʊ], to emerge as the sole winner.

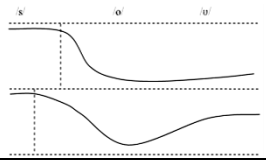
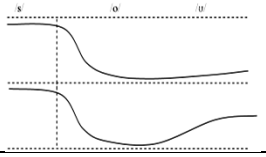
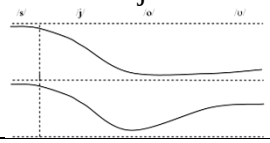
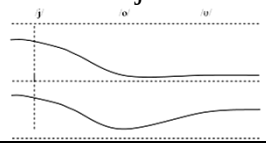
Table 15. Stage 1: An initial fricative before a nonhigh vowel undergoes gliding.

/soʊ/, *sew*	MOVE-AS-UNIT	IDENT-consonantal	*EFFORT$_{mand}$	DEP-glide	**TOTAL**
	3	1.5	1	1	
a. □soʊ	1	0	2	0	**5**
b. soʊ	0	0	4	0	**4**
c. sjoʊ	0	0	2	1	**3**
d. ☞ joʊ	0	1	1	0	**2.5**

In B's Stage 2, depicted in Table 16, the candidate with typical adult coarticulation (a) continues to be ruled out by MOVE-AS-UNIT, and the candidate without coarticulation (b) is ruled

out by *EFFORT$_{mand}$. However, the increased weight of IDENT-consonantal in this stage causes both gliding and glide epenthesis candidates to be appear as possible winners.

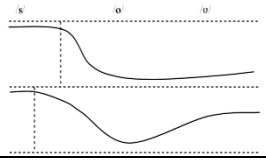
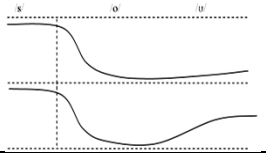
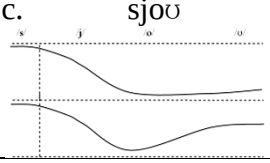
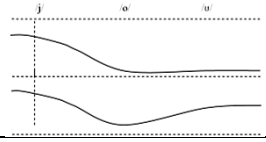
Table 16. Stage 2: An initial fricative before a nonhigh vowel undergoes gliding/glide epenthesis

/soʊ/, *sew*	MOVE-AS-UNIT	IDENT-consonantal	*EFFORT$_{mand}$	DEP-glide	**TOTAL**
	3	2	1	1	
a. □soʊ 	1	0	2	0	**5**
b. soʊ 	0	0	4	0	**4**
c. ☞ sjoʊ 	0	0	2	1	**3**
d. ☞ joʊ 	0	1	1	0	**3**

Lastly, in Stage 3 the lower relative weight of the effort-minimization constraints leads faithful fricative production to emerge as the preferred output. With the weightings adopted here, it remains undetermined whether the faithful fricative is produced with dissociated tongue and jaw movement, as in candidate (a), or with rapid simultaneous transitions, as in candidate (b); this may be a point of variation among speakers.

Table 17. Stage 3: An initial fricative before a nonhigh vowel is realized faithfully.

/soʊ/, *sew*	IDENT-consonantal	DEP-glide	MOVE-AS-UNIT	*EFFORT$_{mand}$	**TOTAL**

	3	2	1	.5	
a. ☞ □soʊ 	0	0	1	2	**2**
b. ☞ soʊ 	0	0	0	4	**2**
c. sjoʊ 	0	1	0	2	**3**
d. joʊ 	1	0	0	1	**3.5**

While the model posited here is accurate in describing B's careful speech in each stage of development, we have not yet accounted for his connected and/or unmonitored speech, where gliding continued to be attested through Stage 3. A likely solution is to assume that the cost of violating effort-minimization constraints is greater in the context of rapid speech, as proposed by Kirchner (1998). In addition, the weight associated with faithfulness constraints may vary with the level of "care and attention" the speaker devotes to a particular utterance (Hewlett, Gibbon, & Cohen-McKenzie, 1998). This would lead to the assignment of a lower weight to IDENT-consonantal in the context of casual speech relative to the highly monitored speech of the therapy setting. One or both of these differences in weighting could give rise to the continuing attestation of gliding in B's casual speech in later stages of development.

6.3 Implementation of constraints: Prevocalic fricatives in high vowel contexts

We now can consider the behavior of the proposed constraint system for a target word with a [+high] vowel, e.g. *see*. The tableaux below consider faithful fricative candidates with and without anticipatory jaw-lowering, as well as gliding and glide epenthesis candidates. The number of violations of MOVE-AS-UNIT, IDENT- consonantal, and DEP-glide incurred by these forms remain unchanged relative to their values in the nonhigh vowel context. On the other hand, the number of violations of *$\text{EFFORT}_{\text{mand}}$ incurred by a candidate is tied to the magnitude of the articulatory transition. To reflect the smaller jaw movement required for the transition from a high initial jaw position to the vowel /i/, the number of violations of *$\text{EFFORT}_{\text{mand}}$ incurred by each candidate has been reduced by one in Tables 18-20.

An additional constraint not entertained in our previous discussion comes into play in the context of a high front vowel. This constraint, *[ji], bans the occurrence of a palatal glide in the

context before a high vowel. The activity of this constraint can be observed cross-linguistically, as in languages like Japanese, which allows [ja], [jɯ], and [jo] but not *[ji].

(23) *[ji]: A palatal glide does not occur in the environment preceding a high front vowel.

This set of constraints allows us to model the divergent behavior of fricatives before high and nonhigh vowels in B's Stage 2. Table 19 shows that with all violations taken into account, the faithful fricative candidate [si:] (with no MOVE-AS-UNIT violation) remains in contention with the unfaithful candidates [ji:] and [sji:]. This accurately characterizes the behavior of fricatives before high vowels in B's Stage 2, where gliding, epenthesis, and faithful fricative production were all attested as possible outcomes. Tables 18 and 20, modeling B's Stages 1 and 3, behave like their counterparts in the environment of a nonhigh vowel, correctly predicting uniform gliding in the first stage and faithful fricative production in the last stage. It has thus been demonstrated that the articulatory-based constraints *EFFORT$_{mand}$ and MOVE-AS-UNIT can replace the positional constraints *SV$_{[+HIGH]}$ and *SV$_{[-HIGH]}$, accurately accounting for the behavior of prevocalic fricatives in high and nonhigh vowel contexts across the stages of B's development.

Table 18. Stage 1: An initial fricative before a high vowel undergoes gliding.

/si:/, *see*	MOVE-AS-UNIT	IDENT-consonantal	*EFFORT$_{mand}$	DEP-glide	*[ji]	**TOTAL**
	3	1.5	1	1	1	
a. si:	1	0	1	0	0	**4**
b. si:	0	0	3	0	0	**3**
c. ☞ ji:	0	1	0	0	1	**2.5**
d. sji:	0	0	1	1	1	**3**

Table 19. Stage 2: An initial fricative before a high vowel is realized variably.

/si:/, *see*	MOVE-AS-UNIT	IDENT-consonantal	* EFFORT$_{mand}$	DEP-glide	*[ji]	**TOTAL**
	3	2	1	1	1	
a. si:	1	0	1	0	0	**4**
b. ☞ si:	0	0	3	0	0	**3**
c. ☞ ji:	0	1	0	0	1	**3**
d. ☞ sji:	0	0	1	1	1	**3**

Table 20. Stage 3: An initial fricative before a high vowel is realized faithfully.

/si:/, *see*	IDENT-consonantal	DEP-glide	MOVE-AS-UNIT	*[ji]	*EFFORT$_{mand}$	**TOTAL**

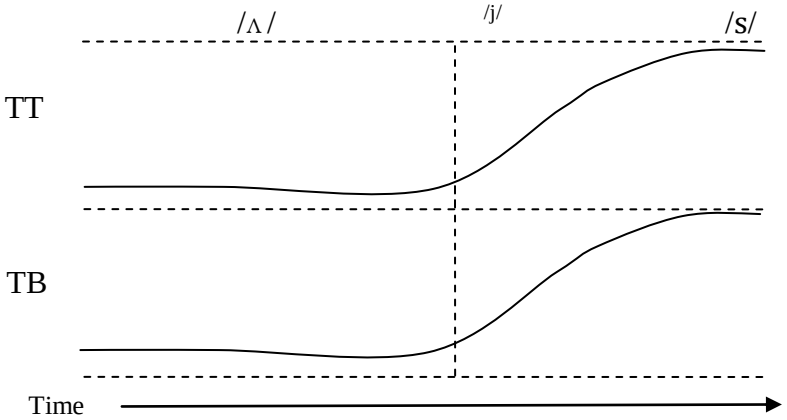
	3	2	1	1	.5	
a. ☞ si:	0	0	1	0	1	**1.5**
b. ☞ si:	0	0	0	0	3	**1.5**
c. ji:	1	0	0	1	0	**4**
d. sji:	0	1	0	1	1	**3.5**

6.4 Implementation of constraints: Postvocalic fricatives

6.4.1 Modeling postvocalic fricatives

This section will demonstrate the convergence of articulatory and perceptual factors that permit postvocalic fricatives to emerge at an earlier stage than their prevocalic counterparts. Above, it was argued that the transition from vowel to coda is habitually longer in duration than the transition from onset to vowel. To reflect the lower mandibular velocity in this context, all postvocalic velars in this section have been assigned violations of *EFFORT$_{mand}$ that are half the magnitude of their counterparts in the fricative-vowel transition.[24] In addition, no violation of MOVE-AS-UNIT is incurred in the vowel-fricative transition, since dissociated lingual and mandibular action in the CV context was specific to the need to hold the tongue high to sustain frication during coarticulatory jaw-lowering. Figure 22 depicts slow, simultaneous raising of the tongue and jaw in the transition from a vowel to a fricative, which incurs a violation of *EFFORT$_{mand}$ of magnitude 1. Although some change in vowel quality is predicted to accompany the change in jaw height depicted in the vowel-fricative transition in Figure 22, the intrinsically lower perceptual salience of formant transitions in the VC context leads to a smaller violation of the perceptually-oriented faithfulness constraint DEP-Glide, here represented with magnitude .5.

Figure 22. Vowel-fricative transition with extended duration



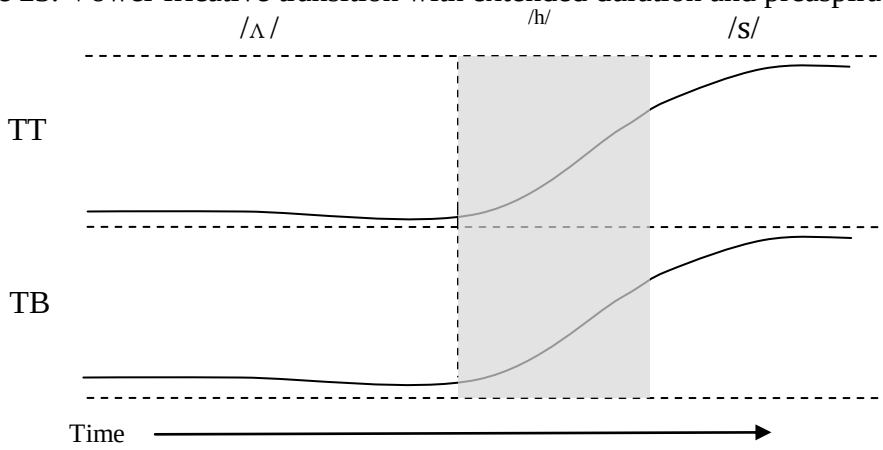
Number of violations: *EFFORT$_{mand}$ (1), DEP-Glide (.5)

Another candidate is needed to reflect B's production of postvocalic fricatives with a preceding interval of aspiration. The pattern of tongue and jaw movement for this candidate is assumed to be identical to the extended, synchronous movement depicted in Figure 22, but here

[24] As noted previously, only candidates that satisfy IDENT(Timing), remaining within the durational interval permitted by the relevant phase window, are considered here. As elsewhere, it can be assumed that the transitions in Figures 22-25 are of the longest duration permitted by IDENT(Timing).

an interval of aspiration obscures the formant movements accompanying this transition period. Below, the aspirated interval is symbolized by graying out a portion of the formant transition. The introduction of aspiration violates a faithfulness constraint DEP-Glottal, but as in the previous case, a violation of magnitude .5 is assigned to reflect the low salience of perceptual cues in the VC context.

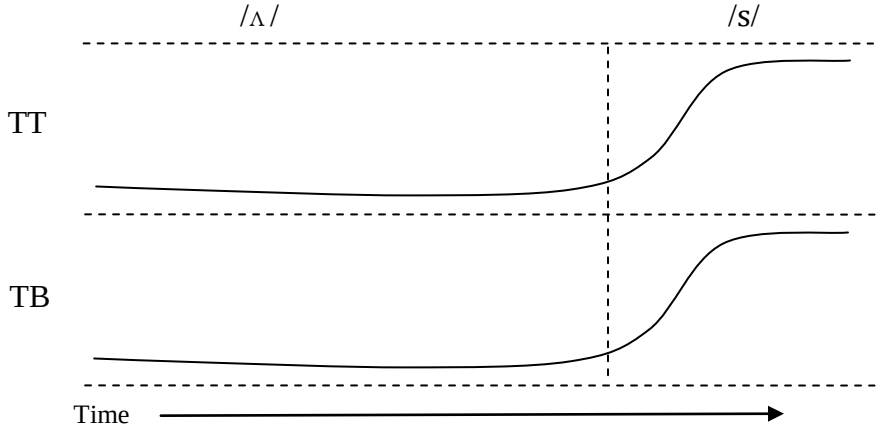
Figure 23. Vowel-fricative transition with extended duration and preaspiration



Number of violations: *EFFORT$_{mand}$ (1), DEP-Glottal (.5)

Two additional candidates will be necessary to complete the analysis of postvocalic fricatives. Figure 24 depicts a relatively rapid vowel-fricative transition, proposed to be comparable in duration to the transition produced by an adult speaker in a context for domain-final lengthening. Here, there is no violation of faithfulness constraints, but the violation of *EFFORT$_{mand}$ is nontrivial.

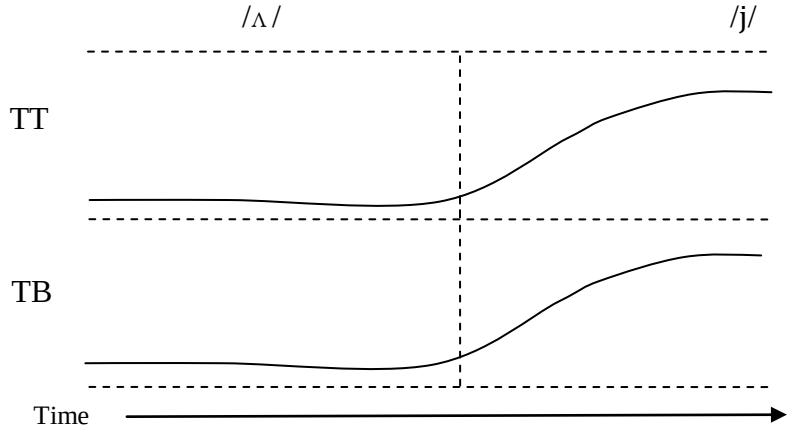
Figure 24. Vowel-fricative transition with rapid transition



Number of violations: *EFFORT$_{mand}$ (2)

Finally, Figure 25 depicts the glide replacement candidate for a fricative in word-final position. In this case, the transition is gradual and the articulatory target is low, resulting in a very small violation of *EFFORT$_{mand}$. This candidate violates IDENT-Consonantal.

Figure 25. Vowel-fricative transition with extended duration



Number of violations: *EFFORT$_{mand}$ (.5), IDENT-Consonantal (1)

6.5 Implementation of constraints: Postvocalic fricatives

Tables 21-23 present the comparison of candidates for the vowel-fricative transition in B's Stages 1-3. The constraints and weights are unchanged with respect to the values posited previously for the fricative-vowel context, with the exception that the faithfulness constraint DEP-glottal has been included in the tableaux that follow. Following our discussion in Section 5.4.4, the weight assigned to DEP-glottal is slightly lower than that assigned to DEP-glide.

The outcome of the comparison of candidates is identical across Stages 1 and 2. Due to the low effort costs associated with the slow vowel-fricative transition, the gliding candidate is never favored over a candidate with faithful realization of fricative manner. The winning candidate is determined to be the form incurring the smallest violation of perceptually-oriented faithfulness, namely the preaspirated form in (c). However, the candidate with pregliding, (b), is only marginally less harmonic. This is consistent with the observation that both of these forms were attested concurrently in B's output, with slightly greater representation of the preaspirated variant.

Table 21. Stage 3: A fricative following a nonhigh vowel is realized with preaspiration.

/ʌ s/, *us*	MOVE-AS-	IDENT-consonantal	*EFFORT$_{mand}$	DEP-glide	DEP-glottal	**TOTAL**

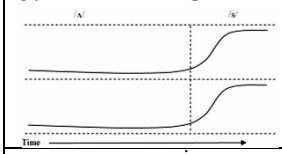
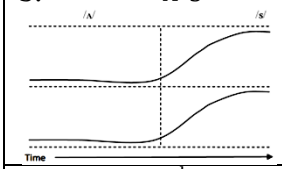
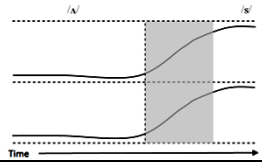
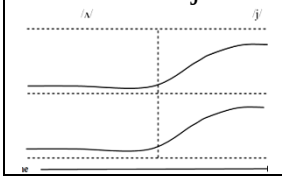
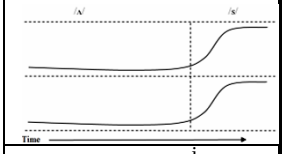
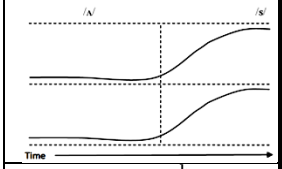
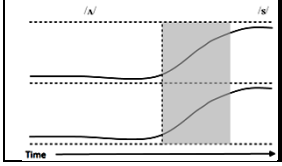
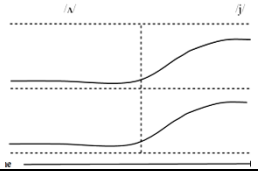
	UNIT					
	3	1.5	1	1	.5	
a. ʌ s 	0	0	2	0	0	**2**
b. ʌ ^{j}s 	0	0	1	.5	0	**1.5**
c. ☞ ʌ ^{h}s 	0	0	1	0	.5	**1.25**
d. ʌ j 	0	1	.5	0	0	**2**

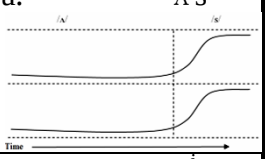
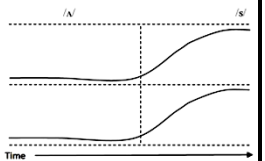
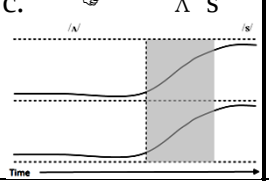
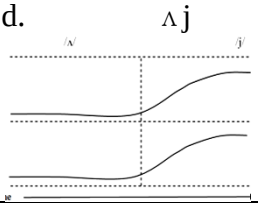
Table 22. Stage 2: A fricative following a [-high] vowel is realized with preaspiration.

/ʌ s/, *us*	MOVE-AS-UNIT	IDENT-consonantal	*EFFORT mand	DEP-glide	DEP-glottal	**TOTAL**
	3	2	1	1	.5	
a. ʌ s 	0	0	2	0	0	**2**
b. ʌ ^{j}s 	0	0	1	.5	0	**1.5**
c. ☞ ʌ ^{h}s 	0	0	1	0	.5	**1.25**

d. ʌj 	0	1	.5	0	0	**2.5**

Finally, Table 23 shows that when a sufficiently low weight is assigned to *EFFORT$_{mand}$, the candidate with preaspiration and the candidate with adultlike realization of the vowel-fricative transition emerge as equally harmonic.

Table 23. Stage 3: A fricative following a [-high] vowel is realized faithfully/with preaspiration.

/ʌs/, *us*	IDENT-consonantal	DEP-glide	DEP-glottal	MOVE-AS-UNIT	*EFFORT$_{mand}$	**TOTAL**
	3	2	1	1	.5	
a. ☞ ʌs 	0	0	0	0	2	**1**
b. ʌ^{j}s 	0	.5	0	0	1	**1.5**
c. ☞ ʌ^{h}s 	0	0	.5	0	1	**1**
d. ʌj 	1	0	0	0	.5	**3.25**

7. Supplementary acoustic analysis

In section 5.2, it was posited that the epenthetic glide that B was observed to produce in a form like [sjak] (‘sock’) can be regarded as an intermediate state in the transition from a fricative to a nonhigh vowel. While the glide is indeed intermediate in terms of jaw height, this characterization seems to make a questionable assumption regarding the placement of the tongue body. In adult articulation, the alveolar fricative is produced with a raised tongue tip but a fairly

low tongue body. By contrast, the tongue body is raised to approximate the palate in typical production of a /j/ glide. Thus, movement through /j/ in the transition from /s/ to /a/ should necessitate an additional gesture raising the tongue body. This is a problem if we wish to characterize glide insertion as an effort-minimizing repair. Note that this concern is specific to the case of the alveolar fricative, since the tongue configuration of the postalveolar fricative is not far distant from that of the palatal glide.

The point of comparison offered by the postalveolar fricative highlights the direction of the analysis that will be pursued here. It is possible B produces not just /ʃ/, but all fricatives, with a significant degree of tongue body elevation. It is a general finding that children's productions of /s/ and /ʃ/ are less distinct than those of adult speakers. In their investigation of /s/ and /ʃ/ fricatives as produced by speakers from three years of age to adulthood, Nittrouer, Studdert-Kennedy, & McGowan (1989) found that that the gap in centroid frequency differentiating /ʃ/ and /s/ increased over time. Moreover, it was argued previously that a child speaker like B can be expected to have difficulty raising one portion of the tongue without also elevating other regions. This hypothesis figured prominently in the analysis of B's velar fronting pattern in Chapter 4, and it was posited that B's coronal stops were also produced with undifferentiated contact spanning anterior and posterior regions of the tongue. Extending this logic, it can be speculated that B additionally found it difficult to produce an alveolar fricative with the typical adult tongue configuration, where the tongue body is lowered to isolate the region of contact between the tongue tip and the alveolar ridge.

This proposal receives some support from the literature on undifferentiated gestures in children with articulatory-phonological disorders. Gibbon (1999) suggested that if a child uses undifferentiated gestures in one context, he is likely to use them in other contexts. The challenging nature of fricative articulation might actually make [+continuant] targets particularly susceptible to this type of production, and numerous studies have documented undifferentiated contact in fricative production. Children who produce distorted fricatives with a greater than typical degree of tongue-palate contact were described by Gibbon & Hardcastle, 1987; Hardcastle, Morgan Barry, & Clark, 1987; Gibbon, Hardcastle, & Moore, 1990; Gibbon, Hardcastle, & Dent, 1995; and Dagenais, Critz-Crosby, & Adams (1994). Many of the children in these studies were characterized as producing lateral fricatives, which were sometimes but not always transcribed in B's productions. Gibbon (1999) also cites cases of children whose fricatives were transcribed as alveolar but were found to be produced with undifferentiated contact. Furthermore, Li (2008) argued that the rather early emergence of /s/ in the inventories of children acquiring English can be partially attributed to the fact that adult listeners accept a wide range of fricative spectra as corresponding to /s/ targets. Indeed, many of B's fricatives that were identified as /s/ on a first-pass transcription were found on review to contain non-canonical fricatives. Taking all of these factors into account, it appears quite possible that B's target alveolar fricatives were produced with more extensive raising of the tongue body than alveolar fricatives produced by adult speakers.

To assess this hypothesis, a subset of sibilant productions was analyzed to determine whether B maintained a typical degree of separation between alveolar and postalveolar fricatives. Since /s/ and /ʃ/ targets were in most cases transcribed as distinct in B's output, there was no expectation for total identity of acoustic properties across the two categories. Instead, it was hypothesized that there would be some degree of overlap between the /s/ and /ʃ/ distributions, with /s/ in particular extending into the range of acoustic values typically associated with the postalveolar fricative. This would not be a unique attribute of this particular speaker: in their

acoustic analysis of young toddlers' productions of alveolar and postalveolar fricatives, Li, Beckman, & Edwards (2008) reported some degree of overlap between the two categories even among children perceived to produce a reliable /s/-/ʃ/ distinction. On the other hand, the adult comparison group in their study produced /s/ and /ʃ/ tokens with no overlap in acoustic parameters.

Given its post-hoc nature, this investigation was unfortunately subject to several limitations. In the period where glide epenthesis was an active process in B's output, fricatives were attested in a limited range of contexts, effectively only /i, u, j/. Moreover, these early therapy sessions were recorded with a portable digital recorder that was not of especially high quality, and most recordings were contaminated by broad-spectrum background noise that had a particularly negative impact on spectral analysis of fricatives. To ensure adequate recording quality and to obtain productions across a more representative range of contexts, fricatives had to be collected from a later stage, after faithful fricative production had replaced glide epenthesis in B's monitored speech (Stage 3). Even in this context, limited data were available, and to collect an adequate number of /s/ and /ʃ/ tokens across a range of vowel contexts, it was necessary to use word-medial prevocalic fricatives in lieu of initial fricatives. For several reasons, the data used here can be assumed to overestimate the accuracy of B's fricative production in the stage of interest. First and foremost, B became noticeably more skilled in fricative production over the several months between Stage 2 and Stage 3. Secondly, B's non-canonical fricative productions were sparsely represented in this data sample. This is not only because non-canonical fricatives were more common at an earlier stage of development, but also because these productions tended to be short and/or characterized by weak spectra that were easily overwhelmed by the formants of neighboring vowels or by reverberation noise. Thus, among the non-canonical productions that did occur in the sample data set, a majority were not suitable for inclusion in the spectral analysis.

For this analysis, data were drawn from two testing sessions during which B's utterances were recorded with a high-quality portable digital recorder (Marantz PMD671); he was 4;3 at the time of this testing. All tokens containing medial alveolar and postalveolar targets were isolated for acoustic analysis.[25] Of 32 tokens identified for analysis, 7 were eliminated due to simultaneous talking or reverberation noise. The remaining 25 tokens were included in an analysis of spectral moments using Praat. For the purpose of this analysis, the midpoint of the frication noise was identified and an FFT spectrum was computed over a 40-ms interval around the midpoint of the interval. The window selected for analysis was adjusted when necessary to avoid interference from neighboring vowels or visible deviations from the steady state of the fricative.

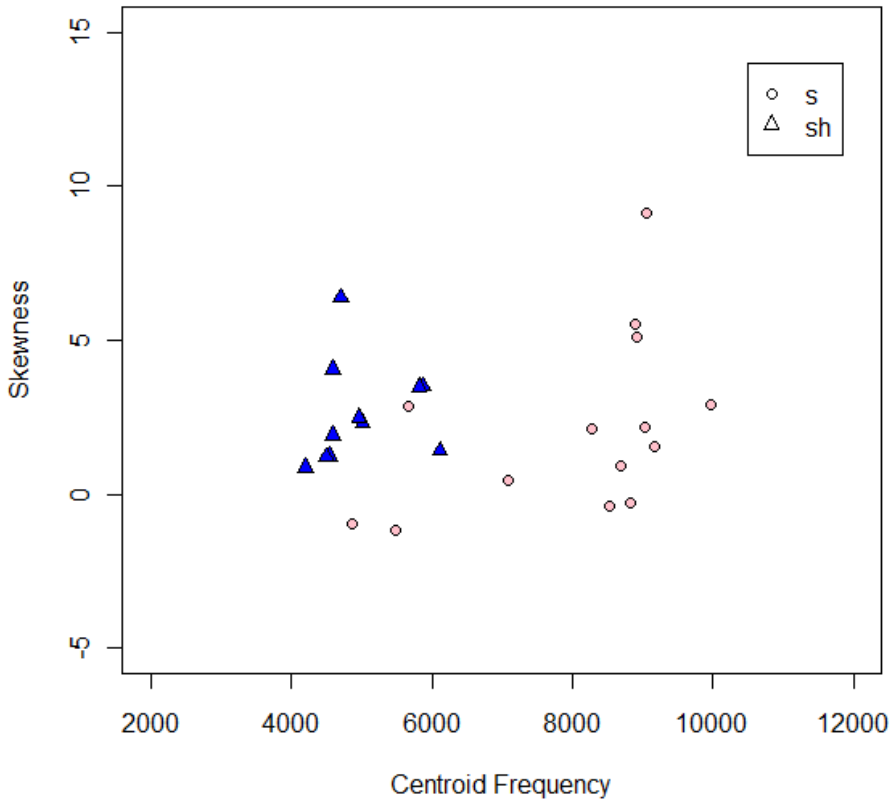
Of the first four spectral moments, the first and third moments (centroid frequency and skewness) were selected to carry out the comparison between /s/ and /ʃ/ targets. The first spectral moment is correlated with the length of the front cavity in fricative production. It thus plays a major role in differentiating between /s/ and /ʃ/, which differ primarily by the location of the point of constriction in the anterior-posterior dimension. The centroid frequency has been found to mark the distinction between alveolar and postalveolar targets in English-speaking toddlers as well as adults (Li, Beckman, & Edwards, 2009). The skewness of the fricative power spectrum, which reflects the relative concentration of energy above and below the mean of the distribution, is also sensitive to the location of the point of constriction in fricative articulation.

[25] In addition to target /s/ and /ʃ/, five tokens were included that contained target /z/, which B neutralized with /s/, as well as two tokens containing target /dʒ/, which B neutralized completely with /ʃ/ (e.g.[bʊʃɛn], 'pigeon').

The skewness is expected to be more positive in the spectrum of a postalveolar fricative, where energy is more concentrated in the frequencies below the mean value (Li et al., 2009).

In Figure 26, skewness is plotted against centroid frequency as a means of visualizing the separation between /s/ and /ʃ/ targets in B's output. Figure 26 shows that B did produce distinct alveolar and postalveolar categories, with the mean centroid frequency for the /s/ target category significantly exceeding that associated with the /ʃ/ category. However, there was overlap between the /s/ and /ʃ/ categories in B's output. As predicted, this overlap was typified by alveolar targets extending into the range characteristically associated with the postalveolar fricative, whereas /ʃ/ targets were more tightly clustered in a smaller frequency range. There was no clear separation between the two groups along the parameter of skewness. In conclusion, incomplete separation of alveolar and postalveolar fricatives was observed, even though limitations on data collection made it necessary to use a sample that was likely to overestimate B's ability to realize a distinction between these categories. This lends credence to the speculation that B's alveolar fricative targets might be produced with an atypically high placement of the tongue body, which in turn supports the hypothesis that the palatal glide represents a plausible intermediate state in the transition from any sibilant to a nonhigh vowel.

Figure 26. Skewness versus centroid frequency in /s/ and /ʃ/ tokens produced by B



8. Other considerations

Before concluding, we can briefly review alternative solutions to the fricative asymmetry problem offered in previous literature. It will be shown that these accounts do not explain the full range of data gathered from B's productions. A final section will reflect on the likelihood that the processes observed to motivate the asymmetric behavior of prevocalic and postvocalic fricatives in this particular child will be found to apply across other children exhibiting a comparable asymmetry.

8.1 Perceptually motivated asymmetries

Chapter 3 of this dissertation reviewed a proposal that children's preference to neutralize contrasts in strong positions can be understood as the reflection of a child-specific pattern of perception (Dinnsen & Farris-Trimble, 2008). Dinnsen & Farris-Trimble cited children's asymmetric acquisition of fricative targets as one instance of a process that can be understood under their perceptually motivated account. However, in Chapter 3 it was demonstrated that B perceived contrasts with significantly greater accuracy in word-initial position, replicating the adult pattern, despite his ongoing tendency to neutralize contrasts in strong positions in production. Thus, Dinnsen & Farris-Trimble's final prominence hypothesis is not supported as an explanation for asymmetric acquisition of fricatives in a child like B.

8.2 Prosodically-conditioned strengthening or weakening

Chapter 4 reviewed Inkelas & Rose's (2008) application of child-specific articulatory limitations to account for a pattern of coronal-velar neutralization in strong positions. Inkelas & Rose analyzed velar fronting as a consequence of consonant strengthening in prosodically strong positions. Studies of adult articulation have shown that consonant gestures are produced with greater magnitude in initial and stressed syllables. According to Inkelas & Rose, young child speakers may detect positional strengthening in adult speech and attempt to replicate the phenomenon. In the context of the child's differently proportioned articulatory anatomy and diminished speech-motor control, however, the output of the attempted strengthening process may deviate from the adult model. It was posited that this phonetically motivated error can become incorporated into the child's phonology over time.

Inkelas & Rose suggested that the positional strengthening account might be applicable to cases of children who neutralize stops with fricatives in word-initial but not word-final contexts: "Given that young children do not have a refined control of the force applied to their articulatory movements, the articulatory enhancement inherent to consonants in strong positions is enough to explain a pattern of stopping in this context" (p. 725). While it would be desirable to extend the prosodic strengthening account to explain child-specific patterns of fricative neutralization, there are several reasons to believe that fricative neutralization in strong position is not amenable to analysis as a positional strengthening phenomenon. First, while asymmetries in the magnitude of consonant gestures in onset versus coda position have been identified for stop consonants (e.g. Keating, 2006), the degree of constriction in sibilant production has been found to show very little variation with prosodic position (Fougeron, 1998, 2001). Secondly, the prosodically-conditioned strengthening account appears relevant only to children who replace fricatives with stops in strong positions, not to children like B, whose substitution of glides for fricatives is in fact a leniting process. It might be possible to model gliding as a means of preserving the [+continuant] feature in a segment that would otherwise become a stop under the influence of positional strengthening. However, the positional strengthening analysis is further challenged by the existence of segmental conditioning effects in B's fricative distribution. An account of the type proposed by Inkelas & Rose would not account for the apparent suspension of prosodically-conditioned strengthening in the environment of a [+high] glide or vowel. Lastly, the positional strengthening analysis cannot explain B's pattern of glottal stop epenthesis to separate a word-medial fricative from the following vowel. In a trochaic word like *waffle* ([wasʔ o]), the fricative occupies a prosodically weak, foot-medial position, not an environment for strengthening. Thus, B's pattern of fricative production is not amenable to analysis as a case of prosodically-conditioned strengthening. Below it will be argued that, even for children who exhibit stopping as opposed to gliding of prevocalic fricatives, the most appropriate analysis invokes asymmetries in the speed rather than the magnitude of gestures across onset and coda contexts.

A different asymmetry in consonant strength was invoked by Redford, Davis, & MacNeilage (1997) to account for the greater frequency of fricatives in coda relative to onset position in babbling. They suggested that the prevalence of coda fricatives might reflect a process similar to spirantization of final stops in adult phonologies. Redford et al. proposed that articulatory energy diminishes over the course of an utterance, giving rise to consonant gestures of lesser magnitude in final position; with sufficient weakening, a stop will be replaced with a spirant. While this might account for a fricative produced at the end of a string of babbled syllables, it does not appear to apply to the case of a child who produces utterance-medial coda

fricatives, which might occur adjacent to a stop in the onset of the following syllable. Moreover, data from spirantization in adult phonologies indicate that while some fricatives require less articulatory effort than the corresponding stops, strident fricatives are in fact more energy-intensive than stops (Kirchner, 1998). Since /s/ is one of the earliest fricatives to emerge in either initial or final position, the early preference for word-final fricatives cannot without further assumptions be analyzed as the consequence of a general decline in energy.

8.3 On the generality of the analysis

Here, detailed longitudinal data were supplemented with acoustic findings to argue that the asymmetric behavior of prevocalic and postvocalic fricatives in B's phonology should be understood as the consequence of articulatory constraints favoring slow, coordinated movements of the tongue and jaw. However, we have not yet discussed the extent to which the motivating factors and repair strategies posited here should be regarded as particular to this child or general across child speakers. Based on the discussion of articulatory maturation in Chapter 2, it is reasonable to assume that several of the key factors in this analysis are widespread across children at an early stage of speech-motor maturation. These include the preference for slow articulatory transitions and the favored status of coordinated movements of the tongue and jaw.

It is less clear to what extent B's pervasive process of final lengthening, which played a crucial role in generating the asymmetric behavior of prevocalic and postvocalic fricatives, is shared by other children in the early stages of phonological development. However, there are indications that this too may be a fairly general property. Final lengthening effects can be observed in early stages of infant babbling and have thus been argued to stem from basic biomechanical principles (Nathani, Oller, & Cobo-Lewis, 2003). Snow (1997) studied two aspects of timing in a longitudinal study of English-acquiring toddlers between one and two years of age, comparing the emergence of VOT contrasts and final syllable vowel lengthening (FSVL) effects. He proposed that vowel length contrasts should be motorically less challenging than the VOT contrast, which requires precise coordination between oral and laryngeal gestures. Unexpectedly, eight out of ten subjects were found to master the VOT distinction earlier than FSVL. Even after children began to maintain a significant durational difference between final and nonfinal syllables, the magnitude of the contrast fell short of Snow's criterion for a mature final lengthening effect. However, the reasoning adopted in this chapter offers a likely explanation for this otherwise puzzling reversal of the order that was predicted based on motor control factors. Rather than positing that these children lacked the motor-control capacity to produce vowels with contrasting duration, we can speculate that their domain-final lengthening process applies at the level of the word rather than the phrase. Further investigation will be needed to determine whether word-final lengthening effects can consistently be detected across children who exhibit asymmetric behavior of onset and coda fricatives.

An additional question is raised by the fact that the process discussed here, fricative gliding, is by no means the most commonly observed repair for prevocalic fricatives in child phonology. While the literature does not offer statistics for the prevalence of fricative gliding, it is generally regarded as a less typical process (Bleile, 2003). More commonly found are children who replace prevocalic fricatives with coronal stops. Since stopping involves replacing a controlled articulatory transition with a ballistic, undifferentiated gesture, it is in keeping with the spirit of the present analysis. However, constraints that were not included in the preceding discussion will need to be invoked to model the substitution of stops for fricatives. While here it was argued that the fricative-vowel transition is dispreferred because it requires a rapid, effortful

mandibular movement, the movement of the jaw is no less rapid when a stop is substituted for a fricative. However, the stop does not incur violations of another constraint in the effort-minimization family that was not invoked in the preceding analysis. This constraint, which can be labeled *EFFORT$_{precise}$, militates against gestures with a small articulatory target. It will still be necessary to invoke *EFFORT$_{mand}$ in accounting for the fricative asymmetry in children with prevocalic stopping, since there is no reason to believe that fricative articulation requires a less precise gesture in coda contexts. The analysis of a child who exhibits stopping in initial but not final position could then take the following form: in the prevocalic context, the combined violations of *EFFORT$_{mand}$ and *EFFORT$_{precise}$ crucially outweigh IDENT-continuant, whereas in final contexts, the diminished weight of *EFFORT$_{mand}$ brings the sum of the *EFFORT violations to a level below the violations of IDENT-continuant. Children with fricative gliding may give similar weights to the markedness constraints, but in their case a high weight must be assigned to IDENT-continuant. It is unclear why some children should show this selective preservation of the [continuant] feature. In the case of a child like B, it is possible that the avoidance of stopping is a consequence of heightened attention to the stop-fricative contrast, possibly encouraged by therapy activities highlighting this distinction. However, only speculation can be offered on this point, since B had already been a recipient of therapy prior to his first encounter with the experimenter, and he exhibited gliding rather than stopping from the earliest recorded session.

9. Conclusion

While a preference for postvocalic over prevocalic fricatives in child speech has been described in previous literature, this bias has been heretofore a puzzle. Here, a detailed case study of one child with prevocalic gliding of fricatives illuminated phonetic factors that give rise to the fricative asymmetry. It was observed that segmental as well as prosodic factors can condition fricative production, with prevocalic fricatives produced most readily in the context of [+high] segments. This suggested that fricative production is constrained by a preference for small or slow articulatory transitions, consistent with the action of effort-minimizing constraints familiar from adult grammars. The force driving fricative neutralization was hypothesized to be *EFFORT$_{mand}$, which limits the velocity of movements of the mandibular articulator. In addition, the child-specific constraint MOVE-AS-UNIT was posited to play a role in giving rise to the glidelike nature of the transition in fricative-vowel contexts. Articulatory studies of adults have indicated that the normal coarticulatory transition from a fricative to a vowel involves anticipatory lowering of the jaw while the tongue remains in a high position. To avoid incurring excessive violations of either MOVE-AS-UNIT or *EFFORT$_{mand}$, a child speaker may be forced to produce a slow, simultaneous lowering of tongue and jaw that has a glidelike perceptual consequence.

The preference for word-final fricatives was posited to reflect the slower rate of articulatory transitions in the VC context, which in turn stemmed from a process of domain-final lengthening that the present subject could be observed to apply at the level of words and syllables as well as phrases. It was hypothesized that a comparable lengthening process in the context of fricative-vowel transitions is blocked by the tighter binding of consonant and vowel gestures in CV relative to VC contexts, as posited in the framework of Articulatory Phonology. In addition, in B's speech a pervasive process of preaspiration before fricative codas had the effect of obscuring atypical formant movements in the vowel-to-fricative transition, minimizing

the violations of perceptual faithfulness incurred by these forms. Additional investigation will be necessary to determine to what extent processes such as word- or syllable-final lengthening or preaspiration of coda fricatives can be observed in child speakers other than the present subject. However, the factors invoked here have roots in general motor and aerodynamic principles and can thus be expected to surface in other child speakers. In total, the incorporation of both general and child-specific constraints on articulation in this analysis made it possible to model an especially problematic set of observations from child phonology.

Chapter 6. Consonant Harmony in Child Phonology

1. On consonant harmony

1.1 Patterns of consonant harmony in child phonology

Consonant harmony is perhaps the most frequently cited example of a child process that deviates from the norms of adult phonology. In this process, nonadjacent consonants undergo assimilation with respect to one or more features. While adult phonologies also permit long-distance processes of consonant agreement, the child pattern is unique in allowing assimilation with respect to major place features. Consonant harmony can be observed in many children developing typically, and children younger than three years of age who exhibit the process are viewed as falling within the normal range of variation (Grunwell, 1981). Assimilation for place of articulation constitutes the canonical example of child consonant harmony. Examples of various types of harmony affecting place of articulation are presented in (1)-(2):

(1) Place harmony with regressive direction of assimilation (Smith, 1973; Pater, 2002):
   a. Velar trigger, coronal undergoer
      [gʌ k] ‘duck’
      [gɪ :gu:] ‘tickle’
   b. Regressive assimilation: Velar trigger, labial undergoer
      [gɪ g] ‘pig’
      [gɪ gʊ] ‘pickle’
   c. Regressive assimilation: Labial trigger, coronal undergoer
      [pap] ‘top’

(2) Place harmony with progressive direction of assimilation (Smith, 1973; Pater, 2002):
   a. Velar trigger, coronal undergoer
      [kok] ‘coat’
   b. Velar trigger, labial undergoer
      [kʌ k] ‘cup’
   c. Labial trigger, coronal undergoer
      [bop] ‘boat’

1.2 Comparison with adult consonant harmony

While consonant harmony for major place features is indeed a distinctive characteristic of child phonology, adult grammars also offer examples of assimilation between non-adjacent consonants. The majority of adult processes of consonant harmony involve assimilation for features that specify the position of the tongue tip/blade in the articulation of coronal consonants (Rose & Walker, 2004). Rose & Walker identify three categories of coronal agreement: for sibilant place, for alveolar versus dental place, and for retroflex versus plain coronal place. (3) repeats an example of sibilant harmony in Kinyarwanda, where an alveolar fricative in a verb root takes on postalveolar place when a postalveolar fricative appears in the suffix (p. 10).

(3) *Kinyarwanda*: /s/ in root becomes /ʃ / when /ʃ / appears in the suffix.
   a. ku-sas-a [gusasa] "to make the bed"
   b. ku-sas-ii-sha [guʃ aʃ iiʃ a] "to cause to make the bed"

Other adult consonant harmony processes affecting secondary place features can be observed, including assimilation for lateral versus retroflex place for liquids, as well as velar versus uvular place for dorsals. Lastly, adult consonant harmony can give rise to assimilation for nasality or laryngeal features. An example of adult nasal harmony is offered in (4), where an obstruent in a particular suffix can be seen to assimilate to a nasal consonant in the verb stem (Rose & Walker, 2004, p. 36).

(4) *Kikongo*: Suffix –idi harmonizes to a preceding non-local nasal
   a. m-bud-idi [mbudidi] "I hit"
   b. tu-kun-idi [tukunini] "we planted"

There are several similarities between consonant harmony processes in children and adults, including a preference for assimilation in the regressive direction (Hansson, 2001). Given this basic congruence between harmony processes in child and adult speakers, here a single functionally-motivated model will be used to derive both phenomena. However, it is essential also to address the areas of divergence between the two cases, namely the much more circumscribed nature of harmony and the absence of major place harmony in adult phonologies. In Section 6, it will be demonstrated that the elimination of child-specific aspects of consonant harmony is a predicted consequence of typical motor maturation.

1.3 Implicational relations in English child consonant harmony

The parameters of consonant harmony, including the direction of assimilation and the participating features, are subject to considerable variation both within and across children. This section will present implicational relationships that have been reported to govern the emergence of primary place harmony in children acquiring English (Pater & Werle, 2001, 2003; Pater, 2002). Integrating data from two longitudinal corpora (Trevor: Compton & Streeter, 1977; Amahl: Smith, 1973), Pater (2002) offered several generalizations regarding the preferred target, trigger, and directionality of consonant harmony in English-speaking children, repeated in (5).

(5) Undergoer: Non-coronal implies coronal
   Trigger: Labial implies velar
   Direction: Progressive implies regressive

Pater asserts that segments with coronal place are more likely to appear as targets of harmony than non-coronal segments. Velar place is regarded as the preferred trigger of harmony; labial triggers are less preferred, and coronal consonants are not generally regarded as possible triggers of harmony in English.[26] Lastly, Pater observes that consonant harmony in the

[26] However, there is attestation of assimilation to coronal in the acquisition of other languages: Rose (2000) describes a French-speaking child for whom C_1VC_2V words were uniformly assimilated to C_2VC_2V, apart from the

progressive direction implies assimilation in the regressive direction. It is here that consonant harmony interfaces with the other processes of neutralization in strong position described in this dissertation. By operating preferentially in the regressive direction, consonant harmony tends to have the effect of preserving a place feature in a weak postvocalic position while neutralizing contrast in the strong word-initial position. This has made it challenging to model consonant harmony using constraints familiar from adult phonology, just as we have seen for other instances of neutralization in strong positions. The following section will examine the model of child consonant harmony advocated by Pater & Werle (2001, 2003) and Pater (2002). This review serves two functions: First, it offers a more detailed look at the patterns of preference that will need to be explained by a successful model of consonant harmony in child English. Second, it illustrates the difficulties that arise in efforts to model child consonant harmony using constraints and principles drawn directly from adult grammar.

2. Modeling child consonant harmony

2.1 Consonant harmony and the markedness hierarchy

Pater (1997, 2002) and Pater & Werle (2001, 2003) have offered insightful analyses of consonant harmony drawn from Trevor's productions in the Compton & Streeter (1977) corpus. They analyzed approximately 10,000 utterances collected between infancy and two years, four months of age. To calculate the percent application of different types of harmony, they coded all stressed syllables containing two oral stops based on the general shape of the target, i.e. TVK for a coronal onset with a velar coda, KVP for a velar onset with a labial coda, etc. Several generalizations emerged from Trevor's productions across the time period of study. First, consonant harmony was observed to apply in both progressive (left-to-right) and regressive (right-to-left) directions in Trevor's output, but progressive assimilation was attested with lower frequency and was eliminated at an earlier stage of development. Second, while both coronal and labial consonants appeared as targets of harmony, coronals assimilated more frequently and continued to participate in harmony long after labials had ceased to assimilate. Finally, Pater & Werle compared labial and velar segments as triggers of harmony in both regressive and progressive directions. In regressive harmony, velar place clearly constituted the strongest trigger. In the progressive direction, however, labial-trigger harmony was attested with similar frequency to velars, and unexpectedly, progressive labial harmony was noted to last slightly longer than labial harmony in the regressive direction. However, these comparisons were based on a relatively small number of data points, a possible reflection of lexical avoidance. Pater (2002) summarized their findings with the proposal that Trevor's grammar could be divided into the three stages reported in (6) below (p. 363).

(6) <u>Stage 1</u>
Consistent regressive velar harmony to labial and coronal undergoers
Variable progressive velar harmony to coronals

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case of a labial C_1, which was observed to resist assimilation. Thus, "gateau" could be seen to emerge as [tato] in this child's speech, while velar place was realized appropriately in other contexts (e.g. [koko] for "coco").

Variable regressive and progressive labial harmony to coronals

Stage 2
Consistent regressive velar harmony to coronals
Variable regressive velar harmony to labials

Stage 3
Consistent regressive velar harmony to coronals

In an early proposal, Pater (1997) suggested that Trevor's stages of consonant harmony could be analyzed using a markedness constraint REPEAT ("Successive consonants must agree in place specification"). This constraint had been posited previously as a means of characterizing reduplicative processes in adult phonology (Yip, 1995). The preferential targeting of coronal place was proposed to reflect the interleaving of REPEAT with a fixed hierarchy of faithfulness constraints for place features, FAITH[DOR], FAITH[LAB] >> FAITH[COR] (Kiparsky, 1994). Pater & Werle (2001, 2003) updated this analysis, replacing REPEAT with the constraint AGREE ("Consonants agree in place of articulation"), which can be specified for direction and trigger place. AGREE constraints are invoked in analyses of adult phonological processes, but only under conditions of strict locality (Lombardi, 1999; Bakovic, 2000); Pater & Werle proposed that in child phonology, these constraints are enabled to operate non-locally. Their analysis consists of the general constraint AGREE, the directional constraint AGREE-L-[DOR] ("A consonant preceding a dorsal must be homorganic with it"), and the three faithfulness constraints protecting velar, labial, and coronal place. Pater & Werle noted that AGREE-L-[DOR] is independently motivated by processes of local assimilation in adult languages. For instance, local assimilation in Korean is always in a regressive direction, and labials and coronals assimilate to velars, whereas only coronals assimilate to labials (de Lacy, 2002).

Pater (2002) offered a complete account of the basic patterns of Trevor's consonant harmony, incorporating insights on markedness proposed by de Lacy (2002). De Lacy argued that the three major places of articulation occupy a fixed scale of markedness, Dorsal > Labial > Coronal. He also proposed a Marked Reference Hypothesis, asserting that any constraint that applies to a certain category on a scale of markedness must also apply to all categories on the scale that are more marked. This generates a stringency scale in which a constraint may single out a marked category to the exclusion of less marked categories, but the reverse is not possible. This approach to markedness is reflected in the series of constraints, repeated in (7), with which Pater proposed to capture the implicational relationship among places of articulation as triggers of harmony.

(7) ←K: Any consonant preceding a dorsal is homorganic.
←PK: Any consonant preceding a dorsal or labial is homorganic.
←PKT: Any consonant preceding a dorsal, labial, or coronal is homorganic.

To capture the generalization that harmony in the progressive direction entails regressive harmony, Pater added a series of bidirectional constraints favoring homorganicity, such as ←K→ ("Any consonant preceding or following a dorsal is homorganic"). Finally, faithfulness constraints in Pater's account are formulated in a stringency relation in the same manner as the

markedness constraints posited above; thus, the relevant constraints are FAITH(K), FAITH(KP), FAITH(KPT). This is in accordance with de Lacy's principle of "faithfulness to the marked," whereby the pressure to preserve marked elements is greater than the pressure to preserve their less-marked counterparts. Pater demonstrated that the proposed set of constraints can capture the pattern of assimilation described in Trevor's first stage of development, where regressive assimilation applied consistently from velar triggers to labial and coronal targets, with variable progressive assimilation of coronals to velars, as well as variable regressive and progressive assimilation of coronals to labial triggers. This is illustrated in Table 1.

Table 1. Modeling Trevor's Stage 1 (Pater, 2002, p. 365)

Input	Output	F(K)	←K	F(KP)	←PK→	F(KPT)
TVK	TVK		*!		*	
	☞ KVK					*
PVK	PVK		*!		*	
	☞ KVK			*		*
KVT	☞ KVT				*	
	☞ KVK					*
KVP	☞ KVP				*	
	KVK			*!		
TVP	☞ TVP				*	
	☞ PVP					*
PVT	☞ PVT				*	
	☞ PVP					*

Pater showed that the same model can describe subsequent stages of Trevor's grammar by invoking successive demotion of markedness constraints (Tesar & Smolensky, 1998; Prince & Tesar, 2000). Table 2 shows that demotion of ←PK→ successfully captures the elimination of progressive and labial harmony from Trevor's grammar as he progressed from Stage 1 to Stage 2. Table 3 depicts Trevor's Stage 3, in which demotion of ←K has eliminated all harmony except for regressive assimilation of a coronal target to a velar trigger

Table 2. Modeling Trevor's Stage 2 (Pater, 2002, p. 366)

Input	Output	F(K)	←K	F(KP)	F(KPT)	←PK→
TVK	TVK		*!			*

	☞ KVK				*	
PVK	☞ PVK		*			*
	☞ KVK			*	*	
KVT	☞ KVT					*
	KVK				*!	
KVP	☞ KVP					*
	KVK			*!		
TVP	☞ TVP					*
	PVP				*!	
PVT	☞ PVT					*
	PVP				*!	

Table 3. Modeling Trevor's Stage 3 (Pater, 2002, p. 366)

Input	Output	F(K)	F(KP)	←K	F(KPT)	←PK→
TVK	TVK			*!		*
	☞ KVK				*	
PVK	☞ PVK			*		*
	KVK		*!		*	
KVT	☞ KVT					*
	KVK				*!	
KVP	☞ KVP					*
	KVK		*!			
TVP	☞ TVP					*
	PVP				*!	
PVT	☞ PVT					*
	PVP				*!	

2.2 Challenges for Pater & Werle's analyses

The analysis put forward in Pater (2002) is highly successful in capturing the implicational relations of directionality and place of articulation that characterize Trevor's data. However, as we saw in Chapter 1, it is theoretically problematic to assume equivalence between local assimilation in adult phonology and the particular processes of neutralization that characterize child speech. In particular, the phonetic motivation that accounts for the regressive directional bias of adult local assimilation does not apply to non-local assimilation in consonant harmony. In the case of local assimilation in consonant clusters, it has been convincingly demonstrated that the regressive bias arises because that the second consonant in a cluster is typically prevocalic, a position that carries stronger perceptual cues than the preconsonantal position of the first consonant (Jun, 1995; Steriade, 2001). However, in child consonant harmony the target of assimilation occupies a perceptually strong prevocalic position, while the consonant that triggers harmony occupies a weaker postvocalic position and is frequently word-final. Thus, while the regressive bias in local assimilation reflects a preference to spread features from a stronger to a weaker position, child consonant harmony favors the perceptually weak segment at the expense of the more salient word-initial consonant. Given these differences, the preference

for the regressive direction in adult local assimilation cannot without further assumptions be invoked as a rationale for the preferred direction of child consonant harmony. Thus, although Pater's use of stringency relations governing place and direction of assimilation is effective in capturing the data from a child like Trevor, it would be preferable to adopt an analysis with independent motivation from the particular properties of child speech.

2.3 A functionally motivated approach to child consonant harmony

This chapter will propose a new analysis of child consonant harmony with roots in both psycholinguistic processing and speech-motor control. It will be argued that child consonant harmony is in large part continuous with functionally motivated analyses of adult harmony processes proposed by Hansson (2001) and Rose & Walker (2004). Noting pronounced parallelism between speech errors and phonological processes of consonant harmony, these approaches have posited that both phenomena have shared roots in psycholinguistic processing. From spreading-activation models of cognitive processing (e.g. Dell, 1986), it is known that targets that are similar but not identical induce elevated processing complexity and increase the frequency of errors. Thus, it will be proposed that both child and adult consonant harmony processes act to simplify the task of speech production by altering similar but non-identical targets to be identical. The system of agreement by correspondence, proposed for adult consonant harmony, here will be adapted to child harmony as well.

However, the account pursued here will diverge from the model for adult harmony in order to incorporate insights from a recent articulatory model of speech errors. Pouplier (2003, 2008) and colleagues have demonstrated that articulatory errors frequently involve simultaneous production of intrusive and target gestures, even when impressionistic transcription suggests a process of categorical segment substitution. Pouplier & Goldstein (2005) additionally demonstrated that intrusive errors have asymmetrical perceptual consequences, such that intrusive velar gestures during a coronal target are perceived as anomalous, while intrusive coronal gestures during velar articulation habitually remain undetected. This can account for the bias of coronal segments to appear as undergoers and velar segments as triggers of harmony, without requiring any separate specifications of scales of markedness. Experimental results from the productions of one child with consonant harmony will be presented, demonstrating that covert contrast was maintained between target and harmonized velar consonants that were perceived to be fully neutralized. This offers support for the hypothesis that child consonant harmony, like the speech errors described by Pouplier and colleagues, can be understood as a process of gestural intrusion. To incorporate these articulatory facts, it will be necessary to make modifications to the model of agreement by correspondence. Here, it will be proposed that articulatory and processing perspectives can be unified in a model of correspondence in which segments in correspondence are under pressure to agree for the presence of gestures rather than features. It will be demonstrated that the articulatory model of correspondence makes correct predictions for both directional preferences and the hierarchy of place features participating in child consonant harmony. Finally, articulatory differences between child and adult speakers will be invoked to account for the absence of major place harmony from adult phonological systems.

3. Speech errors and consonant harmony

Several studies of consonant harmony in adult phonology have observed striking parallels between systematic processes of harmony and incidental speech errors, leading to speculation that the two are rooted in similar functional limitations on speech production (Hansson, 2001; Rose & Walker, 2004; Kochetov & Radisic, 2008). Given children's speech-motor limitations as detailed in Chapter 2 and throughout this dissertation, it is reasonable to suspect that such factors could give rise to consonant harmony of a more extensive nature in children relative to adult speakers. Section 3.1 will demonstrate that consonant harmony parallels the canonical pattern of speech errors in its preference to apply over similar segments, its predominantly regressive direction of assimilation, and in the relative participation of different places of articulation as triggers or targets of assimilation. The sections that follow will present two major approaches to modeling patterns in adult speech errors: a connectionist activation/competition model (cf. Dell, 1986), and an articulatory model (cf. Pouplier, 2003). Insights from both of these models will prove to be crucial in deriving a satisfactory model of child consonant harmony.

3.1 Parallel tendencies in speech errors and consonant harmony

Studies using natural speech corpora as well as experimental paradigms have demonstrated that speech errors arise in a systematic fashion, suggesting that they are not random, but respond to the same principles that shape error-free speech. Of particular interest for present purposes, adult speech errors appear to involve long-distance interactions between consonants. The most canonical type of speech error involves apparent single-segment phonemic substitutions, such as [pap kapkɔ rn] for "pop popcorn." Meyer (1992) estimated that single-segment misorderings comprise around sixty to ninety percent of all speech errors. Errors that affect only a single feature, such as *tik of the tum* for "tip of the tongue," have been reported, but they are considered rare (Shattuck-Hufnagel, 1983). Syllable-level substitutions are likewise attested but regarded as atypical. The segmental nature of most errors has been interpreted as evidence that speech errors generally occur at a phonological rather than a phonetic level of processing. The claim that speech errors arise during phonological encoding is supported by observations that the allophonic features of transposed segments are transcribed as consistent with their new position rather than the underlying one (Shattuck-Hufnagel & Klatt, 1979; Shattuck-Hufnagel, 1983). For example, the /p/ in the error "lumber sparty" for *slumber party* is reported to be unaspirated, consistent with its surface position in a consonant cluster (Fromkin, 1973). On the other hand, more recent research has cast doubt on the status of speech errors as categorical segment substitutions; these findings will be discussed in Section 3.2. The remainder of this section will review patterns of error production that parallel consonant harmony processes.

The first parallel between speech error processes and consonant harmony pertains to the influence of similarity on assimilatory processes. The speech error literature has repeatedly demonstrated a direct relationship between the similarity of two segments and speakers' likelihood of producing an error affecting this pair (Shattuck-Hufnagel & Klatt, 1979; Dell, 1984, 1986; Fowler, 1987; Goldrick & Blumstein, 2006; Shattuck-Hufnagel, 1992; Vousden, Brown, & Harley, 2000). For speech errors, the relevant notion of similarity encompasses factors of featural composition, prosodic position, and stress. The similarity of neighboring material also plays a role: it has been demonstrated that segments are more likely to participate in errors if they are adjacent to identical segments or occupy the onset of syllables with identical codas (MacKay, 1970; Dell, 1984). In adult phonology, the application of consonant harmony depends crucially on the presence of multiple shared features between target and trigger, with harmony

processes typically limited to highly similar segments. In child consonant harmony, which is in general a less constrained process, systematic effects of similarity on the application of harmony have yet to be documented.[27] However, Section 6.3 of this chapter will argue that the less frequent occurrence of child consonant harmony with a labial trigger or target can be understood as the consequence of an articulatory standard of similarity.

A second similarity between speech errors and consonant harmony involves the characteristic bias of the directionality of assimilation. In Section 1.2, we saw that assimilation in child consonant harmony typically operates in a regressive direction; Pater (2002) proposed that the attestation of progressive harmony in child speech implies the presence of regressive harmony. This parallels the speech error literature, where it has repeatedly been found that anticipatory (regressive) speech errors outnumber perseveratory errors in typical adult productions. Stemberger (1989) reported that 60% of adult speech errors are anticipatory in nature, while Schwartz, Saffran, Bloch, & Dell (1994) found that 75% of errors in a corpus of naturally-occurring adult speech were anticipatory. However, the prevalence of anticipatory errors appears to be lower in certain groups, including adults with aphasia (Schwartz et al., 1994) and young children (Stemberger, 1989). Dell, Burger, & Svec (1997) conducted a detailed investigation of factors that influence the directionality of speech errors. They demonstrated that the proportion of anticipatory errors can be predicted from the overall error rate: perseveratory errors are more likely to be observed when the total incidence of error is high, either in a challenging context (e.g. rapid and/or novel utterances), or in the productions of very young or disordered speakers. This finding extends the parallel with child consonant harmony, since it has been demonstrated that progressive harmony is most commonly observed in the early stages when the overall application of harmony is most robust. As the total rate of application of harmony falls off, assimilations become predominantly or exclusively regressive in nature.

A final parallel between consonant harmony and speech errors involves the asymmetric behavior of different places of articulation as targets and triggers of assimilation. In the discussion of child consonant harmony above, it was noted that coronal consonants readily assimilate to velars, but the reverse pattern is not observed. A similar discrepancy has been reported in adult speech errors. Stemberger (1991) reported that velar place was more likely to replace coronal place in speech errors than the reverse. This is a striking finding in that speech errors are generally subject to a frequency bias, whereby more frequent segments are less likely to appear as error targets than lower-frequency segments (Motley & Baars, 1975). Since /t/ is more frequent than /k/ in English, the preference for velar-to-coronal errors represents an exception to this generalization, an "anti-frequency bias." A very similar result has been reported for errors affecting alveolar and postalveolar fricatives, whereby low-frequency /ʃ/ was more likely to replace high-frequency /s/ (Shattuck-Hufnagel & Klatt, 1979; Stemberger, 1991). Hansson (2001) described the same "palatal bias" in adult processes of consonant harmony. Stemberger (1991) interpreted the antifrequency bias as the consequence of coronal underspecification, combined with a preference for addition of material in speech errors. (This

[27]Several factors are likely to have contributed to this gap in the literature. First, opportunities to investigate the effect of featural similarity on child consonant harmony may be limited by the application of other phonological processes. For instance, if a child exhibits fricative stopping and contextual voicing in addition to consonant harmony, the features [continuant] and [voice] may not take on a full range of values and thus cannot be included in the investigation. In addition, it is possible that the striking phenomenon of major place harmony has simply garnered more attention than more generic harmony processes, which certainly do have attestation in child speech (e.g. [ʃiʃɛl] for *seashell*). In spite of these mitigating factors, there is a clear need for systematic investigation of the prediction that correspondence relations in child consonant harmony are sensitive to similarity effects.

addition or *intrusion* bias is recognized as another general characteristic of speech errors; Stemberger and Treiman (1986) reported that repetitive productions of a sequence such as *puck plump* tended to elicit "pluck plump" but not "puck pump" errors.) Stemberger hypothesized that because coronals are underspecified for place of articulation, they create a particularly accommodating target for intrusion of place specifications from other segments, generating the antifrequency bias for coronals. An alternative interpretation of this finding, related to the perceptual characteristics of coronal and velar segments, will be pursued in Section 4.2.

In conclusion, there are pronounced similarities between systematic processes of consonant harmony and accidental speech errors with respect to the influence of similarity, the preferred directionality of assimilation, and the relative susceptibility of different places of articulation to appear as targets of assimilation. Having established this parallelism, we are free to draw on theoretical models of speech errors for insight into the mechanism of consonant harmony. Section 3.2 will review psycholinguistic models that have described the properties of speech errors as the consequence of spreading activation and competition in a connectionist framework. Subsequently, Section 3.3 will review recent developments linking adult speech errors to functional limitations of motor control processes. Insights from both of these approaches will play an important role in accounting for the properties of child consonant harmony.

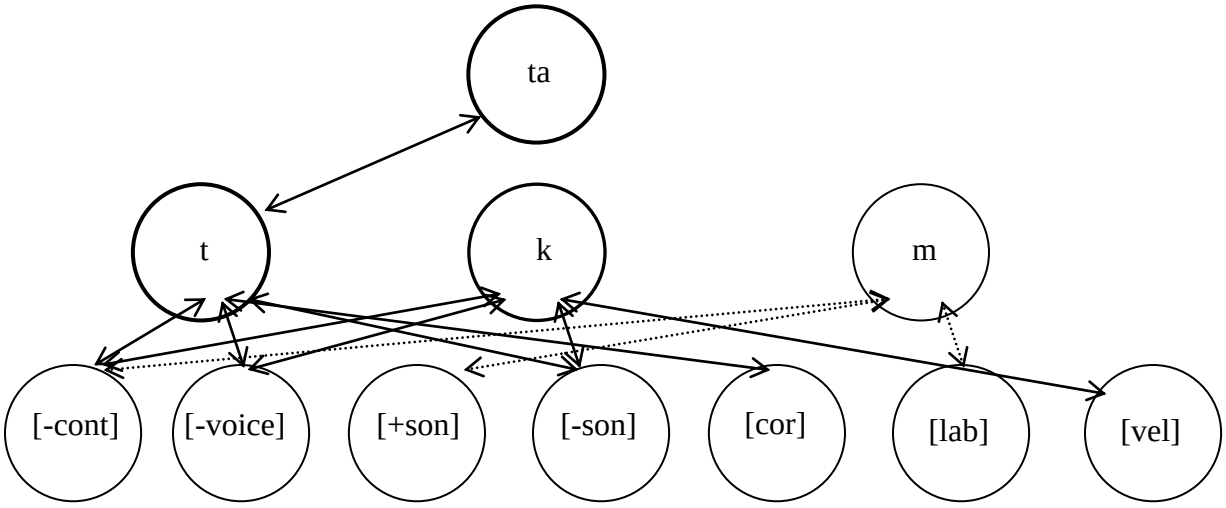
3.2 Psycholinguistic processing model of adult speech errors

Processing-oriented models of speech errors have made important advances in explaining why the similarity of targets plays a role in predicting assimilatory speech errors. The basic insight behind this approach holds that the psycholinguistic encoding of the plan for an utterance is complicated by the presence of similar but non-identical targets in proximity to one another. One means of limiting the processing complexity associated with utterance planning is to change similar sequences into identical sequences. This possibility has been explored in models of adult consonant harmony as agreement by correspondence (Hansson, 2001; Rose & Walker, 2004). In this approach, segments can enter into a correspondence relationship with one another by virtue of featural similarity, whereupon they become subject to output-output faithfulness constraints that militate for identity between corresponding segments. In Section 5 of this chapter, it will be argued that child consonant harmony also can be modeled as a process of agreement by correspondence. The current section demonstrates that the psycholinguistic underpinnings of agreement by correspondence provide an explanation for both the influence of similarity and the regressive directional bias of processes of consonant harmony.

In connectionist models of speech production, target forms are represented at a number of different levels of processing. In Dell's (1986) model of phonological encoding for production, activation begins at the level of a word, which spreads to onset and rhyme nodes, thence to segment and feature nodes. When a node is activated, it spreads its activation to related nodes at other levels, with the strength of the spreading activation dictated by the weight of the connection. These connections are characterized as bidirectional, such that "units on either end will excite one another when activated, or inhibit one another when not activated" (Frisch, 2004, p. 352). Figure 1 illustrates how bidirectional connections to shared features give rise to competing activation of similar segments. The syllable node, /ta/, activates the /t/ node at the segment level, which in turn spreads activation to its various features. Activation from these features then spreads back to segment-level nodes, including other segments that share features with /t/. Note that the level of activation afforded to a segment with several features in common

with /t/, such as /k/, is greater than the activation of a more dissimilar segment, such as /m/. If two targets have many shared features, they will become activated to a similar degree, increasing the likelihood that one will be mistakenly selected for the other (McClelland & Rumelhart, 1981; Dell, 1986; Frisch, 2004).

Figure 1. Bidirectional spreading causes similar activation of segments with shared features



In addition to activating the relevant targets for a given wordform, the speech processor has the responsibility of placing these elements in their proper order. It is in this process of serialization that competing activation of similar targets comes to play a prominent role. Before a motor plan is executed, all of the components of the plan have been activated to some degree; this activated state is sometimes described in terms of representation of segments in an output buffer (Fromkin, 1971; MacKay, 1970; Reich, 1977). If similar segments coexist in the buffer, the control system responsible for putting these elements in order must choose between two segments with a similar degree of activation, a difficult task. Thus, the activation/competition model of phonological processing offers an explanation for the higher frequency with which speech errors affect featurally similar segments.

Connectionist models have additionally offered an explanation for the regressive directional bias in speech error processes. Dell, Burger, & Svec (1997) argued that the anticipatory bias of speech errors is rooted in the functional requirements of speech production. They argue that the processor faces three functional requirements in the production of serially ordered sequences of speech sounds: it must activate the current target, deactivate previous targets, and prepare to activate upcoming targets. Of these three functions, they argue that deactivation is the easiest, invoking a "throw-away principle: Getting rid of what is already activated is easier than activating what is needed" (p. 768). The processor thus faces its greatest challenge at the onset of word production, when all of the targets in the phonological output buffer are activated to some extent. At the end of the word, forms that were previously in competition with the target have been suppressed, giving rise to the prediction of greater

accuracy in word-final relative to word-initial contexts. When errors are assimilatory in nature, this asymmetry will give rise to bias toward assimilation in the regressive direction.

3.3 Articulatory analyses of adult speech errors

3.3.1 Limitations of transcription-based analyses of speech errors

Until recently, it was widely assumed that the great majority of speech errors involve phonotactically well-formed segment substitutions (Wells, 1951; Fromkin, 1971; Dell, Juliano, & Govindjee. 1993). However, instrumental evidence suggests that reliance on impressionistic transcription to categorize speech errors as well-formed or ill-formed may cause us to underestimate the frequency of non-phonemic errors. Processes of automatic perceptual prefiltering may prevent listeners from detecting ill-formed segments (Pouplier & Hardcastle, 2005). In the past decade, there has been a significant accumulation of evidence from both acoustic and articulatory studies showing that speech errors often have a gradient character and may violate phonotactic principles (Frisch & Wright, 2002; Pouplier, 2003, 2008; Pouplier & Goldstein, 2005; Goldstein, Pouplier, Chen, Saltzman, & Byrd, 2007). Given our present focus on the role of articulatory limitations in giving rise to the characteristic processes of child phonology, this speech-motor characterization of speech errors will be of particular interest.

3.3.2 Intrusive gestures in speech errors

New evidence regarding the nature and origin of speech errors has been drawn from studies using electromagnetic midsagittal articulography (EMMA) during error elicitation paradigms (Pouplier, 2003; Goldstein et al., 2007). These studies have revealed that errors perceived as categorical substitutions may involve simultaneous production of multiple gestures, such that a target gesture co-occurs with an intrusive error gesture. Articulator placement was tracked as subjects produced repetitive alternating sequences (*top cop* or *sop shop*). While an error affecting the phrase "top cop" might be transcribed as [kap kap], the articulatory data revealed that such errors frequently involved significant raising of both tongue tip and tongue body, with both gestures varying in magnitude. Other errors revealed intrusive tongue tip raising during velar stop targets, as well as tongue body raising during alveolar sibilants. These findings provide evidence against the hypothesis that speech errors must be phonotactically well-formed, since "no lexical representation for English specifies both a coronal and dorsal closure for the same prevocalic position," although this configuration does arise by means of coarticulation (Pouplier, 2008, p. 117). Both Pouplier and Goldstein et al. found that intrusive gestures constituted the most frequently occurring error type, although well-formed substitutions (i.e. production of an error gesture with reduction of the target gesture) were also observed by each. Goldstein et al. (2007) reported that 27% of speech errors in their study were intrusive in nature, versus 3% omission and 4% substitution errors. The prevalence of intrusion errors provides articulatory confirmation for the addition bias in speech errors that Stemberger (1991) reported based on transcription data. Pouplier (2008) reported that significantly more errors occurred in the context of repetition with a coda consonant (*top cop* or *sop shop*) as opposed to an alternating sequence with no codas (*taa kaa*). In addition, the bias whereby intrusive gestures outnumbered other types of errors was observed only in the context of stimuli with a coda consonant. While the precise cause underlying this effect remains somewhat unclear, there is evidence that the

presence of a coda consonant acts as a trigger for the production of intrusive errors in repetitive speech tasks.

3.3.3 A gestural model of speech error production

Drawing on this evidence of the pervasive nature of intrusive error gestures, Pouplier, Goldstein, and colleagues have offered a new model of speech errors using the framework of articulatory phonology (Browman & Goldstein, 1992). The gestural model was offered as an alternative to models in which speech errors arise as the consequence of competition between segments in a spreading-activation model of speech processing, as described in Section 3.2 (Dell, 1986). In place of competition between segments, this model posits competition between gestural coupling relations, where alternating articulatory movements tend to shift into a more stable mode of oscillation (Pouplier, 2008).[28] In typical speech production, phonotactically well-formed sequences of gestures constitute a stable mode of coordination. However, the system can be destabilized if a rhythmic attractor is introduced into the environment, potentially triggering a shift to a different mode of coordination. Particular pressure is generated when some gestures occur in a 1:1 ratio in an utterance string, while other gestures occur in a complex frequency ratio. Repetitive production of *top cop* provides an example of this situation: in every production of the phrase, there is only one coronal and one velar gesture for every two labial gestures. Thus, the ratio of different places of articulation is 1:2. When an intrusion error gives rise to simultaneous production of /t/ and /k/ gestures, the system would appear to have shifted into a maximally stable 1:1 ratio, where every gesture occurs twice per phrase. Note that the new coordination mode may come at the expense of phonological well-formedness, as in the case of simultaneous velar and coronal closure.

While the articulatory model of speech errors proposed by Pouplier and colleagues can offer important insights for our understanding of consonant harmony processes, the notion that speech errors serve to optimize the ratio of different place gestures in the oscillatory movement of speech does not transfer to the context of consonant harmony. Unlike speech errors elicited in a laboratory setting, consonant harmony is not restricted to repetitive speech; it occurs in isolated words as well as in strings representing a variety of places of articulation. For instance, a child with consonant harmony might utter the isolated word *duck* as [gʌ k]. While Pouplier (2008) reported that intrusive error gestures are induced by coda consonants, the intrusion errors reported by Pouplier (2003) and Goldstein et al. (2007) consistently involved superimposition of two different places of articulation in an alternating sequence of onsets (e.g. ***t**op **c**op*). In fact, speech errors between onset and coda consonants, either within a single word or between words, are all but unattested in the adult speech error literature. While intrusive gestures during alternating onset sequences can be understood as optimization of the ratio of place gestures, this logic does not translate to onset-coda interactions in consonant harmony. In fact, in a target word with a coronal onset and a velar coda (e.g. *duck*), tongue-tip and tongue-body gestures already occupy a 1:1 ratio with respect to one another. If the harmonized output involves simultaneous

[28] Pouplier and colleagues point out that the shift in coupling relations that they describe for speech errors can also be observed in other natural systems. This general pattern of "rhythmic synchronization…of coupled oscillators" carries the label of oscillator entrainment, and it has been observed in tasks involving finger-tapping and limb oscillations (Haken, Peper, Beek, & Daffertshoffer, 1996; Strogatz & Stewart, 1993). The intrusion bias reported for speech errors also has a basis in the general properties of coordinated movement: Peper et al. (1995) showed that in hand-tapping tasks, the stable state is achieved by addition rather than elimination of movements, such that the highest-frequency oscillator comes to dominate in a case of entrainment.

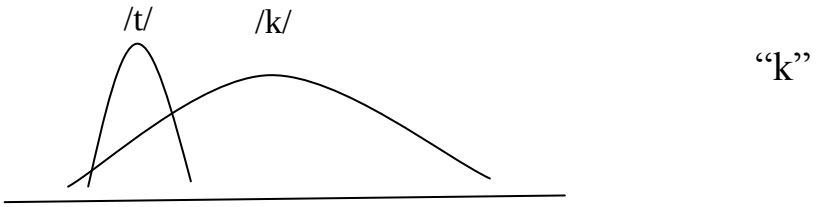
production of a target coronal and an intrusive velar gesture, the ratio of tongue-tip to tongue-body gestures has shifted to a less optimal value, 1:2.

While it will not be possible to make direct use of Pouplier's gestural model of error production in an analysis of child consonant harmony, there are other insights that do have relevance for both error and harmony processes. Specifically, new directions for modeling consonant harmony are suggested by the finding that coproduction of target and intrusive error gestures can give rise to the percept of categorical substitution. The following section demonstrates that the hierarchy of target and trigger place observed in child consonant harmony can be analyzed in terms of the perceptual asymmetries described by Pouplier & Goldstein (2005).

3.3.4 Perceptual origins of place asymmetries

We saw above that speech errors involving coronal and velar place are subject to a puzzling "antifrequency" effect. While it is typically reported that high-frequency segments are more likely to occur as substitutions for lower-frequency items, in the case of coronals and velars it is the lower-frequency velar place that is more likely to substitute for high-frequency coronal place. Pouplier & Goldstein (2005) pointed out that perceptual biases may have a distorting effect on studies that use impressionistic transcription to describe the relative frequency of different error types: if certain errors are more readily perceived than others, these will be overrepresented in error counts. They offered a new, perceptually-motivated account of the antifrequency bias in coronal and velar speech errors. In the articulatory investigations of speech errors reported above (Pouplier, 2003; Goldstein et al., 2007), coronal and velar gestures were equally likely to appear as targets and triggers in speech errors. Pouplier & Goldstein thus posited that a perceptual asymmetry must be the source of the antifrequency bias reported in transcription-based studies of speech errors. They hypothesized that the particular vulnerability of coronals in speech error processes can be understood as a manifestation of their general perceptual weakness in contexts of competition with other place gestures. Chen (2003) suggested that listeners' readiness to perceive coronals as targets of assimilation was a consequence of the relatively short duration of the tongue tip gesture. When a coronal gesture is coproduced with a velar gesture, the coronal place is unlikely to be detected perceptually, since the larger, slower tongue body gesture can completely overlap the rapid movement of the tongue tip. This articulatory relationship is schematized in Figure 2.

Figure 2. Simultaneous coronal and velar gestures are perceived as velar



Pouplier & Goldstein tested their hypothesis by asking listeners to classify the initial consonant in recorded examples of speech errors, collected over the course of their production experiments. The stimuli included both instances of coronal intrusion during velar production

and velar intrusion during coronal production, with a range of gestural magnitudes. Pouplier & Goldstein reported an asymmetry whereby productions involving a coronal target with an intrusive velar gesture were perceived as anomalous, whereas errors involving a velar target and an intrusive coronal gesture typically were not detected by listeners. This strongly supported their hypothesis that the coronal-velar asymmetry reported in impressionistic transcription of speech errors is in fact a property of listeners' perceptual biases.

While Pouplier & Goldstein did not investigate speech errors involving labial place, the same logic can be pursued in this case. With a duration falling in between the rapid coronal and slow velar gestures, labial gestures can be expected to predominate over coronal but not velar place in cases of simultaneous closure. Byrd (1992) demonstrated that listeners who heard overlapping coronal and labial targets tended to perceive assimilation of a coronal to a following labial, whereas the influence of a coronal gesture on a preceding labial was more restricted in nature. In cases of simultaneous labial and velar closure, the predicted outcome is less clear. Although the velar gesture is long enough to fully overlap a labial gesture, the visual salience of labial gestures can be expected to erode the dominance of velar place. However, the relatively limited participation of labial place in child consonant harmony will be revisited with an alternative analysis in Section 6.3, where it will be posited to reflect an articulatory metric of similarity.

Previous accounts of child consonant harmony have invoked scales of markedness to explain the observation that coronal consonants frequently assimilate to velar (and sometimes labial) place in harmony, whereas the reverse pattern of assimilation is not attested. However, a new possibility is opened if we assume that child consonant harmony, like speech errors, involves simultaneous production of both target and intrusive place gestures. On this account, implicational relations between places of articulation can be derived directly from perceptual asymmetries, with no need to encode scales of markedness into the constraints that drive harmony. The absence of harmony proceeding from a coronal trigger to a noncoronal target is thus understood as a natural consequence of the transient nature and consequently low perceptual salience of coronal gestures. The hypothesis that child consonant harmony involves coproduction of intrusive and target gestures is a question for empirical verification. While instances of simultaneous closure might in impressionistic transcription be recorded as categorical segment substitution errors, it should be possible to detect the posited coproduction through instrumental measures. The hypothesized coproduction in child consonant harmony was supported in an experimental investigation, reported in Section 4.

4. Experimental investigation of consonant harmony

On the hypothesis that child consonant harmony is a process of gestural intrusion, as described for adult speech errors by Pouplier and colleagues, an experiment was conducted to look for covert contrast between harmonized and target productions in child speech. While there has been extensive investigation of covert contrast in child phonology (see summary in Chapter 2), there is a gap in the literature for the process of consonant harmony. In his meta-analysis of covert contrast in developmental phonology, Scobbie (1998) reports knowing of "no cases in which supposed consonant harmony has been shown to involve only an apparent change in place of articulation" (p. 348). On the other hand, velar fronting has been studied relatively thoroughly in this literature (Young & Gilbert, 1988; Forrest et al., 1990; Tyler, Edwards & Saxman, 1990;

Tyler, Figurski, & Langsdale, 1993, Edwards, Gibbon, & Fourakis, 1997). This literature has demonstrated that it is possible for velar and coronal targets to differ phonetically while presenting perceptually as a single place of articulation. Studies of covert contrast in velar fronting have employed a variety of analytical techniques, including comparison of voice onset time, F2 height and F2 transition slope, spectral moments analysis, and electropalatography. This section will present an experiment using acoustic measurements to test the hypothesis that covert contrast can be maintained in the process of child consonant harmony. The experiment compared VOT and F2 data collected from target velar consonants versus perceptually identical consonants that were the product of coronal assimilation to a velar trigger in the productions of one child with consonant harmony. Although this child's harmonized productions were perceived as categorical segment substitutions, the analysis revealed that a significant difference was maintained between harmonized coronals and true velars. This finding of covert contrast supports the hypothesis that consonant harmony, like speech errors, can be understood as a process of coproduction of target and intrusive gestures.

4.1 Methods

4.1.1 Participants

For this investigation, recordings were obtained from four typically developing children recruited from a preschool in Cambridge, MA. Children ranged in age from two years, five months to four years, seven months, with a mean age of three years, three months. One of the four children was observed to exhibit consonant harmony effects across spontaneous and elicited contexts for speech production. Two subjects were female; the child exhibiting consonant harmony was male. Participating children were not diagnosed with any communication disorder and had no known history of cognitive or hearing impairment and no gross abnormality of the articulatory apparatus.

The primary subject of this investigation, J, is a male who was two years, eleven months of age at the time testing was conducted. J was born in South Korea, but he had been in a monolingual English-speaking environment since he was adopted at seven months of age. Although J was recruited as a typically developing participant, and he was not receiving speech-language services at the time of testing, he did show some qualitative signs of delay in speech and language development.[29] At the time of testing, J's intelligibility was significantly reduced secondary to multiple phonological processes, described in greater detail below. He also showed signs of delay in syntactic development, producing mostly one- to two-word utterances with limited inflectional morphology. J presented as a socially appropriate but highly distractible child. The following subsection will offer a more detailed characterization of processes in J's phonology, with a particular emphasis on the patterns of consonant harmony he exhibited.

[29] Because standardized measures of speech and language function were not administered in connection with this experiment, only impressionistic characterizations of J's speech and language functions are available.

4.1.2 Phonological processes in subject J

J exhibited a number of developmental phonological processes over the course of his evaluation. In addition to consonant harmony, he exhibited robust processes of initial voicing, final devoicing, cluster simplification, and stopping; these processes are illustrated in (8)-(10).

(8) Contextual voicing: Initial segments are voiced, final segments are voiceless.
- a. [gaʊ] ‘cow’
- b. [gɔ k] ‘dog’

(9) Cluster simplification
- a. [noʊ] ‘snow’
- b. [gai] ‘sky’

(10) Stopping
- a. [duw] ‘shoe’
- b. [gɪ :ŋ] ‘singing’

A total of fourteen phonological changes were reported in J’s output. Eight of these processes are included among the ten most prevalent processes of phonological development scored on the *Khan-Lewis Phonological Analysis-2nd Edition (KLPA-2).* Given J’s young age, these processes were regarded as developmentally appropriate. Thus, while J did exhibit a large number of phonological substitutions, at the time of testing there was no compelling evidence that he should be regarded as phonologically disordered.

J exhibited a consistent pattern of place harmony characterized by regressive assimilation of both coronal and labial targets to following velars, as illustrated in (11). No assimilation was observed in environments for progressive harmony (12). The examples in (13) and (14) show that coronal and labial stops were realized faithfully in non-harmonizing environments. Unfortunately, data were not collected to determine whether regressive harmony from a labial trigger to a coronal target was part of J’s pattern of consonant harmony.

(11) Place harmony: Coronal and labial segments assimilate to a following velar.
- a. [gʌ k] ‘duck’
- b. [gɪ k] ‘pig’

(12) No progressive harmony.
- a. [gæ t] ‘cat’
- b. [gat] ‘got’

(13) No context-free backing of coronals.
- a. [ajduwit] ‘I do it’
- b. [dæ oʊ] ‘tail’

(14) No context-free backing of labials
- a. [bebi] ‘baby’
- b. [babej] ‘bye-bye’

To quantify the strength of consonant harmony processes in J's speech, all contexts for harmony (words in which a coronal or labial segment appeared before a velar consonant with an intervening vowel) were identified in the transcript of his testing session. The number of instances in which consonant harmony was observed in each environment was then used to calculate the percent application of each type of harmony. As Table 4 shows, both types of consonant harmony were attested with greater than 90% application in relevant contexts. This strongly suggests that consonant harmony was not an incidental or intermittent phenomenon for J, but constituted a robust process in his phonology at that point in time.

Table 4. Percent application of two types of consonant harmony in J's output

Harmony Type	**# of contexts observed**	**% application of harmony**
Coronal-Velar (TVK → KVK)	34	94%
Labial-Velar (PVK → KVK)	8	100%

4.1.3 Stimulus design

Because regressive harmony from a velar trigger to a coronal target is the most common and robustly occurring type of consonant harmony, it was determined that minimally different stimuli of the form KVK and TVK were most likely to produce the desired effect of perceived coronal-velar neutralization. The nonwords selected for this experiment were *duggen* ([dʌ gə n]) and *guggle* ([gʌ gə l]), assigned to visually distinct imaginary creatures. Given the potentially subtle nature of the contrasts under investigation, the phonetic properties of the target nonwords were tightly controlled. Stimuli were selected that differed only in the first consonant of the initial CVC, since formant deformations associated with the transition to a different vowel or the anticipation of a different coda consonant could represent a significant confound. At the same time, the possibility of confusion between forms dictated that the target words should not be too similar. In particular, a monosyllabic minimal pair (e.g. [tug]-[kug]) would create an ambiguous result if no difference were found between the two targets in a child's production: it would be unclear whether the child was targeting distinct underlying forms but neutralized the coronal-velar distinction, or whether he simply had confused two very similar words at the level of underlying representation. For this reason, a second syllable was introduced to further differentiate the stimuli. Finally, the stimuli selected use a mid vowel, which does not pose any confounding effect of palatalization and furthermore has been associated with a more durable form of harmony than assimilation across front vowels (Pater & Werle, 2001).

4.1.4 Procedure

Both of the target nonwords were taught and elicited over the course of a single testing session. To familiarize participating children with the target nonwords, two brief stories were created, each featuring one imaginary creature (the *duggen* or the *guggle*). These stories were generated as Microsoft PowerPoint slide shows. Each story featured approximately twenty tokens of one target nonword. During the teaching phase, the child and the experimenter viewed the slide show on the experimenter's laptop computer while the experimenter read the text of the story using child-directed intonation. A particular effort was made to pronounce the nonword targets in a clear, hyperarticulated fashion. After the teaching phase for the target *duggen*, the child was engaged in a sentence-repetition game until at least ten tokens of the target were collected. Target sentences, matched for number of syllables, described an activity the *duggen*

would carry out, such as "The *duggen* is dancing" or "The *duggen* is spinning." A complete list of stimulus sentences is presented in Appendix B. Children subsequently heard a story introducing the *guggle* character. At least ten tokens of the word *guggle* were then elicited in a game reenacting the story, in which the child was prompted to produce repeated tokens of the utterance, "Are you a *guggle*?" Each story and the related play activity could be conducted in less than ten minutes.

The entire interaction between experimenter and child was recorded using a Marantz Professional Portable Solid State Recorder (PMD671). Target stimuli were then extracted for analysis with Praat software (Boersma & Weenink, 2008). Formant settings were manipulated until it was visually determined that individual formants were optimally continuous and maximally distinct from one another. For the two female subjects, formant tracking was optimized when two formants were identified in a 4000-Hz range, while optimal formant tracking for the male subjects was observed when three formants were identified in a 5000-Hz range. The following measurements were recorded for each token: VOT, height of F2 at vowel onset, and height of F2 at vowel midpoint. VOT was measured from the consonant burst to the first local minimum associated with the onset of periodicity. Vowel offset was measured as the peak of the last spike preserving the characteristic waveform observed throughout the vowel. Vowel midpoint was calculated from vowel duration unless F2 tracking appeared aberrant at the calculated midpoint, in which case a visually determined steady state of the vowel was used for F2 measurements. Across all participating children, a total of six tokens were eliminated due to background noise or other defects. All *duggen* and *guggle* tokens produced by typically developing children were transcribed with a target-appropriate coronal or velar onset. For harmonizing subject J, all tokens of both *duggen* and *guggle* were transcribed with a velar onset.

4.2 Results

4.2.1 Control subjects

Table 5 presents mean values for VOT, F2 at onset, and F2 at midvowel for sets of *duggen* and *guggle* tokens produced by the three control subjects. Standard deviations are in parentheses.

Table 5. Average values for *duggen* and *guggle* tokens; *SD* in parentheses

Subject	Target	N	VOT (ms)	F2 Onset (Hz)	F2 Mid (Hz)
S (m, 4;7)	*duggen*	12	19 (8.4)	2524 (86.1)	2212 (249.3)
	guggle	8	25 (5.2)	2152 (60.0)	1897 (144)
I (f, 2;5)	*duggen*	11	30 (22)	2567 (160.5)	2407 (173.9)
	guggle	13	26 (10)	2324 (181)	2049 (183.8)
E (f, 3;1)	*duggen*	8	23 (7.5)	3019 (285.5)	2835 (222.7)
	guggle	9	22 (6.2)	2782 (242.4)	2542 (434.9)

Student's *t*-test was used to test the significance of the difference between *duggen* and *guggle* sets for each child; results of this analysis are presented in Table 6. Because these children consistently produced perceptually distinct coronal and velar targets, significant differences between sets were anticipated. Based on previous studies, it was predicted that F2 at onset would be the most reliable indicator of the difference between coronal and velar targets.

Consistent with this prediction, all three children exhibited a higher mean F2 at onset for coronal than for velar targets. This difference reached significance in two of three children and appeared as a trend approaching significance in the third child. Two of three children additionally showed a significant difference in F2 at midvowel, with coronal targets exhibiting a higher F2 than velars. This was interpreted as an assimilatory effect in which the anterior consonant conditions fronting of the adjacent vowel (cf. Flemming, 2003). Voice onset time did not appear as a predictor of consonant place in this dataset, with no significant influence of VOT emerging in any of the three subjects.

Table 6. Results of *t*-tests comparing *duggen* and *guggle* tokens

Subject	**Parameter**	**Degrees of freedom**	***t*-value**	***p*-value**
S (m, 4;7)	VOT	10	-1.80	0.10
	F2 at onset	18	11.39	**1.2 e -09**
	F2 at midvowel	17.8	3.57	**0.002**
I (f, 2;5)	VOT	13.5	0.56	0.58
	F2 at onset	22	3.50	**0.002**
	F2 at midvowel	21.7	4.89	**7.1 e -05**
E (f, 3;1)	VOT	13.7	.21	.833
	F2 at onset	13.9	1.84	*.09*
	F2 at midvowel	12.2	1.77	0.10

In summary, analysis of the productions of three subjects without a process of consonant harmony indicated that velar and coronal targets can indeed be differentiated acoustically based on the height of the second formant at the onset of vowel production. The following section will investigate these acoustic parameters in subject J, for whom coronal and velar place were consistently perceived to be neutralized in the environment preceding a velar coda consonant.

4.2.2 Covert contrast in J's consonant harmony

On the hypothesis that child consonant harmony involves simultaneous production of a target gesture and an intrusive harmonizing gesture, it was speculated that instrumental analysis would allow us to detect the presence of the intrusive gesture. The most direct evidence for coproduction can be drawn from articulatory measures such as electropalatography or EMMA, as used by Pouplier and colleagues. Since this technology is less feasible for use with child speakers, here the acoustic signal was analyzed for evidence of covert contrast. Although both *duggen* and *guggle* tokens in J's output were transcribed with velar onsets, it was predicted that the two sets would differ significantly in the height of the second formant at vowel onset. Specifically, consistent with the pattern observed in children with an overt coronal-velar contrast, it was predicted that mean F2 at onset would be significantly higher for coronal relative to velar targets. Table 7 presents mean VOT and F2 values from J's productions of *duggen* and *guggle.* As hypothesized, the value of F2 at the onset of the vowel was higher for *duggen* targets. Table 8 shows that this difference reached significance at the $p < .05$ value. This demonstrates that seemingly categorical place neutralization in child consonant harmony can in fact involve covert contrast.

Table 7. Average values for *duggen* and *guggle* tokens; *SD* in parentheses

Subject	Target	N	VOT (ms)	F2 Onset (Hz)	F2 Mid (Hz)
J (m, 2;11)	*duggen*	11	20 (3.3)	2504 (327.4)	1937 (184.8)
	guggle	16	20 (3.0)	2228 (263.5)	1863 (171.9)

Table 8. Results of *t*-tests comparing *duggen* and *guggle* tokens

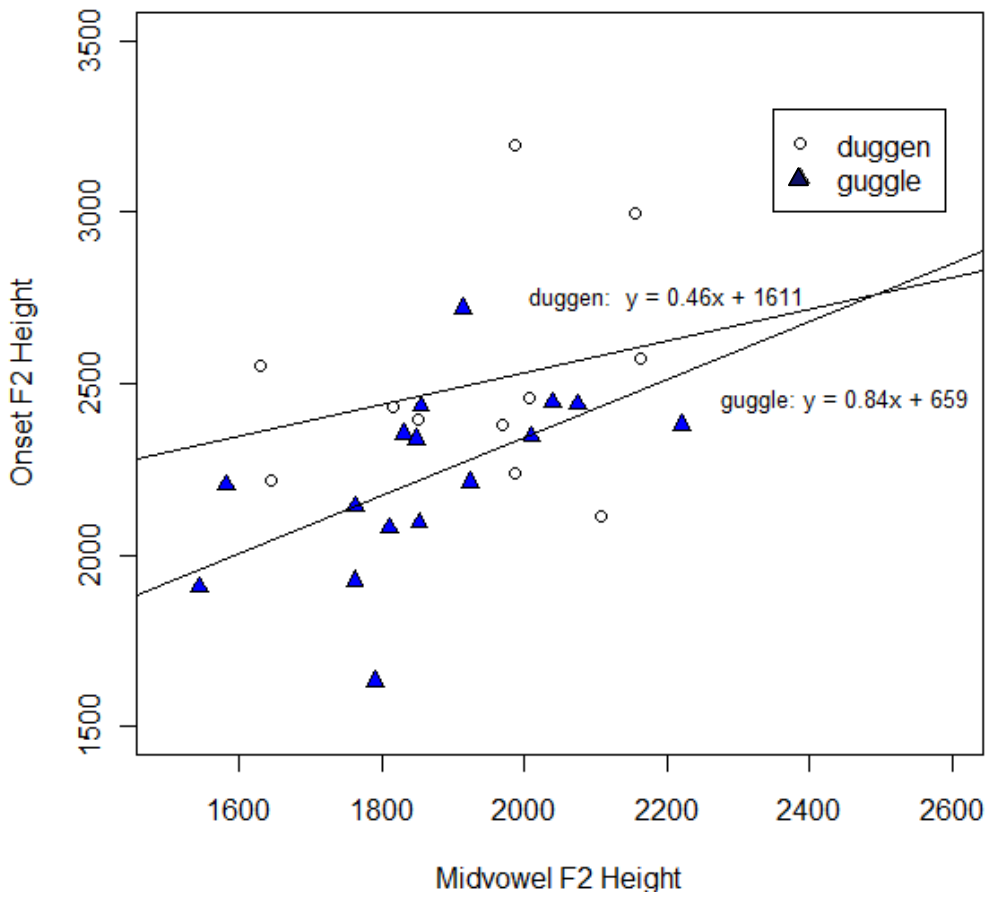
Subject	Parameter	Degrees of freedom	*t*-value	*p*-value
J (m, 2;11)	VOT	20	-0.56	0.58
	F2 at onset	18	2.32	**0.032**
	F2 at midvowel	20	1.05	0.31

As an additional test to evaluate the distinctness of the *duggen* and *guggle* sets, locus equations were calculated for each set of utterances. Locus equations are generated as a linear regression over F2 frequencies, with F2 at onset plotted as a function of F2 at midvowel (Lindblom, 1963). It has been demonstrated that a linear equation of the form [F2onset = k * F2mid + c] accurately describes adult F2 values, with the further finding that slope and y-intercept values vary predictably as a function of consonant place (Sussman, Hoemeke, & McCaffrey, 1992). Sussman et al. also showed that locus equations, which change over the course of phonological development, can consistently be used to differentiate consonant place in child speakers. Note that while a variety of vowels were represented in the data used to calculate locus equations in Sussman et al. 1992, locus equations in the present study were collected using a single target vowel, [ʌ]. The goodness of fit of the linear approximation here was limited by the restricted range of $F2_{mid}$ values represented, resulting in low values for Pearson's product moment correlation (*r*).

Linear regression over J's 11 *duggen* tokens resulted in a locus equation [$F2_{ons}$ = .46*$F2_{mid}$ + 1611]. The R^2 value for the regression was .06, indicating that the linear model was a fairly poor fit for these data points. Linear regression for the 15 *guggle* tokens resulted in the locus equation [$F2_{ons}$ = .84*$F2_{mid}$ + 659]. The R^2 value for the regression was .30, indicating a somewhat better fit of the linear model. The slopes of the locus equations calculated over J's productions fell in the predicted direction, /g/ > /d/, based on children who maintain an overt contrast between velar and coronal place.

Figure 3 is a plot of all *duggen* and *guggle* tokens featuring F2 height at onset versus F2 height at midvowel. The separation of underlying /d/ and underlying /g/ indicated by the results in Table 8 can be confirmed visually in this graph. Along the y-axis, while there is overlap between the two data sets, all of the highest F2-onset values are associated with the *duggen* data set, while the low outliers belong to the *guggle* set. The general visual impression is that tokens with underlying /d/ have higher F2 at onset than tokens with underlying /g/, consistent with the result of the *t*-test discussed reported above. There is complete overlap between the two data sets along the x-axis, reflecting the absence of a systematic difference in vowel height at midpoint across the two sets.

Figure 3. Scatter plot and locus equations illustrating covert coronal-velar contrast



To test the significance of the difference between the locus equations calculated for underlying /d/ and underlying /g/ forms, linear distances were calculated from each data point to one of the regression lines. These values were used to compare the average residual distance of underlying /d/ consonants from the *duggen* regression line with the average distance of underlying /g/ consonants from the same line. If J produced coronal and velar targets with significantly different formant transition patterns, there should be a reliable difference in the residual distances of the two sets of data points from a single regression line. A *t*-test revealed that the residual distance of *duggen* tokens from the coronal regression line was significantly greater than the residual distance of *guggle* tokens from the same line ($p = .027$). This supported the hypothesis that J was maintaining a covert contrast between /d/ and /g/ targets, such that harmonized /d/, perceived as /g/, was underlyingly more "d-like." The results of this analysis are summarized in Table 9.

Table 9. Residual distance of *duggen* and *guggle* tokens from calculated *duggen* trendline

Target	**Mean residual difference (Hz)**	**Results of paired *t*-test**		
		t-value	DF	*p*-value
duggen	-1.8 (316.1)	-2.44	16.3	**.027**
guggle	264.9 (215.6)			

The same procedure was carried out a second time, but this time J's productions were compared against the locus equations that Sussman et al. (1992) reported for typically

developing children's productions of velar and coronal targets. It was predicted that the average distance of *duggen* data points from the coronal locus equation reported by Sussman et al. would be less than the average distance of *guggle* data points from the same line. The results of the paired *t*-test are presented in Table 10. As predicted, the mean distance of the *duggen* tokens from the coronal trendline reported by Sussman et al. was significantly smaller than the mean distance of *guggle* tokens from that line. This provided further confirmation for the hypothesis that J's underlying coronals were more "d-like" than his underlying velars.

Table 10. Distance of *duggen* and *guggle* tokens from Sussman et al. (1992) velar locus equation

Target	**Mean residual difference (Hz)**	**Results of paired *t*-test**		
		t-value	DF	*p*-value
duggen	-140.5 (316.3)	-2.14	16.9	**.047**
guggle	96.9 (226.9)			

In conclusion, clear evidence was found to indicate that J maintained covert contrast between velar and coronal target consonants that were perceived to be neutralized in an environment for consonant harmony. These findings will be incorporated into a formal phonological analysis of child consonant harmony in the following section.

5. Incorporating functional pressures into a formal model of harmony

The finding of covert contrast between underlying /g/ and harmonized /d/ provides support for the hypothesis that some child consonant harmony, like some adult speech errors, involves simultaneous production of a target gesture and an intrusive harmonizing gesture. This model of child consonant harmony has the advantage of deriving asymmetries in the participation of different places of articulation as targets or triggers of assimilation. However, it was shown previously that Pouplier's analysis of intrusive gestures as oscillator entrainment does not transfer straightforwardly to the case of child consonant harmony, where harmony between onset and coda cannot be viewed as optimizing the ratio of speech gestures. To sustain the hypothesis that child consonant harmony involves gestural intrusion, it will be necessary to posit some motivating factor other than oscillator entrainment. This motivation will be drawn from an activation/competition model of speech processing (Dell, 1986), as discussed in Section 3.2. This is the same approach that has been taken in models of adult consonant harmony as agreement-by-correspondence (Hansson, 2001; Rose & Walker, 2004), which hold that consonant harmony is motivated by the functional pressure to avoid sequences of similar but non-identical sounds. It will be demonstrated that child consonant harmony is also amenable to analysis using the formalism of agreement by correspondence. To incorporate insights from Pouplier's articulatory model of assimilation, the agreement by correspondence model will be updated to operate over gestures rather than features. It will be demonstrated that this articulatory version of correspondence accommodates the possibility of simultaneous production of target and harmonizing gestures, making it possible to model the covert contrast reported in the Section 4.

5.1 Consonant harmony as agreement by correspondence

Despite striking parallels between consonant harmony and speech error processes, we presumably do not wish to maintain that child consonant harmony is truly a speech error phenomenon. While children are, in fact, more prone to sporadic articulatory slips than adults—Wijnen (1992) found that two- to three-year-old children produced speech errors at seven times the average adult rate of one to two errors per thousand words—child consonant harmony typically manifests itself in a systematic fashion that is more suggestive of a phonological process. In keeping with the approach adopted elsewhere in this dissertation, here consonant harmony will be analyzed as a phonological process grounded in articulatory-phonetic pressures. Section 1 showed that adult phonologies also feature processes of nonlocal consonant agreement with a bias for operation in a regressive direction. Given the basic parallelism between consonant harmony processes in children and adults, it is highly desirable to unify the two under the same formalism. Thus, this section will review analyses of adult consonant harmony as agreement by correspondence, and the following section will demonstrate that this approach can be extended to model child consonant harmony as well.

Since the great majority of assimilatory processes involve local relations between segments, efforts have been made to address consonant harmony within the framework of local feature-spreading. It has been proposed that adult harmony processes conform to strict locality, such that all segments within a domain of harmony participate in the harmonizing process, even when the effects are not perceptible (Flemming, 1995; Gafos, 1995; Ní Chiosáin & Padgett, 2001). However, Hansson (2001) has argued against the hypothesis that consonant harmony is limited to strictly local assimilation. He points out that the strict locality hypothesis depends on the assumption that the spreading feature can be realized with no detectable influence on the intervening segment(s). While this is a reasonable claim for cases of coronal harmony, where minor differences in tongue blade configuration might go undetected during the intervening vowel, the logic does not hold for all cases of adult consonant harmony. For instance, Hannson notes that in Bantu languages, long-distance interactions of nasals with voiced stops can be observed with no influence on the intervening vowel, even though the nasal feature can be realized on a vowel. These observations have led to analyses in which consonant harmony appears as the product of truly non-local relations among segments (Walker, 2000; Hansson, 2001; Rose & Walker, 2004). Walker (2000) proposed that certain segments establish a relation of correspondence by virtue of their similarity to one another. This relation is then subject to faithfulness constraints that militate for further similarity between corresponding segments. Rose & Walker (2004) formalized this correspondence relation as seen in (15) (p. 21):

(15) CORR-C↔C: Let S be an output string of segments and let Ci, Cj be segments that share a specified set of features F. If Ci, Cj ∈ S, then Ci is in a relation with Cj, that is, Ci and Cj are correspondents of one another.

Rose & Walker (2004) argued that agreement by correspondence is rooted in the psycholinguistic finding that similar but non-identical articulatory targets pose a challenge for phonological planning and speech-motor execution In Section 3.2, we reviewed this psycholinguistic motivation as it relates to speech errors, drawing on an activation/competition model of speech processing as proposed by Dell (1986). By virtue of bidirectional spreading activation, two targets with a large number of shared nodes will be activated to a similar degree, creating a high likelihood that one will be selected in place of the other for a given position in the serial order of segments in a word. One way to alleviate this processing difficulty is to change

the competing targets to be fully identical, eliminating the challenge posed by serial ordering. Hansson (2001) and Rose & Walker (2004) have proposed that the pressure to avoid problematic juxtapositions of similar but non-identical segments may be phonologized in the form of IDENT-Correspondence constraints, which give rise to consonant harmony.

The question that arises next pertains to which or how many features must be shared in order for a correspondence relation to be established between two segments. Rose & Walker suggest that correspondence constraints occupy a fixed hierarchy in which constraints enforcing a relation between very similar segments are high-ranked, while constraints linking less similar segments appear lower in the hierarchy. Their hierarchy, which they maintain is not stipulated but based on superset relations, is reproduced in (16).

(16) CORR-T↔T >> CORR-T↔D >> CORR-K↔T >> CORR-K↔D
"identical stops" "same place" "same voicing" "any oral stops"

The correspondence hierarchy is then incorporated into a series of faithfulness constraints that militate for identity between corresponding segments, as seen in (17) for the example of voicing agreement (p. 23).[30] Finally, Rose & Walker propose that the constraints enforcing identity between corresponding segments can be specified for directionality. This provides a means of capturing the regressive directional preference of adult consonant harmony, a bias that is also observed in speech errors and is thus analyzed as a reflection of processing constraints, discussed in Section 3.2. (18) offers an example of a constraint to capture assimilation for nasality that operates solely in a regressive (right-to-left) direction (p. 43).

(17) IDENT-CC(voice): Let C_i be a segment in the output and C_j be any correspondent of C_i in the output. If C_i is [voice] then C_j is [voice].

(18) IDENT -C_RC_L(nas): Let C_L be a segment in the output and C_R be any correspondent of C_L such that C_R follows C_L in the sequence of segments in the output (R>L). If C_R is [nasal], then C_L is [nasal].

On the hypothesis that correspondence constraints are rooted in functional limitations on speech processing, we might expect such constraints to be especially active in child speech, where the challenges of motor planning and execution play a particularly prominent role. Here it will be assumed that IDENT-CC has a higher weight in the phonology of a child with limited speech-motor capacity than in the grammar of a skilled adult speaker. However, an additional articulatory factor will be invoked to explain the contrast between adult and child consonant harmony with respect to the availability of major place harmony, discussed in Section 6.

Several problems with the analysis of consonant harmony via agreement by correspondence have recently been raised by Gallagher & Coon (in press). Gallagher & Coon argue that by allowing IDENT-CC constraints to operate over individual features, traditional models make incorrect predictions for possible processes of consonant harmony. They propose that all true long-distance consonant harmony processes create total identity between segments, whereas instances of harmony for individual features can be shown to involve only local feature-spreading. Their data are drawn from Chol (Mayan), which has harmony processes that give rise

[30] Rose & Walker assume monovalence of laryngeal features, but they maintain that their analysis would not by changed by the adoption of binary features.

to both total and partial identity. When two plain stridents or two ejective consonants cooccur in a root, they must agree for all features. When an ejective consonant and a non-ejective strident co-occur in a root, on the other hand, they are required to agree only for anteriority. It is challenging to model both of these processes simultaneously using CORR-CC constraints. If two segments are similar enough to enter into a correspondence relationship for the purpose of anteriority harmony, it is unclear why this relationship does not also make them subject to the full suite of constraints that elsewhere impose total identity between segments in correspondence. Further, Gallagher & Coon point out that the use of feature-specific IDENT-CC constraints misses the special psycholinguistic status of total identity between segments, which in the standard correspondence model "can only be analyzed as an accidental side effect of multiple single feature harmonies" (p. 30). In addition, if total identity is achieved by a number of single correspondence constraints for individual features, we would expect to find single-feature harmony processes corresponding with each of these, yet a number of the harmonies thus predicted are unattested. Gallagher & Coon propose that true cases of long-distance consonant agreement can be modeled under a new relationship, LINK, with linked constraints subject to an IDENTITY constraint that is satisfied exclusively by total featural agreement. It is argued that single-feature agreement processes are mediated by strictly local feature-spreading, and also are not subject to a similarity requirement in the manner of segments that enter into the LINK relationship.

Gallagher & Coon make a persuasive argument against the use of single-feature correspondence constraints. While the basic formalism of CORR-CC and IDENT-correspondence constraints will be retained in the analysis that follows, these constraints have been modified to militate for identity at the level of articulatory gestures rather than features. This articulatory version of correspondence will be seen to avoid a number of the concerns that served as motivation for Gallagher & Coon's proposal. However, their proposal may be relevant for further elaboration of the articulatory-based model of consonant harmony, particularly if the analysis is to be extended to include a full spectrum of adult consonant harmony processes. This possibility is left as a topic for future investigation.

5.2 Modeling child consonant harmony as correspondence

While the incorporation of insights from Pouplier's articulatory account of speech errors has been expressed as a goal by Rose & Walker (2004) as well as throughout the preceding discussion, formal integration of these factors has yet to be fully achieved. As noted above, Pouplier's oscillator entrainment analysis does not extend straightforwardly to consonant harmony between onsets and codas, which is attested in adult phonologies as well as in child harmony processes. The onset-coda interaction fails to fill the posited function of optimizing the ratio of gestures in the oscillatory movement of speech. Furthermore, speech errors affecting onsets and codas are effectively unattested in the literature. Thus, although Rose & Walker cite Pouplier's articulatory findings, the primary motivation for consonant harmony in their correspondence approach must be derived from Dell's processing model. While these processing factors are incorporated into the present model as well, a simple activation/competition model does not suffice to account for child consonant harmony in light of the results presented in the previous section. In Dell's spreading-activation model, multiple segments enter into competition with one another, but the output of this competition can only be a single, well-formed segment. Pouplier and colleagues have criticized activation/competition models of speech errors on this basis, since instrumental analysis has demonstrated that many speech errors have a gradient,

nonphonemic character. The covert contrast reported in Section 4 revealed that child consonant harmony can also have a gradient character, which was speculated to be the consequence of intrusive gestures as proposed by Pouplier. Thus, a complete model of child consonant harmony would appear to require a combination of processing and articulatory factors.

Here it will be argued that consonant harmony serves to simplify the process of speech-motor planning by favoring simultaneous rather than sequential activation of gestures in the plan for an utterance. In contrast with Dell and colleagues' assumption that segments in an output form must be activated in strict linear succession, articulatory gestures are free to overlap with each other. Insights from Articulatory Phonology (Browman & Goldstein, 1992) will play an important role in this analysis, but the full formalism of that framework will not be adopted here. In particular, it will be necessary to maintain some notion of the segment, or at least of the timing slot in which a collection of features co-occur, which lacks independent status in Articulatory Phonology. It would not be impossible to frame the present analysis using features in an autosegmental model rather than gestures. However, the use of gestures captures the fundamentally articulatory basis of the process. It also allows us to draw on other articulatory properties that will be of relevance for modeling child consonant harmony, such as the bias favoring gestural intrusion over deletion of gestures (Pouplier, 2003; Goldstein et al., 2007).

We begin the analysis with a review of the combined processing and articulatory factors that contribute to a child's process of consonant harmony. It will be assumed that at the level of motor planning, the gestures to be executed in a given utterance are represented in an output buffer with some degree of anticipatory activation. To execute a series of gestures in the correct linear order, it is necessary to activate one gesture at a time while inhibiting all later gestures. This can be presumed to pose a challenge for the child speaker, who does not possess a particularly developed capacity for inhibition. Kent (1983) made particular note of child speakers' tendency to execute multiple gestures simultaneously in what he termed the "everything moves at once principle" (p.70). For example, the child who produced [^{m}bõ] for the target word *pen* (Ferguson & Farwell, 1975) conforms to the everything-moves principle by executing the velar-lowering gesture in near synchrony with the labial gesture.[31] The difficulty posed by serial ordering of gestures is particularly acute at the beginning of an utterance, when the target gesture for the first timing slot faces substantial competition from subsequent gestures with a comparable degree of activation. This can lead to simultaneous execution of both gestures at the start of an utterance.

Thus far, we have identified motor planning challenges that might be expected to give rise to speech errors in child productions. To capture the systematic nature of consonant harmony, it will be necessary to encode these pressures as part of a grammatical process. With adjustments to reflect the articulatory motivation underlying the process, the desired formalization can be accomplished by adopting the formalism of agreement by correspondence, which has been used to model adult processes of consonant harmony. (19) restates a constraint from Rose & Walker's IDENT-Corr family, updated to reflect the hypothesis that agreement requires gestural rather than featural identity. As framed below, IDENT-CC(place) militates for segments in correspondence to agree with respect to the presence of a gesture targeting a particular constriction location.

[31] Note, however, that our present focus will be restricted to interactions among place of articulation gestures. Thus, examples like this one, in which place interacts with nasal or laryngeal features, will largely be left for future consideration.

(19) IDENT-CC(place): Let C_i be a segment in the output and C_j be any correspondent of C_i in the output. If C_i contains a gesture with constriction location α, then C_L contains a gesture with constriction location α.

To encode the regressive directional bias observed in child consonant harmony, we can invoke a directional IDENT-C_RC_L constraint like that posited by Rose & Walker, with modifications to reflect gestures as opposed to features as the means of achieving assimilation (20). Recall that the regressive bias stems directly from processing pressures (Dell, Burger, & Svec, 1997) which are highly relevant to the present model of harmony as the consequence of motor planning pressures. Recall that in the spreading-activation model, upcoming targets all receive some degree of anticipatory activation, whereas past targets are suppressed. In the same way, a gestural target associated with a timing slot early in the word will be deactivated after that slot passes, posing a lesser degree of competition for an articulatory target later in the word. Note that suppression of a target is based on the lexical representation, with the result that the child does not incorrectly suppress an upcoming gestural target even if it was executed as an intrusive gesture earlier in the utterance. As formulated in (20), IDENT-C_RC_L is satisfied by an intrusive gesture at the left edge of the word, whether the target gesture is realized or reduced.

(20) IDENT-C_RC_L(place): Let C_L be a segment in the output and C_R be any correspondent of C_L such that C_R follows C_L in the sequence of segments in the output (R>L). If C_R contains a gesture with constriction location α, then C_L contains a gesture with constriction location α.

While the formulation of IDENT-C_RC_L(place) seen in (20) accommodates the case where consonant harmony is realized with an intrusive gesture, it does not guarantee this outcome. Additional factors will need to be invoked to ensure that child consonant harmony involves gestural intrusion rather than complete segment-level replacement.[32] A ready solution is presented by the intrusion bias for speech errors that was described previously. Recall that a preference to insert additional material instead of deleting existing content has been documented both in impressionistic transcription of speech errors (Stemberger & Treiman, 1986) and in articulatory studies (Pouplier, 2003, 2008; Goldstein et al., 2007). To reflect the articulatory motivation for this process, here input-output faithfulness constraints will be formulated as MAX-Gesture and DEP-Gesture. The intrusion bias documented in speech error studies can be encoded on the assumption that the weight assigned to MAX-Gesture is uniformly higher than that accorded to DEP-Gesture. These constraints are stated in (21)-(22).

(21) MAX-Gesture: Every gesture in the input has a corresponding gesture in the output.

(22) DEP-Gesture: Every gesture in the output has a corresponding gesture in the input.

While we have proposed an update to the IDENT-Corr family of constraints to reflect the gestural basis of the proposed agreement process, we have not yet addressed any modifications that may be needed for the set of correspondence-establishing constraints themselves. In fact, the

[32] If complete replacement were a possible outcome, we would expect to find cases in which a coronal trigger supplants a non-coronal undergoer, yet cases of coronal-trigger harmony are unattested at least in English child data.

definition of correspondence will remain unchanged in the gestural account, but the standard of similarity by which segments enter into correspondence with one another can be revised. Recall that in Rose & Walker's model, segments enter into a correspondence relationship by virtue of shared features. However, on the hypothesis that agreement by correspondence involves gestures rather than features, we can consider adopting a more directly articulatory standard of similarity involving the properties of gestures. In Articulatory Phonology, gestures are specified by articulator (e.g. lips, tongue tip, or tongue blade), constriction degree (e.g. closed, critical, narrow/mid/wide), and constriction location (e.g. labial, dental, alveolar, postalveolar, etc.). For our purposes, the vocal tract variables of articulator and constriction degree will play the most active role in defining articulatory similarity. Laryngeal features and nasality, which are specified on separate tiers in articulatory phonology, are expected to play a smaller role in the determination of similarity than features of immediate relevance for oral place gestures. These features will not be included in the preliminary model of child consonant harmony to be offered below. However, it will be necessary to incorporate specifications on other tiers if the articulatory model of correspondence is to encompass adult harmony processes, where these features do appear to factor into the computation of similarity. The articulatory definition of similarity will be explored in greater detail in Section 7. Below, (23) presents an abbreviated hierarchy of gesturally-defined correspondence constraints. The lower-ranked correspondence relationship holds over any two gestures specified for the constriction degree [close], that is, any two stops. The higher-ranked correspondence constraint represents a point of departure from the formalism of articulatory phonology. While [lips], [tongue tip], [tongue blade] etc. all have equivalent status as specifications of the active articulator, here it will be assumed that active articulators sharing a single anatomical structure (namely, tongue tip and tongue body) are viewed as more closely related from an articulatory perspective than articulators that are anatomically separate. This will allow us to model the divergent behavior of labial place as a participant in consonant harmony, to be discussed in detail in Section 5.3.

(23) CORR-T↔K >> CORR-P↔K
"both stops with a shared major articulator" "both stops"

A small number of additional constraints will be needed to complete the model of child consonant harmony. To reflect differences in perceptual salience across different gestural intrusions, we can include the perceptually oriented faithfulness constraint IDENT-PLACE(percept). This constraint, repeated in (24), was previously invoked as part of the discussion of velar fronting in Chapter 4. This constraint penalizes changes that are perceptually apparent to the listener, such as intrusion of velar place during coronal articulation, but not covert changes such as coronal intrusion during a velar gesture.

(24) IDENT-PLACE(percept): A segment that is [α place] in the input is associated with the perceptual correlates of [α place].

Finally, on the hypothesis that child consonant harmony involves gestural intrusion, our model will require a constraint pertaining to the production of complex stops (i.e. simultaneous constriction at multiple places of articulation). This constraint, HAVE-ONE-PLACE, is presented in (25).

(25) HAVE-ONE-PLACE: A stop consonant is produced with no more than one point of constriction of the oral articulators.

Here it will be necessary to be explicit about the differences between consonant harmony and velar fronting. In cases of consonant harmony between coronal and velar gestures, consonant harmony and velar fronting would appear to converge on a similar articulatory outcome involving simultaneous closure in coronal and velar regions. However, HAVE-ONE-PLACE was not invoked in the analysis of velar fronting in Chapter 4, reflecting the difference between a single undifferentiated constriction in that case versus multiple points of constriction in the present phenomenon. Unlike velar fronting, consonant harmony does not involve a context-free preference for undifferentiated coronal and velar closure; simultaneous closure is specific to contexts where coronal and velar gestures are specified within a single syllable. (Recall that subject J maintained a significant acoustic distinction between an underlying velar in the context of a velar coda consonant versus an underlying coronal target in the context of a velar coda consonant.) Because a child like J exhibits the capacity to produce discrete lingual gestures, MOVE-AS-UNIT must be outweighed by one or more other constraints. These might include IDENT-place or *$\text{EFFORT}_{\text{mand}}$, which penalizes movements of the heavy mandibular articulator and thus disprefers any articulatory pattern that uses jaw movement where tongue movement would suffice. Importantly, partial suppression of the effects of MOVE-AS-UNIT does not entail that this constraint has been rendered completely inactive in the grammar of such children. A telling example can be drawn from the results reported by Edwards, Fourakis, Beckman, & Fox (1999), discussed previously in Chapters 3 and 4. Edwards et al. demonstrated that typically developing four-year-olds who produced velar targets in a roughly adultlike fashion could still be seen to recruit the tongue-jaw complex in a more ballistic gesture for the production of coronal stop targets. Recall that the use of undifferentiated lingual contact to produce velar targets results in a substantial violation of IDENT-place, while a coronal target produced with undifferentiated contact incurs only a minimal violation of perceptually-oriented faithfulness. This suggests that MOVE-AS-UNIT effects continue to manifest themselves in contexts where faithfulness constraints exert relatively less pressure. Residual effects of MOVE-AS-UNIT will be invoked as part of the discussion of the elimination of major place harmony in the transition to adult grammars, to be seen in Section 6.2.

The differing perceptual consequences of simultaneous coronal and velar closure in velar fronting and consonant harmony can be attributed to different sequencing of release gestures across the two contexts. These sequencing differences, in turn, reflect the distinct motivations underlying the two processes. In velar fronting, it was argued that the rotational component of jaw movement causes the posterior tongue to contact the palate in advance of the tongue tip, a sequencing that is specific to the case in which the tongue rides passively on an active mandible. With coronal closure initiated late in the course of the rolling posterior-to-anterior movement of linguopalatal contact, the coronal release will be phased at the tail end of the total duration of the gesture, with the result that the listener detects perceptual cues to coronal place. In the case of consonant harmony, which is driven by factors at the level of processing rather than motor execution, the pressure to simplify the motor plan favors simultaneous initiation of both gestures ("everything moves at once"). This will give rise to the typical pattern in which the offset of the more rapid coronal gesture precedes the offset of the velar gesture. This difference in gestural phasing accounts for the fact that the undifferentiated lingual gestures in velar fronting is

systematically perceived to have coronal place, whereas simultaneous points of coronal and velar closure in consonant harmony are associated with the percept of velar place.

In summary, here it was proposed that the correspondence analysis of consonant harmony can be updated to reflect motor planning pressures that give rise to simultaneous execution of competing articulatory gestures at the start of an utterance. In this model, consonant harmony has functional roots in the child's need to avoid strictly ordered sequences of gestures that are similar but not identical in their articulatory properties. To simplify the task of motor planning, the child may realize two gestures simultaneously at the onset of an utterance. The preference for synchronous realization of competing gestures reflects the articulatory bias to insert rather than delete gestural content. Finally, the preferred regressive directionality of consonant harmony reflects the fact that motor planning becomes simpler over the course of an utterance as previously executed targets are suppressed. The following sections illustrate the implementation of the proposed constraints in a schematic representation of processes in child consonant harmony.

5.2.1 Implementation of correspondence constraints: Regressive assimilation

We can begin by modeling the most canonical type of consonant harmony, where assimilation is strictly regressive and proceeds from a velar trigger to a coronal target. Weights for all of the constraints described in the previous section are proposed in Table 11. Recalling that children produce both anticipatory and perseveratory sequencing errors with substantially greater frequency than adults, we can assume that motor planning poses a particular challenge for young speakers. The CORR-T↔K constraint, whose weight effectively dictates how similar two stop targets must be to enter into competition with one another, is accordingly assigned a high weight. Note, however, that in subsequent sections additional factors will be seen to contribute to the qualitative contrast between child and adult harmony processes, whereby only the former permits major place harmony. The next highest weight is assigned to MAX-Gesture; in accordance with the articulatory-based anti-deletion bias, MAX-Gesture is weighted more heavily than DEP-Gesture. The directional constraint IDENT-C_RC_L(place) also receives a substantial weight. Minimal weights are assigned to the general constraint IDENT-CC(place), which will play an active role only in the context of progressive harmony, to HAVE-ONE-PLACE, and to IDENT-PLACE(percept).

Table 11. Specification of constraint weightings for regressive harmony

Constraint Name	**Weight**
CORR-T↔K	3
MAX-Gesture	2.5
IDENT-C_RC_L(place)	2
IDENT-CC(place)	.5
DEP-Gesture	.5
HAVE-ONE-PLACE	.5
IDENT-PLACE(percept)	.5

In Table 12, the proposed constraints and weights are implemented for the target word "duck." In the first candidate, distinct subscripts on the onset and coda consonants indicate that they do not stand in a correspondence relation to one another and are not subject to the IDENT-

CC constraints. Because the heavily-weighted CORR-T↔K violation will prevent this candidate from emerging as a winner, in all other candidates the onset and coda consonants are in correspondence, marked by identical subscripts. Joined symbols, e.g. [g͡d] and [k͡t], are used to represent lingual consonants produced with simultaneous coronal and velar closure.

Table 12. Modeling regressive coronal-to-velar harmony with covert contrast

/dʌ k/, "duck"	CORR-T↔K	MAX-Gest	IDENT-C_RC_L (place)	IDENT-CC (place)	DEP-Gest	IDENT-PLACE (percept)	HAVE-ONE-PLACE	**SUM**
	3	2.5	2	.5	.5	.5	.5	
a. d_xʌ k_y	3	0	0	0	0	0	0	**3**
b. d_xʌ k_x	0	0	1	2	0	0	0	**3**
c. d_xʌ t_x	0	1	0	0	1	1	0	**3.5**
d. g_xʌ k_x	0	1	0	0	1	1	0	**3.5**
e. ☞ g͡d$_x$ʌ k_x	0	0	0	1	1	1	1	**2**
f. g͡d$_x$ʌ k͡t$_x$	0	0	0	0	2	1	2	**2.5**

The winning candidate in Table 12 is [g͡dʌ k] (e), where the onset consonant involves coproduction of the coronal target gesture and an intrusive velar gesture. This satisfies the directional IDENT-C_RC_L constraint with minimal violation of input-output faith—namely, without deletion of gestural content. In accordance with Pouplier & Goldstein's (2005) characterization of listeners' perception of coarticulated coronal and dorsal gestures, it is presumed that listeners would perceive and transcribe the winning candidate as [gʌ k]. One violation of the perceptually-oriented faithfulness constraint IDENT-PLACE (percept) is thus incurred; however, the low weight assigned to this constraint prevents it from impacting the outcome of the comparison of candidates.

Table 13 depicts the same system in a context for progressive harmony ("cut"). Since we have proposed to model a stage in which consonant harmony is exclusively regressive, we do not expect a harmonized form to win out in this comparison. Indeed, the progressive harmony candidate (*[kʌ k]) does not emerge as a winner in Table 7, but neither does the unassimilated candidate (*[kʌ t]). Instead, the winning candidate is [k͡tʌ t] (e), reflecting intrusion of the coronal gesture from coda to onset position. This is precisely the same outcome we saw for velar-to-coronal harmony in Table 12. The crucial difference is that in this case, the coarticulated consonant should not be perceived to deviate from its target velar place (Pouplier & Goldstein, 2005), and no violation of IDENT-PLACE (percept) is incurred. The present model thus derives the asymmetric behavior of coronal and velar place directly from the perceptual properties of coarticulated velar and coronal closures, without invoking markedness or faithfulness constraints targeting specific places of articulation.

Table 13. Modeling regressive velar-to-coronal harmony with covert contrast

/kʌ t/, "cut"	CORR-T↔K	MAX-Gest	IDENT-C_RC_L (place)	IDENT-CC (place)	DEP-Gest	IDENT-PLACE (percept)	HAVE-ONE-PLACE	**SUM**
	3	2.5	2	.5	.5	.5	.5	
a. k_xʌ t_y	1	0	0	0	0	0	0	**3**
b. k_xʌ t_x	0	0	1	2	0	0	0	**3**
c. k_xʌ k_x	0	1	0	0	1	1	0	**3.5**
d. t_xʌ t_x	0	1	0	0	1	1	0	**3.5**
e. ☞ $\widehat{kt}_x$ʌ t_x	0	0	0	1	1	0	1	**1.5**
f. $\widehat{kt}_x$ʌ $\widehat{kt}_x$	0	0	0	0	2	1	2	**2.5**

Note that while the experimental results presented in Section 4 support the hypothesis that child consonant harmony involves simultaneous production of target and intrusive gestures, the possibility of an intrusive coronal gesture during velar target production was not directly investigated. To substantiate the outcome posited in Table 13, it will be necessary to compare near-minimal word pairs in which a word-initial velar occurs with following coronal and velar segments (e.g. *guddle* versus *guggen*). On the analysis pursued here, a child with an active process of consonant harmony should produce *guddle* with coarticulated coronal and velar gestures, while *guggle* should involve only a velar gesture. This covert contrast should be detectable by comparison of acoustic or articulatory measurements.

5.2.2 Implementation of correspondence constraints: Bidirectional assimilation

The constraint weights listed above can be modified to capture an earlier stage of development in which consonant harmony applies fairly freely, operating in both regressive and progressive directions. In this case, equally high weights are granted to the directional constraints IDENT-C_RC_L(place) and CORR-T↔K. The general constraint IDENT-CC(place) also receives a substantial weight, opening the possibility of progressive as well as regressive harmony. The weights assigned to MAX-Gesture, DEP-Gesture, HAVE-ONE-PLACE, and IDENT-PLACE(percept) remain unchanged in this model. The updated weights are represented in Table 14.

Table 14. Specification of constraint weightings for regressive and progressive harmony

Constraint Name	**Weight**
CORR-T↔K	3
IDENT-C_RC_L(place)	3
MAX-Gesture	2.5
IDENT-CC(place)	2
DEP-Gesture	.5
HAVE-ONE-PLACE	.5
IDENT-PLACE(percept)	.5.

These weights are implemented in the tableaux that follow. To test this system's ability to deal with progressive harmony, we begin with the target "cut." Table 15 shows that a form characterized by assimilation in the progressive direction, candidate (f), does emerge as the most harmonic under the proposed set of weightings. Given our assumptions regarding the perceptual consequences of overlapping velar and coronal gestures, listeners are predicted to transcribe the winning candidate as [kʌ k]. It thus incurs only a single violation of perceptually-oriented faithfulness. Note, however, that the winning candidate in this case involves coarticulated production in both onset and coda positions. In fact, with the weightings assumed here, intrusive gestures at both edges of the syllable are predicted even in a target not conventionally regarded as a context for progressive harmony, as in the case of "duck," depicted in Table 16. In effect, this model indicates that harmony in the progressive direction occurs only in an early stage that requires total identity between corresponding consonants. The suggestion that consonant harmony in the progressive direction is a phenomenon qualitatively distinct from regressive harmony echoes previous analyses by Goad (2004) and Fikkert, Levelt, & van de Weijer (to appear).

Table 15. Modeling progressive coronal-to-velar harmony

/kʌ t/, "cut"	CORR-T↔K	IDENT-C_RC_L (place)	MAX-Gest	IDENT-CC (place)	DEP-Gest	IDENT-PLACE (percept)	HAVE-ONE-PLACE	**SUM**
	3	3	2.5	2	.5	.5	.5	
a. k_xʌ t_y	1	0	0	0	0	0	0	**3**
b. k_xʌ t_x	0	1	0	2	0	0	0	**7**
c. k_xʌ k_x	0	0	1	0	1	1	0	**3.5**
d. t_xʌ t_x	0	0	1	0	1	1	0	**3.5**
e. $\widehat{kt}_x$ʌ t_x	0	0	0	1	1	0	1	**3**
f. ☞ $\widehat{kt}_x$ʌ $\widehat{kt}_x$	0	0	0	0	2	1	2	**2.5**

Table 16. Modeling progressive velar-to-coronal harmony

/dʌ k/, "duck"	CORR-T↔K	IDENT-C_RC_L (place)	MAX-Gest	IDENT-CC (place)	DEP-Gest	IDENT-PLACE (percept)	HAVE-ONE-PLACE	**SUM**
	4	3	2.5	2	.5	.5	.5	
a. d_xʌ k_y	1	0	0	0	0	0	0	**4**
b. d_xʌ k_x	0	1	0	2	0	0	0	**7**
c. d_xʌ t_x	0	0	1	0	1	1	0	**3.5**

d. $g_x \wedge k_x$	0	0	1	0	1	1	0	**3.5**
e. $\widehat{gd}_x \wedge k_x$	0	0	0	1	1	1	1	**3.5**
f. ☞ $\widehat{gd}_x \wedge \widehat{kt}_x$	0	0	0	0	2	1	2	**2.5**

5.3 Extending the account to labial consonant harmony

While the previous section addressed only the canonical case in which coronal and velar place appear as participants in consonant harmony, here the account will be extended to cover harmony involving a labial trigger or target. Recall that labial consonants assimilate to velar triggers in some children with consonant harmony, but for other children, only coronals appear as the target of harmony. Likewise, in some children coronal targets assimilate to labial triggers, but this process tends to be eliminated at an earlier stage than assimilation of a coronal target to a velar trigger. One possible means of accounting for this difference would involve dividing the constraints IDENT-C_RC_L and IDENT-CC into a family of constraints that specifically reference a particular place of articulation. However, in the previous analysis a unified IDENT-CC(place) constraint was preferred on the grounds that the asymmetric behavior of velar and coronal place follows directly from the perceptual properties of simultaneous velar and coronal closures. Because the duration of the labial gesture is intermediate between the rapid coronal and slow velar gestures, it is reasonable to suppose that overlapped coronal and labial gestures would tend to be perceived as labial, but with lower consistency than the more dramatic velar-coronal overlap (Byrd, 1992). Likewise, an intrusive velar gesture might tend to override the percept of a coproduced labial gesture, but with potentially lower consistency than it dominates the percept of a coronal target.[33] This would lead to a greater frequency of tokens in which the underlying target gesture was perceptually evident despite the presence of the harmonizing gesture, for either coronal-to-labial or labial-to-velar assimilation. On the other hand, Jun (1996) reported that listeners perceived both labial and velar components of overlapped /pk/ clusters unless the magnitude of the labial gesture was reduced in magnitude. Since Jun's stimuli were intervocalic, it remains unclear what perceptual consequence should be expected if gestural coproduction were to occur in a word-initial context.

While the perceptual consequences of overlapping labial and velar gestures remain a topic for further investigation, the articulatory model of correspondence pursued here offers another possible explanation for the less robust participation of labial place in harmony with coronal or velar gestures. Above, it was posited that gestures that activate a single articulatory structure, namely the tongue, should be viewed as more similar to one another than a gesture that affects an anatomically separate articulator, the lips. While studies of both speech errors and adult consonant harmony have demonstrated that correspondence relations are more likely to be established between highly similar targets relative to less similar targets, this phenomenon has yet to be documented in the context of child consonant harmony. On the present analysis, the contrast between labial harmony and velar-coronal harmony provides the first indication that

[33] If harmony in which a labial target assimilates to a velar trigger does indeed involve coproduced velar and labial gestures, the labial component of the closure should be detectable visually. To my knowledge, studies of child consonant harmony involving visual inspection or instrumental measurements of articulation have yet to be conducted.

child consonant harmony too is subject to a similarity effect. In Table 17, the weight assigned to the correspondence constraint CORR-P↔K, which applies to any two stops, is lower than that previously assigned to CORR-T↔K, which applies to lingual stops. Other weightings are left as they were in Table 11, which modeled regressive assimilation from a velar to a coronal.

Table 17. Specification of constraint weightings for labial harmony

Constraint Name	**Weight**
MAX-Gesture	2.5
IDENT-C_RC_L(place)	2
CORR-P↔K	1
IDENT-CC(place)	.5
DEP-Gesture	.5
HAVE-ONE-PLACE	.5
IDENT-PLACE (percept)	.5

Table 18 implements the adjusted weightings in a context for regressive harmony from a velar trigger to a labial target, "pick." This tableau demonstrates that with a sufficiently low weight assigned to CORR-P↔K, the candidate with no correspondence between consonant targets ([p_x I k_y]) emerges as the winner. Crucially, this allows a PVK target word to emerge with faithful place at the same time a TVK target word (e.g. "duck") undergoes regressive consonant harmony. This approach allows us to model differences in the application of consonant harmony for labial versus lingual targets. It also supports the prediction that child consonant harmony, like other types of agreement by correspondence, should apply more robustly in the context of more similar segments.

Table 18. Modeling regressive labial-to-velar harmony with covert contrast

/p I k/, "pick"	MAX-Gest	IDENT-C_RC_L (place)	CORR-P↔K	IDENT-CC (place)	DEP-Gest	IDENT-PLACE (percept)	HAVE-ONE-PLACE	**SUM**
	2.5	2	1	.5	.5	.5	.5	
a. ☞ p_x I k_y	0	0	1	0	0	0	0	**1**
b. p_x I k_x	0	1	0	2	0	0	0	**3**
c. p_x I p_x	1	0	0	0	1	1	0	**3.5**
d. k_x I k_x	1	0	0	0	1	1	0	**3.5**
e. $\widehat{kp}_x$ I k_x	0	0	0	1	1	1	1	**2**
f. $\widehat{kp}_x$ □ $\widehat{kp}_x$	0	0	0	0	2	2	2	**3**

6. On the maturational elimination of major place harmony

While the shared properties of consonant harmony processes across child and adult speakers make it desirable to model these two with common formalism, it also is essential to account for fundamental differences between harmony processes in children and adults. While consonant harmony affecting major place features is regularly reported in child speakers, it is systematically absent from adult processes of consonant harmony. In this section, it will be argued that articulatory factors predict the elimination of major place harmony in the typical course of motor maturation. The first section will offer evidence that repetition of identical gestures is favored in child speech, a general preference that extends outside of the specific context of consonant harmony. The following section will review evidence that this preference is not active in adult phonologies; in fact, adult languages actively disprefer reduplicated sequences relative to alternating sequences. Note that this reversal of the child preference cannot be captured simply by lowering the weight of the scale of CORR-CC constraints: lowering the weight of CORR-CC such that consonants that differ by major place feature no longer enter into correspondence with one another would predict *chance* rather than *below-chance* occurrence of homorganic sequences. Thus, some additional mechanism will need to be incorporated to explain the discrepant behavior of child and adult speakers. In Section 6.3, it will be argued that this contrast is rooted in articulatory factors, namely the child speaker's limited ability to take advantage of the opportunities for anticipatory coarticulation that adult speakers exploit in the production of alternating but not repetitive sequences.

6.1 Child preference for repetition

There is considerable evidence that in the speech of young children, repetitive production of identical segments is preferred over alternating production of distinct targets. Pater (1997) initially analyzed consonant harmony as the consequence of a constraint REPEAT ("Successive consonants must agree in place specification"), although this constraint was eliminated from his later analyses. His invocation of a repetition-favoring constraint was based on the assessment that "It seems likely that for children at an early stage of development, there is an advantage to gestural repetition at some level of speech production" (p. 235). We previously encountered the child speaker's preference for repetition in Chapter 2, where it was posited that infants babble by setting the tongue in a fixed configuration, then alternating between open and closed cycles in a simple mandibular oscillation (MacNeilage & Davis, 1990; Fletcher, 1992; MacNeilage & Davis, 1995). Redford, MacNeilage & Davis (1997) extended the frame-dominance hypothesis to cover CVC syllables in babbling and first words, predicting that these should feature identical onset and coda consonants separated by a vowel with compatible place features. In their assessment, C1 and C2 were found to share a single place of articulation over 75% of the time, and the intervening vowel also shared features with greater than chance frequency.

Kent (1992) suggested that the repetitive nature of young infants' babbling should be viewed as one instance of a more general phenomenon of repetitive movement patterns in the early stages of motor control. He points out that infants' predilection for rhythmic, repetitive gross motor movements (e.g. kicking, banging) peaks between 6 and 9 months of age, the same time that typically developing children extensively produce repetitive sequences in canonical babbling (Stark, 1979; Elbers, 1982; Mitchell & Kent, 1990). Over the course of motor maturation, repetitive production of identical gestures ceases to be obligatory, with Fletcher

(1992) noting that the capacity to shift back and forth between alternating articulatory postures constitutes a major milestone in the development of speech-motor control.

Even after children emerge from the babbling stage, however, they continue to show signs of their early preference for gestural repetition. For present purposes, it is important to consider cases in which the intervening vowel does not carry the same point of constriction as the surrounding consonants, since vowel place is not always constrained in child consonant harmony. In fact, the child preference for reduplication continues to be documented well after vowels take on a differentiated place of articulation. The forms in (26), drawn from the productions of a typically developing 19-month-old child, show that reduplication can apply across a variety of vowel contexts (Kilpatrick, Barlow, & Cragg, 2007).

(26) Reduplicated wordforms demonstrating independence of consonant and vowel place

a.	[bɛ bɛ]	'bread'
b.	[bʊ bʊ]	'book'
c.	[baba]	'ball'

This section has demonstrated that repetitive production of identical place gestures is broadly preferred in child speech. This preference emerges in contexts other than consonant harmony as conventionally defined, and it is not limited to cases where the intervening vowel shares its place of articulation with consonants on either side. In the following section, this finding will be juxtaposed with evidence that sequences of identical consonants are actively dispreferred in adult phonologies, reversing the child preference.

6.2 Adult avoidance of repetition

Repetitive production of identical gestures in child speech is widely regarded as a means of limiting the articulatory complexity of an utterance (Dressler, Dziubalska-Kolaczyk, Gagarina, Kilani-Schoch, 2005). Since adult phonologies are also known to favor processes that minimize articulatory effort, it is surprising to find that adult languages express the reverse preference, actively dispreferring homorganic consonant sequences. Avoidance of similar segments in adult phonology has been documented extensively in connection with the phenomenon of the Obligatory Contour Principle, or OCP (Goldsmith, 1979). The canonical example of OCP effects is provided by the underrepresentation of segments with homorganic place in Arabic triconsonantal roots (McCarthy, 1986, 1994). Pierrehumbert (1993) and Frisch, Pierrehumbert, & Broe (2004) demonstrated that the coocurrence restrictions in Arabic are gradient, mediated by similarity effects and the presence of intervening segments. Gradient similarity avoidance effects have also been identified in English (Berkley, 2000). Having identified some degree of similarity avoidance in each of eight languages sampled, Pozdniakov and Segerer (2007) have argued that a dispreference for homorganic consonant sequences can be regarded as a cross-linguistic universal. Frisch (2004) proposed that OCP effects can be understood as the consequence of competition between similar segments in a spreading activation model of psycholinguistic processing. Frisch's approach played a role in shaping the present analysis of consonant harmony, which shares the notion that similar but non-identical segments present increased difficulty for the processor. However, there is no reason to believe that fully identical segments give rise to processing difficulty, since activation of the wrong target in such a case will be without repercussions for either the speaker or the listener. Instead, the analysis to follow will endorse the notion that the difficulty posed by sequences of identical consonants is articulatory in

nature (Walter, 2007; Rochet-Capellan & Schwartz, 2005). It will further be demonstrated that the articulatory discrepancy between reduplicated and variegated sequences is specific to the context of mature articulation, where anticipatory coarticulation facilitates the production of series of alternating place. Because child speakers have an intrinsically limited capacity for this type of effort-minimizing coarticulation, repetitive and alternating sequences have an equivalent status in child articulation.

An articulatory account of the avoidance of reduplicated consonant sequences, the Biomechanical Repetition Avoidance Hypothesis, was proposed by Walter (2007). She argued that gestural repetition is dispreferred relative to production of heterorganic sequences because it is more costly in terms of articulatory effort. This elevated cost is attributed to several factors, including the need for rapid reversal of the articulatory trajectory, the absence of a rest interval for participating muscles, and the unavailability of any period of overlapping coarticulation between adjacent gestures. This last factor will be of greatest interest for present purposes. Walter points out that in an alternating series of consonant gestures, the second gesture begins to move towards its target before the first gesture is complete. When identical gestures are used in succession, however, "the onset of the second gesture necessarily entails that the offset of the first is entirely completed (or as completed as it is going to be). This means that a given span of milliseconds cannot 'count double' as the offset and onset of two identical gestures" (p. 35). Thus, the production of repetitive consonant sequences is less efficient than production of alternating sequences, which allow for anticipatory coarticulation. Walter substantiated her claim with evidence that vowels between identical consonant gestures are longer in duration than vowels between heterorganic targets.

Similar conclusions were drawn by Rochet-Capellan & Schwartz (2005), who used a reiterant speech task to comment on the motivation for repetition avoidance in adult languages. They reported that at slow rates of speech, speakers produce one CV syllable per jaw cycle, but at faster rates, they can undergo a phase transition such that an entire CVCV disyllable is produced in a single jaw cycle. However, the association of multiple syllables to a single jaw cycle was exclusive to cases where the second consonant gesture could be anticipated during production of the first consonant, as in the case of a coronal following a labial ([pata]). When the target disyllable featured reduplicated sequences of identical place (e.g. [papa]), the transition from one to two syllables per jaw cycle was blocked, a reflection of the unavailability of anticipatory coarticulation in successive activations of the same gesture. Since reducing the number of mandibular cycles clearly tends to limit the expenditure of articulatory effort, Rochet-Capellan & Schwartz concluded that avoidance of reduplicated forms in adult languages is a reflection of economy of energy, since "alternating movement of two different articulators allows the attainment of fast rate production with little energy consumption" (p. 4).

The finding that reduplicated consonant sequences are less energy-efficient than alternating sequences provides an articulatory motivation for adult phonologies' avoidance of major place harmony. While this effort-based avoidance of reduplicated gestures may be associated with a specific markedness constraint disfavoring repetition, for present purposes it can be subsumed under the constraint *EFFORT$_{mand}$ ("Minimize the velocity of the mandibular articulator"), which was invoked in previous chapters. *EFFORT$_{mand}$ militates for economy in movements of the mandible, leading the adult speaker to favor coarticulated productions that minimize the number and/or magnitude of jaw gestures. In adult languages, *EFFORT$_{mand}$ has a higher weight than the constraint that establishes correspondence between stops with differing place specifications (CORR-T↔K). In this manner, considerations of articulatory effort block the emergence of major place harmony in adult phonologies. The following section will argue that

child-specific articulatory limitations erase the effort advantage that is enjoyed by candidates with alternating consonant place in mature speech, permitting motor-planning factors to emerge in the form of major place harmony.

Before we proceed to the discussion of child consonant harmony, however, it should be noted that the processing factors that cause gestures to enter into correspondence relations are still underlyingly present in adult phonology, and they can be expected to surface when the action of *EFFORT$_{mand}$ is neutralized by other factors. Most notably, *EFFORT$_{mand}$ is not predicted to prevent harmony for minor place features, where multiple activations of the same gesture are specified in the input. Provided that *EFFORT$_{mand}$ is ranked below input-output faithfulness (i.e., the language does not actively dissimilate homorganic sequences), all candidates under active consideration will incur identical violations of the preference against multiply activating a single articulator. This clears the way for CORR-CC and IDENT-CORR constraints to simplify the motor-planning component of the utterance by creating total identity between similar but non-identical segments, namely consonants that differ for minor place.

6.3 MOVE-AS-UNIT interacts with repetition avoidance

Above, we reviewed considerations of articulatory economy that have been posited to underlie the dispreference for repetitive sequences of identical gestures observed in adult phonologies (Rochet-Capellan & Schwartz, 2005; Walter, 2007). There is reason to believe that these factors are not relevant to the speech of young children. In keeping with the principle of mandibular dominance discussed in Chapter 2 and throughout this dissertation, we assume that a young child's tongue movements are closely tied to jaw movements. This makes it likely that the one-to-one mapping of syllables to jaw gestures will be upheld at any rate of articulation, with no possibility for a transition to the more efficient manner of production posited by Rochet-Capellan & Schwartz (2005). More generally, the capacity for anticipatory coarticulation is diminished in a child whose ability to execute independent lingual movements is limited by an active MOVE-AS-UNIT constraint. Thus, while alternating consonant place is favored in adult speech because of the effort advantage conferred by anticipatory coarticulation, this advantage is neutralized in the context of child articulation. Without an articulatory reason to prefer alternating place, other underlying pressures can emerge—namely, the motor-planning preference for reduplicated production that was detailed earlier in this chapter.

The developmental progress from the child preference for reduplication to the adult preference for variegation can be represented with the relative weights assigned to MOVE-AS-UNIT, *EFFORT$_{mand}$, and the scale of correspondence constraints. Recall that it was posited that in adult speakers, *EFFORT$_{mand}$ has a higher weight than MOVE-AS-UNIT or CORR-P↔K, the constraint enforcing correspondence between any oral stops. In fact, in previous discussion it was suggested that the weight of the latter two constraints is near zero. Through the action of high-weighted *EFFORT$_{mand}$, the adult speaker is motivated to produce consonant sequences with anticipatory coarticulation; sequences of identical gestures, which block this coarticulation and thus incur larger violations of *EFFORT$_{mand}$, are actively dispreferred. In the proposed grammar for a child with consonant harmony, the weights of both IDENT-CORR(place) and MOVE-AS-UNIT are greater than that assigned to *EFFORT$_{mand}$. (Further reflections on the status of MOVE-AS-UNIT and *EFFORT$_{mand}$ will be offered immediately below.) In such a child, an articulatory plan featuring anticipatory coarticulation will be ruled out due to its violations of MOVE-AS-UNIT. Thus, for the child speaker, a candidate with alternating place and a candidate with reduplicated place have an equivalent low availability of anticipatory coarticulation. In this case, the relative

weighting of input-output faithfulness and the correspondence constraint CORR-P↔K will determine whether the child will exhibit consonant harmony or faithful realization of alternating place. In light of the processing limitations faced by the immature speaker, the weight of CORR-P↔K can be presumed to be relatively high in child grammar, with the result that consonant harmony for major place should be predicted to emerge in some child speakers. By eliminating the articulatory advantage for alternating over reduplicated place gestures, MOVE-AS-UNIT plays a crucial role in explaining this contrast between child and adult speakers.

Let us address a few questions raised by the articulatory account of the maturational elimination of major place harmony. It was argued that MOVE-AS-UNIT plays a crucial role in allowing consonant harmony for major place to arise in child speakers. However, it will be noted that MOVE-AS-UNIT is less active in children with consonant harmony relative to other groups of child speakers under consideration in this dissertation. Unlike children who exhibit velar fronting, speakers with consonant harmony demonstrate the ability to produce initial velar targets with a discrete velar gesture as opposed to an undifferentiated lingual gesture. Above, it was posited that in children who exhibit the canonical pattern of place harmony,

A first question pertains to the fact that children who exhibit consonant harmony, unlike children with an active process of velar fronting, do have the capacity to produce discrete lingual gestures. It is thus legitimate to ask whether MOVE-AS-UNIT, having been demoted to the point where discrete lingual gestures are available, can be sufficiently active to block anticipatory coarticulation. In fact, the evidence indicates that emerging effects of MOVE-AS-UNIT can still be expected in children in whom the process has been partially suppressed. Above, we reviewed results reported by Edwards et al. (1999) suggesting that a ballistic manner of production persists longer into development for coronal than for velar targets. Here, it was suggested that this discrepancy reflected the greater violation of perceptually-oriented faithfulness that is incurred by a velar target produced with undifferentiated linguopalatal contact. Because undifferentiated place is typically perceived as coronal, there is only a small perceptual penalty when this type of closure is substituted for a coronal target. Accordingly, it was speculated that MOVE-AS-UNIT becomes inactive in child speakers as it is demoted below perceptually-oriented faithfulness. On this analysis, it is possible for MOVE-AS-UNIT to be weighted below faithfulness in a child speaker (permitting the production of discrete lingual gestures including velar place) while still carrying a higher weight than *$\text{EFFORT}_{\text{mand}}$. So long as MOVE-AS-UNIT remains competitive with $\text{EFFORT}_{\text{mand}}$, it should be possible to observe its effects in other domains, as in the blocking of anticipatory coarticulation detailed above.

This brings us to our second question. The present hypothesis regarding the maturational elimination of major place harmony rests on the assumption that anticipatory lingual coarticulation is decreased in child speech relative to adult productions. This position is supported in work by Kent and colleagues, who have argued that articulation in speakers with diminished speech-motor control has a segment-by-segment nature, characterized by "pulling apart" of the typical interval of coarticulation. Kent (1983) supported this proposal with acoustic analysis of the word *box* as produced by three four-year-old children and three adults. He found that lingual anticipation of the coda consonant during vowel production was less extensive in the children's productions relative to the adult utterances. In a similar vein, Edwards et al. (1999) demonstrated that F2 height at the point of transition from a coronal stop to a back vowel was higher in children with articulatory-phonological disorders relative to typically developing children. This was taken to indicate that the more limited speech-motor control abilities of the

children in the disordered group rendered them less capable of anticipating the upcoming vowel in their placement of the lingual closure.

However, at the same time that these investigations have documented more extensive coarticulation in more skilled speakers, other studies have supported the opposite claim, arguing that children exhibit more extensive coarticulation than adults. It is important to address these findings in order to maintain the present claim that decreased coarticulation plays a role in enabling major place harmony in child speakers. Nittrouer and colleagues have shown that sensitivity to the place of an upcoming vowel, as indicated by F2 height during fricative articulation, is greater in young child speakers relative to older children (Nittrouer & Studdert-Kennedy, 1987; Nittrouer, Studdert-Kennedy, & McGowan, 1989). These findings have been replicated across several age groups. While the discrepancy between the results reported by Kent and colleagues versus Nittrouer and colleagues are puzzling, Bates, Watson, & Scobbie (2002) have pointed out that some of this heterogeneity may reflect differing responses to different types of coarticulation in child phonology. Taking up this insight, here it is posited that non-agreeing findings on child coarticulation reflect the distinction between coarticulation in the sense of gestural coproduction and coarticulation in the sense of articulatory target undershoot. Coarticulation of the latter type is free to occur in child speech with equal or greater magnitude relative to adult productions, but the former type appears to be restricted in immature speakers. An example of this contrast was seen in the discussion of fricative gliding in Chapter 5. Recall that adults produce a fricative-vowel transition with coarticulation of the first type, lowering the jaw in anticipation of the upcoming vowel while maintaining a high tongue position to produce frication. It was argued that this type of coarticulation is blocked in a speaker like B due to an active MOVE-AS-UNIT constraint. To minimize effort without violating MOVE-AS-UNIT, the child speaker may produce a smaller gesture, falling short of the articulatory target specified by the adult model. This was the analysis adopted for B's process of fricative gliding, where the action of *$\text{EFFORT}_{\text{mand}}$ caused him to undershoot the jaw target for an initial sibilant, replacing it with a glide. Nittrouer and colleagues' finding of vowel-conditioned variation in fricative F2 height could also be understood as undershoot of fricative target place in anticipation of an upcoming vowel. While additional research will be necessary to substantiate the proposed split between types of coarticulation in child speech, the evidence is sufficient to defend the present claim of children's diminished capacity for anticipatory coarticulation as worthy of further consideration.

6.4 More interactions with MOVE-AS-UNIT: Velar fronting and consonant harmony

In addition to asking what role MOVE-AS-UNIT might play in the grammar of a child with an active process of consonant harmony, we can reflect on how consonant harmony effects might emerge in children for whom MOVE-AS-UNIT is sufficiently high-weighted to ban most discrete lingual gestures. Specifically, here we will return to the finding that a harmonizing environment appeared to facilitate faithful production of initial velars in case study subject B, whose velar fronting pattern was described in detail in Chapter 4.

In a child who consistently produces target word-initial velars with undifferentiated lingual place, fronting is expected to obscure the activity of CORR-T↔K and IDENT-CORR(place).[34] However, Chapter 4 presented evidence that consonant harmony contexts can be facilitative for the production of onset velars in a child with positional velar fronting. Case study

[34] However, with sufficiently high-ranked CORR-P↔K, such a child could show harmony between coronal and labial targets without exhibiting coronal-velar or labial-velar harmony. I am not aware of any reports of such systems.

subject B was found to produce velar targets in strong contexts with significantly increased accuracy when another velar was present in the word; a similar effect was noted in Chiat's (1983) case study of a child who fronted velars in strong positions. Recall that in Chapter 4, the likelihood of velar fronting was found to vary with the force of articulatory closure in a given context, with the lighter articulatory contact in prosodically weak positions facilitating faithful production of velar place. To support this analysis, it would be desirable to demonstrate that a velar onset followed by a velar coda is produced with lower gestural amplitude than a velar onset followed by a coda with a different place of articulation. In fact, this characterization recalls Walter's (2007) proposal that similarity avoidance in adult phonology is a reflection of the greater articulatory effort associated with the production of reduplicated consonant sequences. Walter suggested that this difficulty could lead to articulatory undershoot in sequences of identical consonants. This proposal was substantiated experimentally: phonetic lenition was observed with significantly greater frequency in consonants that occurred in a reduplicative sequence in a nonword production task (e.g. *ba**g**a**g**eet* versus control *ba**d**a**g**e*t). Walter also found that velar consonants were significantly more susceptible to lenition than labials, echoing Lavoie's (2000) finding that velar place is particularly susceptible to lenition cross-linguistically.

Walter's results suggest that speakers plan a lower articulatory target in reduplicated consonant sequences, a means of offsetting the extra articulatory effort required by repeated activations of identical gestures. In accordance with our discussion in Chapter 4, a lower target height is associated with a lesser violation of MOVE-AS-UNIT. Thus, it is correctly predicted that initial velars should be produced with greater accuracy when followed by one or more velar targets. However, this analysis faces a challenge from the argumentation advanced above, where it was held that the limited capacity for anticipatory coarticulation exhibited by speakers like B tends to undermine the articulatory advantage for variegated over reduplicated sequences. This suggests that a uniform degree of coarticulatory undershoot could be expected across the contexts of reduplicated and alternating sequences of gestures. In actuality, though, Walter posits additional factors that contribute to articulatory undershoot in reduplicated production. Multiple activations of a single articulator might be less efficient than alternating activations because they do not provide even a brief rest interval for the participating muscles. In addition, a rapid reversal of the articulatory trajectory—requiring that the momentum of the release gesture be offset and immediately reversed—requires greater force than a gestural alternation in which momentum shifts to a new direction. Accordingly, there is reason to believe that even children with a highly limited capacity for anticipatory coarticulation have reason to exhibit articulatory undershoot in the context of reduplicated consonant sequences.[35] Functional articulatory factors that drive coarticulatory undershoot in the production of reduplicated consonant sequences thus provide a straightforward explanation for the finding that B exhibited greater accuracy when producing a velar target in the context of another velar.

Chapter 4 also reported a significant interaction between consonant harmony environment and vowel context in B's velar production accuracy. This effect revealed that the velar accuracy advantage associated with the consonant harmony environment was greater in the context of a back vowel relative to a nonback vowel. This is consistent with the functional

[35] The reader might wonder whether we have just overturned the motivation for major place harmony in child speakers, namely the articulatory equivalence of reduplicated versus alternating consonant sequences. In fact, even with the factors cited above, major place harmony will continue to be a possibility for any child speaker in whom the *EFFORT savings associated with variegated production do not offset the cost of MOVE-AS-UNIT violation.

articulatory analysis pursued here, suggesting that target undershoot is greater when the dorsal articulator is activated not only in the two consonants but also in the intervening vowel.

7. Implications for other harmony types

The discussion thus far has focused on the phenomenon of major place harmony between oral stops. This final section will examine the predictions made for other types of harmony by the present model of consonant harmony as gestural agreement. Above, it was proposed that the similarity criterion by which segments enter into a correspondence relation with one another might be updated to reflect articulatory factors, incorporating insights from Articulatory Phonology. This section will reflect on the application of child consonant harmony between consonants that differ for the features [nasal], [voice], and [continuant]. It was noted previously that data regarding the influence of similarity on the application of consonant harmony are unfortunately scarce. Here, preliminary data collected from the Amahl corpus (Smith, 1973) will be presented. When data for the comparison in question are not available, the predictions of the current analysis are presented for the purpose of future investigation.

7.1 Nasal triggers or undergoers

Major place harmony between nasal and oral segments is not uncommon in child consonant harmony. Examples of place agreement between a nasal trigger and an oral undergoer and an oral trigger and a nasal undergoer are depicted in (27); data are drawn from the Amahl corpus (Smith, 1973).

(27) Examples of place harmony between nasal and oral consonants
a. [gɪ ŋgɔ ŋ] ‘ding-dong’
b. [ŋeɪ k] ‘snake’

To date, no systematic study appears to have investigated whether child consonant harmony is more robust in the context of two oral stops relative to two nasal stops. However, comparing the last stage in which each type of harmony is recorded in the Amahl corpus, these two processes appear to have been eliminated almost simultaneously. This suggests that the application of place harmony may be independent of the nasal feature. As it was noted above, it is not obviously the case that features on other tiers (nasal, laryngeal) should play a role in assessing the similarity of consonant place gestures.

On the other hand, Smith does note a point of contrast between the application of harmony in oral-oral and oral-nasal pairs. He states his rule for progressive assimilation from a velar trigger to a coronal target to apply only between two oral stops, as progressive velar assimilation between an oral and a nasal consonant was not attested. This contrast is illustrated in (28)-(29).

(28) Pairs of oral consonants participate in progressive place harmony
a. [gug] ‘good’
b. [bigik] ‘biscuit’

(29) Pairs differing for [nasal] do not participate in progressive place harmony

a. [gin] ‘skin’
b. [gɔ :nə] ‘corner’

This contrast provides a preliminary indication that the strength of application of child consonant harmony can be affected based on agreement or non-agreement for the feature [nasal]. Furthermore, if the articulatory model of correspondence is to be extended to account for adult harmony processes, it will be necessary to arrive at some mechanism for judging the similarity of targets based on their association with articulatory specifications on other tiers. This question is left open for future investigation.

7.2 Voicing contrast

At the present time, no data appear to be available regarding the role of voicing contrasts in determining the strength of application of child consonant harmony. Smith (1973) is uninformative on this point because Amahl consistently voiced onsets and devoiced non-sonorant codas throughout the duration of his period of active consonant harmony. Contextual voicing processes and/or perceptually unreliable contrasts are likely to pose a challenge in any effort to gather data on the role of voicing in child consonant harmony. However, since agreement for laryngeal features has been demonstrated to have an impact on the application of consonant harmony in adult phonologies, it would be worthwhile to investigate this factor in the child case as well. Here it is predicted that voicing should pattern in the same fashion as nasality in determining the strength of application of consonant harmony, since both are specified on separate tiers from the place feature that participates in the assimilation.

7.3 Fricative triggers or undergoers

If we draw on the gestural parameters set forth in Articulatory Phonology to define an articulatory standard of similarity for the correspondence relation, we make a specific prediction regarding consonant harmony between stop and fricative targets. These two classes differ with respect to the vocal tract variable of constriction degree: stops carry the specification [close], fricatives [critical]. A stop and a fricative can thus be regarded as articulatorily less similar than two stops and should therefore be less likely to enter into a correspondence relationship. However, this type of assimilation is in fact attested in the Amahl corpus (Smith, 1973). Many of these instances involve assimilation between an oral stop and a stopped fricative, as depicted in (30). However, harmony can also be observed between a stop and a fricative that preserves its fricative manner, seen in (31).

(30) Place assimilation applies to stopped fricatives
a. [geik] ‘shake’ (Stage 12)
b. [giŋiŋ] ‘singing’ (Stage 1)

(31) Place assimilation applies to faithful fricatives
a. [ɣi:k] ‘seek’ (Stage 7)
b. [ɣæk] ‘shack’ (Stage 4)

Note that the existence of harmony between continuant and noncontinuant segments is not in itself problematic for the model of correspondence adopted here. It could indeed prove a problem if this analysis were framed in the full formalism of Articulatory Phonology, where the vocal tract variable of place could not pattern as distinct from the variable of constriction degree,

since both are attributes of a single gesture. For present purposes, it will be assumed that these properties can pattern separately, and attestation of harmony between stop and fricative segments merely suggests that Amahl's phonology imposed a low threshold of similarity for segments to enter into correspondence with one another. In the case of harmony in which a coronal segment assimilates to a velar, the data provide preliminary support for the predictions of the model in which correspondence is mediated by articulatory similarity. While Smith does not comment on the relative strength of velar place harmony for fricative versus stop targets, he does report that harmony to liquids and glides was eliminated in advance of harmony to obstruents and nasals.

However, similarity-based expectations for the strength of different types of harmony are violated by Amahl's pattern of harmony between labial triggers and coronal undergoers. Smith reports that after Amahl's Stage 3, labial harmony ceased to apply to oral stops but continued to apply to coronal fricative targets. However, these targets were uniformly realized as glides, as illustrated in (32). In later stages of development, fricative-initial lexical items could sometimes be seen to alternate between stopped and glided forms; in these cases, the glide but not the stopped form exhibited harmony, as illustrated in (33).

(32) Place assimilation applies between labial consonants and glided fricatives

a. [wæp]	'sap' (Stage 4)
b. [wɛ pəd]	'shepherd' (Stage 9)

(33) Place assimilation is exclusive to glided fricatives

a. [wa:p]	'sharp' (Stage 10)
b. [da:p]/*[ba:p]	'sharp' (Stage 10)

These findings are problematic for the hypothesis that child consonant harmony is sensitive to factors of similarity: from an articulatory as well as a featural perspective, /s/and /p/ are less similar than /t/ and /p/. However, the present case clearly involves interactions between consonant harmony and other child phonological processes Note in particular that outside of the context of labial harmony, Amahl realized coronal fricatives as stops rather than glides. This led Smith to propose that labial harmony could be understood to feed a process of labial fricative gliding, which in turn blocked the application of fricative stopping. One possible explanation for these data might posit that for Amahl, the constraint enforcing correspondence between any two lingual gestures (CORR-S↔K) was weighted above HAVE-ONE-PLACE, which in turn outweighed the constraint CORR-F↔K establishing correspondence between any two consonants. Producing a glide could present a means of realizing simultaneous lingual and labial gestures without incurring a fatal violation of HAVE-ONE-PLACE. (Here it is necessary to assume that the glide transcribed as [w] was not truly labiovelar, but instead involved labial and coronal or labial and undifferentiated lingual gestures.) However, the action of IDENT-Continuant could block gliding from applying to labial stops. This analysis will not be pursued in detail as part of the present investigation; however, the data from Amahl are presented here as an illustration of the complexities that arise in efforts to model child consonant harmony, which is likely to interact with other child processes in non-obvious ways. It is clear that there is a need for further investigation of child consonant harmony in relation to the scales of similarity proposed here, with special attention to the role of any competing phonological processes.

8. Conclusion

This chapter reviewed the child pattern of consonant harmony, one of the most commonly cited examples of the asymmetries between child and adult phonologies. Adult phonologies do afford examples of long-distance consonant assimilation that are qualitatively similar to child consonant harmony, but in adults the phenomenon is much more restricted and does not induce changes in major place of articulation. The challenge is thus to capture the commonalities between child and adult harmony systems without making incorrect predictions for adult phonological typology. Here it was posited that child and adult consonant harmonies share a functional motivation rooted in the properties of speech-motor planning. Systematic similarities between consonant harmony processes and assimilatory speech errors suggest that both of these can be understood to reflect the processing difficulty associated with proximal occurrences of similar but non-identical targets. Thus, both child and adult speakers experience pressure to simplify the task of speech production by replacing similar targets with fully identical segments. The more extensive nature of assimilatory errors in child speakers was interpreted as a reflection of child-specific articulatory limitations that have already been discussed in previous chapters. Previous work has demonstrated that in adult speech, variegated consonant sequences can be produced more efficiently than reduplicated place sequences, a consequence of the availability of anticipatory coarticulation in the context of alternating place gestures. However, it was argued that the unskilled speaker's preference to move the articulators in a single unit tends to negate the effort advantage associated with anticipatory coarticulation. This accounts for the finding that child consonant harmony can affect major place of articulation, whereas adult harmony is limited largely to contexts where multiple activations of a single articulator are underlyingly specified (i.e. minor place harmony).

Here it was argued that both child and adult consonant harmony can be modeled using the formalism of agreement by correspondence (Hansson, 2001; Rose & Walker, 2004). However, modifications to this model were proposed in order to accommodate insights from the articulatory model of speech errors proposed by Pouplier and colleagues. Pouplier demonstrated that a large percentage of speech errors that are perceived as categorical substitutions actually involve simultaneous production of intrusive and target gestures. They demonstrated that simultaneous production of target coronal and intrusive velar gestures tended to be perceived as anomalous, while intrusive coronal gestures during velar target production typically were not detected. It was hypothesized that child consonant harmony also involves coproduction of target and intrusive gestures, in which case the asymmetric behavior of coronal and velar sounds as targets and triggers of harmony can be understood as the direct consequence of perceptual asymmetries. The hypothesis was supported by acoustic investigation of the productions of one child with consonant harmony, who was found to maintain covert contrast between target and harmonized velar forms. To incorporate articulatory factors into the model of agreement by correspondence, it was proposed that segments that enter into a correspondence relation are then subject to pressure to agree for the presence of an articulatory gesture. This gestural version of the IDENT-CORR type of constraint is satisfied when target and intrusive gestures are coproduced in the manner described by Pouplier. A directional variant of IDENT-CORR, reflecting a regressive bias rooted in psycholinguistic processing factors, predicts that gestural intrusion should apply preferentially at the left edge of the word. In this model, coronal and velar intrusions are equally likely to occur, but perceptual asymmetries prevent the listener from detecting intrusive coronal gestures. Harmony involving labial gestures is less robust than coronal-velar harmony because a

lower weight is assigned to the constraint militating for correspondence between consonants that do not share the same articulatory structure. This provided a preliminary indication that child consonant harmony, like adult harmony and speech error phenomena, is sensitive to the similarity of competing targets. The role of psycholinguistic and articulatory factors in predicting patterns of child consonant harmony is an area that would benefit greatly from further investigation, particularly to substantiate the claim that targets with more similar articulatory properties are subject to greater assimilatory pressure than less similar targets.

Chapter 7. Conclusion

1. Phonetically informed analysis of child-specific phonological processes

This dissertation has offered a phonetically motivated solution to the problem presented by child-specific phonological processes that lack counterparts in adult phonological typology. If the constraints governing child speech are identical to those that are active in adult speakers, we predict that every phonological process attested in child speech should emerge somewhere in the range of variation of adult grammars. However, many of the common processes of child phonology have found no equivalents in extensive investigations of adult phonological typology.

The present investigation focused on a child-specific pattern of positional neutralization, whereby child speakers tend to preserve contrasts in weak (non-initial) contexts while neutralizing contrasts in strong (word-initial or pretonic) positions. To model these processes with positional faithfulness constraints, which have been used in analyses of positional neutralization in adult phonologies, it would be necessary to create of a new set of constraints favoring faithfulness to targets in weak positions. However, positing such constraints makes an incorrect prediction for phonological typology, namely that enhanced faithfulness to weak positions should emerge as a feature of some adult languages. The application of positional markedness constraints to child processes of featural neutralization in strong contexts is similarly problematic. The puzzle is only heightened when we consider perceptually-motivated analyses of positional neutralization in adults. While experimental evidence has persuasively demonstrated that the phonetic cues to most phonemic contrasts are strongest in prevocalic positions, child phonological processes tend to maximize contrast in postvocalic positions. Thus, the child patterns present a striking exception to an otherwise uniform pattern of enhanced faithfulness in perceptually prominent contexts.

The analyses presented here have demonstrated that the differences between child and adult patterns of positional neutralization can be understood as a response to different phonetic pressures experienced by the two groups. In light of current trends to incorporate functional phonetic considerations into phonological modeling, it would be surprising if child phonology were found not to be sensitive to child-specific pressures on articulation. It has been argued that phonological systems are shaped by principles of efficiency in communication, including minimization of articulatory effort (Flemming, 1995, 2002). On the hypothesis that the definition of efficient transmission differs across child and adult speakers, we actively predict divergence between child and adult phonologies. Articulatory limitations offer an obvious starting point in the search for factors that constrain child but not adult speech processing. These limitations will be eliminated over the course of typical motor maturation, causing the child-specific processes to disappear along with them. The following section will briefly review the child-specific articulatory limitations that were invoked as part of the present effort to model child phonological processes. The imperfect nature of the mapping from child productions to adult listeners' perception and transcription also played a key role in the analyses pursued here.

2. Summary of the analysis

2.1 Differences between skilled and unskilled speech-motor control

An extensive literature documents systematic differences between the unskilled speech-motor control of child speakers and the skilled articulatory movements of adult speakers. It was demonstrated that child speech is characterized by variable and inconsistent movement patterns, slow rate, disrupted rhythm, and a decreased capacity for coordination between articulators and functional systems. The slower speed of children's articulatory gestures played an active role in the analysis of child-specific processes pursued here. The velocity of articulatory transitions has been invoked as a proxy for biomechanical effort in effort-minimization constraints employed in models of adult phonological processes (Boersma, 1998; Flemming, 2001, 2008). It was thus posited that children's slow speech gestures reflect a higher weight assigned to constraints limiting the rate of articulator movements in child relative to adult phonologies.

However, the primary work of accounting for child-specific phonological processes was accomplished by a single constraint whose manifestation in adult phonology is minimal or null. This constraint, MOVE-AS-UNIT, limits the child's capacity for differentiated control of independent articulators, instead favoring unitary movements of the entire tongue-jaw complex. It has been demonstrated that in the early stages of motor maturation, there is a need to simplify the act of motor control by restricting degrees of movement freedom. By moving multiple structures as a single rigid unit, the child reduces the complexity of the motor plan to a level that he can reliably control. Independent lingual movements appear to be particularly challenging for the developing motor system, since the tongue as a muscular hydrostat requires coordinated action of numerous intrinsic and extrinsic muscles. This leads the child speaker to prefer gestures dominated by movements of the jaw, whose simple hinge joint poses a much more manageable motor task. Thus, in the articulation of very young children or children with speech-motor deficits, the tongue may appear as a passive participant, relying on the action of the mandible. This simplification comes at the expense of flexibility and precision in a child's movement patterns. Thus, young children's speech is dominated by simple, ballistic gestures, with speech-motor movements that require refined control emerging later in the course of development (Kent, 1992).

The child preference for jaw-dominated gestures has been invoked in the "frames, then content" hypothesis advanced by MacNeilage & Davis (1990) to account for sound patterns in infant babbling. They argued that the preferential cooccurrence of certain consonant-vowel combinations in babbling and early words reflects children's tendency to produce cycles of mandibular oscillation during which the tongue remains in a fixed position. While MacNeilage & Davis reported specifically on children in the very early stages of speech development, the influence of mandibular dominance continues to make itself known in older children. In particular, after children have demonstrated some degree of tongue-jaw dissociation by producing differentiated consonant-vowel combinations, they continue to show a preference for ballistic movements of the tongue-jaw complex (Edwards, Fourakis, Beckman, & Fox, 1999). In the present work, it was argued that this pressure to move the articulators in synchrony can be identified as a motivating force behind several phonological processes observed in the course of both typical and disordered development. These claims are reviewed in brief in the following section. The absence of equivalent processes from adult speech, which has presented a problem for previous analyses, receives a ready explanation in the present approach. As a motor activity

becomes routinized over the course of repetitive practice, the child acquires an increasing number of degrees of freedom in articulatory control, and the pressure to move the articulators simultaneously in a maximally simple pattern recedes. Because jaw-dominated gestures call for large movements of a heavy articulator, the unitary movements that were previously favored will be eliminated under the action of constraints militating for conservation of biomechanical effort. Thus, over the course of motor maturation, the most economical and thus preferred form of articulatory control makes a natural transition from coordinated tongue-jaw cycles to differentiated movements of individual articulators. Together with the rise of faithfulness constraints, these articulatory factors can account for otherwise problematic differences between child and adult grammars.

2.2 Perceptual nonequivalence of skilled and unskilled speech production

Over the course of the present efforts to model phenomena in child phonology, another important theme emerged pertaining to the reliability of impressionistic transcription as an indication of the acoustic and articulatory realities of child speech. While perceptual biases play a role even in the encoding of adult speech, the gap between what is produced and what is perceived appears to be especially prominent in the context of child productions, as indicated by the high frequency with which instrumental analyses reveal covert contrast in child productions where adult listeners reported complete neutralization. This reflects the adult listener's tendency to impose his own phonemic categories on productions that may not in fact conform to those principles, just as an English speaker listening to the three-way laryngeal contrast in Korean consonants tends to perceive the two-way contrast of his own phonological system (Weismer, 1984). The analyses pursued here have exploited this finding that the mapping between gestures produced by a child speaker and features perceived by the adult listener is not one-to-one. A particularly prominent role was played by the finding that young speakers tend to produce consonant constrictions using large, undifferentiated areas of linguopalatal contact. While electropalatographic evidence reveals that these closures often span multiple places of articulation, adult listeners may perceive only a single place feature. Since undifferentiated linguopalatal contact is associated with a ballistic or jaw-dominated manner of gestural production, it can be inferred that speech sounds produced by children with limited speech-motor control may often involve a broader region of closure than what is transcribed by the adult listener.

2.3 Three child-specific speech processes reflecting motor-control limitations

This dissertation investigated three child speech processes that have posed a challenge for formal phonological modeling on the assumption of continuity between child and adult grammars. It was demonstrated that each of these processes can be modeled in a satisfactory fashion using child-specific constraints grounded in the limitations imposed by immature articulatory control. Previously, it was noted that positional asymmetries in child grammar resist formal modeling in terms of the positional faithfulness constraints that have been invoked in adult grammars. Here, the positional nature of velar fronting and fricative gliding processes was presented as the consequence of differences in articulatory force and timing across initial and final positions, while the regressive directional preference of consonant harmony was cast as a bias intrinsic to speech-motor planning, evident in speech errors as well as phonological processes.

2.3.1 Positional velar fronting

Velar fronting is a well-known example of children's tendency to neutralize phonemic contrast in strong contexts. In the fronting process, velar place is neutralized with coronal place in word-initial and pretonic contexts exclusively. Inkelas & Rose (2003, 2008) suggested that child-specific articulatory considerations play a role in positional velar fronting. Specifically, they posited that velar fronting occurs when some children make a phonologically appropriate effort to strengthen consonants in prosodically strong positions, yet their diminished speech-motor control and differently proportioned vocal anatomy prevents them from doing so without altering the perceived place of articulation of the target. In Chapter 4, this analysis was extended and formalized using additional data collected from case study subject B. In B's pattern of production, the accuracy of velar articulation was conditioned not only by position but also by the voicing specification of the target, such that voiced velars were realized more accurately than their voiceless counterparts. B also exhibited a tendency to produce velar targets with glottal closure immediately preceding or following the velar closure. Taken in combination, these phenomena suggested that B produced velars more accurately in the context of low levels of intraoral pressure, while elevated levels of pressure tended to induce fronting. The relation between intraoral pressure and velar fronting can be understood as follows. It has been demonstrated that to avoid spirantization, consonant gestures in contexts of high intraoral pressure are produced with greater articulatory force, represented as a greater height of the articulatory target. In Chapter 2 it was argued that violations of MOVE-AS-UNIT are sensitive to the height of the articulatory target, such that gestures are penalized more heavily as they require larger excursions of the tongue from its stable base position in the jaw. Discrete lingual gestures in contexts that require a high level of articulatory force are thus blocked by large-magnitude violations of MOVE-AS-UNIT. Instead, lingual consonant targets in these contexts will be realized with unitary movements of the tongue-jaw complex, giving rise to an undifferentiated pattern of linguopalatal contact. The typically coronal percept associated with these undifferentiated gestures was attributed to the habitual phasing of the release of the velar component of closure in advance of the coronal release, a consequence of the geometry of tongue-palate contact during coordinated action of the tongue and the mandible. Anterior displacement of the region of constriction may also occur as a consequence of compression of the tongue body during forceful linguopalatal contact. In total, the present account endorsed Inkelas & Rose's insight that the problematic phenomenon of velar-coronal neutralization in strong position can best be understood through incorporation of child-specific limitations on articulation. The incorporation of the MOVE-AS-UNIT constraint made it possible to formalize this account and also to account for additional factors, such as voicing, whose role in conditioning the accuracy of velar production would otherwise be mysterious.

2.3.2 Prevocalic fricative gliding

Constraints on articulation were also invoked to explain a problematic pattern in the acquisition of fricatives, whereby postvocalic fricatives emerge in advance of fricatives in prevocalic contexts. While this pattern has been described in numerous children, it has not previously received a satisfactory explanation. Here, new light was cast on the issue using data from case study subject B. It was demonstrated that B produced fricatives with enhanced accuracy in the context [+high] segments. This was suggestive of a preference to produce small articulatory transitions, which can be encoded using effort-minimization constraints (*EFFORT:

"Minimize articulator velocity") that have been demonstrated to play a role in shaping adult patterns of coarticulation. In addition to the asymmetric behavior of high and nonhigh vowels, B exhibited an interesting pattern whereby prevocalic fricatives were either replaced with a glide or separated from the following vowel by an apparent epenthetic glide. It was proposed that these glidelike segments could in fact be understood as the perceptual consequence of a protracted transition from the high jaw target of a sibilant fricative to the low target of a nonhigh vowel. To explain why these elongated transitions should arise in child but not adult speakers, we again look to the child preference for simultaneous movement of the tongue and the jaw. Articulographic imaging has revealed that the adult fricative-to-vowel transition is characterized by a period of anticipatory jaw-lowering during which the tongue remains in a high position to sustain frication. For a child speaker, this type of coarticulation incurs a potentially problematic violation of MOVE-AS-UNIT. An alternative pattern, in which the jaw is held high until completion of the fricative, would involve too rapid a movement (large violation of *EFFORT) if it were to match the timing of the transition as produced by adults. Thus, the child is obligated to lower the tongue and jaw simultaneously in a slower gesture, even though this incurs a faithfulness violation by creating the percept of a glide.

The advantage for faithful fricative production in word-final contexts was posited to reflect the slower rate of the articulatory transition from vowel to fricative in this environment. Empirically, this proposal was supported by the observation that B exhibited a process similar to adult phrase-final lengthening that applied at the level of words and syllables as well as phrases. To explain why this type of lengthening was available in the context of vowel-fricative but not fricative-vowel transitions, the Articulatory Phonetic notion of characteristic timing relationships between consonant and vowel gestures was invoked. It was hypothesized that tighter temporal binding of consonant and vowel gestures in CV relative to VC contexts prevents the execution of the fricative-vowel transition over an extended interval comparable to the elongated vowel-fricative transition. Finally, coda fricatives were further favored by a systematic process of preaspiration that obscured the perceptual consequences of B's extended transitions from vowel to fricative, which might otherwise have been perceived as offglides or changes in vowel quality. There is a need for further study of children exhibiting asymmetric acquisition of fricatives, since it is not known at present to what extent B's patterns such as word- and syllable-final lengthening and preaspiration might be general across child speakers at a comparable stage of development. However, the success of the articulatory approach in explaining a particularly problematic set of data suggests that factors of effort minimization and speech-motor control should be taken into consideration in future investigations of fricative acquisition.

2.3.3 Child consonant harmony

Finally, Chapter 6 reviewed the phenomenon of child consonant harmony, one of the most commonly cited examples of an asymmetry between child and adult phonologies. Like velar fronting and fricative gliding, consonant harmony tends to preserve phonemic contrast in prosodically weak positions while neutralizing contrasts in strong positions. In other respects, however, consonant harmony poses a rather different puzzle than the phenomena of velar fronting and fricative neutralization. In particular, processes of consonant harmony do occur in adult phonologies, but adult harmony is rather limited in nature and never affects major place of articulation, the most commonly described pattern in child harmony. It was proposed that the commonalities across child and adult harmony processes reflect a shared motivation in constraints on phonological processing. Meanwhile, the absence of major place harmony from

adult phonological systems was attributed to child-specific articulatory limitations, notably, a diminished capacity for anticipatory coarticulation reflecting the limitation on discrete lingual gestures imposed by an active MOVE-AS-UNIT constraint.

Both child and adult consonant harmony have striking parallels with speech error processes, suggesting that all three stem from a similar motivation. This possibility was explored by Hansson (2001) and Rose & Walker (2004), who suggested that consonant harmony in adults has roots in spreading-activation models of cognitive processing (e.g. Dell, 1986). They argued that adult consonant harmony serves to simplify speech production by altering similar but non-identical targets to be fully identical. Both this psycholinguistic motivation and their formalism of agreement by correspondence were adapted to child consonant harmony in the present analysis.

However, the account pursued here diverged from Rose & Walker's model in order to incorporate insights from a recent articulatory model of speech errors. Pouplier and her colleagues have demonstrated that a large percentage of speech errors that are perceived to be categorical substitutions actually involve simultaneous production of intrusive and target gestures. Another key result from the speech error literature was Pouplier & Goldstein's (2005) finding that listeners typically did not detect intrusive coronal gestures during velar target production, whereas simultaneous production of target coronal and intrusive velar gestures tended to be perceived as anomalous. On the hypothesis that child speakers are in fact producing simultaneous intrusive and target gestures in the process of consonant harmony, the asymmetric behavior of coronal and velar place as triggers and targets of consonant harmony is predicted as a natural consequence of these perceptual factors. This proposal was supported with a finding of covert contrast between target and harmonized velar gestures in one child's productions of minimally different nonwords. To incorporate these articulatory findings into the model of agreement by correspondence, it was proposed that IDENT-CORR constraints militate for two segments in correspondence to agree with respect to the presence of an articulatory gesture. This constraint can be satisfied by simultaneous coproduction of target and intrusive gestures; a directional variant of the IDENT-CORR constraint expressed a preference for an intrusive gesture at the left edge of the word. With motivation from both processing and articulatory factors, this model was seen to make correct predictions for the directional preference as well as the hierarchy of place features participating in child consonant harmony.

The absence of major place harmony from adult phonology received an explanation drawing on the MOVE-AS-UNIT constraint that was invoked to analyze other child-specific phenomena earlier in the dissertation. Adult languages are known to favor variegated over reduplicated consonant sequences. One explanation for this preference holds that alternating place gestures enjoy an articulatory effort advantage due to the greater availability of anticipatory coarticulation in this context. In the child speaker, MOVE-AS-UNIT tends to block the discrete lingual gestures by which skilled speakers anticipate upcoming articulatory targets. With the availability of anticipatory coarticulation thus diminished, the articulatory advantage for alternating over repetitive gestures is neutralized. This allows the processing factors described above to play a more active role, giving rise to processes of major place harmony which are blocked in adult consonant harmony.

Finally, it was posited that harmony involving labial gestures is less robustly attested than coronal-velar harmony because the constraint establishing correspondence between consonants carries a lower weight when target gestures are less similar in their articulatory properties. This analysis of labial harmony represents preliminary evidence that child consonant harmony, like

adult harmony and speech errors, is sensitive to the similarity of competing targets. It was noted that there is a distinct need for further investigation of the role of similarity in dictating the strength and duration of child consonant harmony. On the whole, it appears that the incorporation of functional considerations of processing and articulation has considerable potential to advance our understanding of child consonant harmony in both its parallels with and deviations from harmony processes in adults.

2.4 Incorporating motor limitations into phonology

Throughout this dissertation, it was argued that the systematicity of child speech processes can best be captured using phonological constraints that are sensitive to articulatory limitations. This proposal is by no means unique to the modeling of child phonological processes, since phonetically-based accounts of adult phonological processes now occupy an established place in the literature. However, the most appropriate means by which phonetic factors can be incorporated into the grammar remains an open question. Chapter 1 included a comparison of directly phonetic versus phonetically grounded constraints in phonological modeling. In the former approach (cf. Flemming, 2001, 2008), scalar phonetic data such as the height of an articulatory target are incorporated directly into the assessment of violations of markedness constraints. In the phonetically grounded alternative (cf. Hayes, 1999), categorical phonological principles are selected that conform to basic phonetic principles but sacrifice complete phonetic effectiveness for the sake of formal symmetry. The weight of the evidence from the studies reported here suggests that child processes can most adequately be modeled using directly phonetic constraints. Thus, the articulatory constraints invoked in these analyses, MOVE-AS-UNIT and *EFFORT$_{mand}$, were modeled as weighted constraints sensitive to gradient phonetic differences.

In the case of velar fronting, presented in Chapter 4, it was shown that the constraint MOVE-AS-UNIT must be sensitive to a number of different levels of articulatory strength. Because the computation of articulatory strength incorporates components of prosodic context and laryngeal states (voicing and/or pre- or post-glottalization), it is quite cumbersome to specify a scale of constraints referring to each level of articulatory strength by its combination of predictive factors. A more efficient approach is to scale the magnitude of the violation of MOVE-AS-UNIT directly to the height of the articulatory target in each context. Note that the pattern of velar fronting reported here provides evidence against Hayes's (1999) claim that grammars uniformly partition phonetic space in a simple and symmetrical manner, an argument advanced in favor of phonetically grounded constraints. The present data suggest that, at least in child phonology, it is possible for phonetic preferences to be obeyed at the expense of formal simplicity.

In the analysis of prevocalic and postvocalic fricatives presented in Chapter 5, direct phonetic scaling also appeared in connection with the constraint *EFFORT$_{mand}$. The magnitude of the violation of *EFFORT$_{mand}$ incurred by a candidate is scaled to the velocity of a mandibular gesture, where changes in both the size and the duration of the articulatory transition can be varied. It should in principle be possible to encode the influence of mandibular velocity using a scale of phonetically grounded, categorical constraints. However, in Chapter 5 it was shown that gradient differences in F1 height made a near-significant contribution to the prediction of fricative accuracy in a logistic regression model (p = .07). This suggests that violations of *EFFORT$_{mand}$ are assessed in a continuous fashion from scalar phonetic data, as posited in analyses of adult patterns of coarticulation (Flemming, 2001, 2008).

3. On the relation between errors in production and perception

All of the proposals discussed in the previous section drew on articulatory factors as the motivation for child-specific phonological processes. An alternative hypothesis that was entertained but discarded in an early chapter is the notion that child-specific phonological processes reflect an immature pattern of perception. Dinnsen & Farris-Trimble proposed that children's anomalous tendency to neutralize contrasts in prominent (word- and foot-initial) positions could be attributed to a child-specific predilection to attend to contrasts in word-final contexts. This proposal reflects Slobin's (1973) notion that children pay attention to the ends of words, and it is potentially related to the child speaker's task of word segmentation. However, Chapter 3 presented the results of a perceptual experiment that failed to support Dinnsen & Farris-Trimble's hypothesis. This experiment engaged case study subject B, known to exhibit multiple patterns of neutralization in strong position, in a nonword discrimination task where phonemic contrasts were presented in both word-initial and word-final positions. Despite his tendency to preserve contrast in word-final contexts in production, B exhibited an adultlike perceptual advantage for phonemic contrasts in word-initial contexts. This supported our argument that B's preference to neutralize contrast in strong position is the consequence of articulatory rather than perceptual factors.

On the other hand, it was not the case that B's perceptual ability conformed entirely to the standards of adult phonology. Instead, he exhibited difficulty discriminating precisely those segmental contrasts he tended to produce in error, namely the coronal-velar place distinction. This finding of parallel deficits in perception and production has been reported in a number of studies of children with articulatory deficits (Hoffman et al., 1985; Raaymakers & Crul, 1988; Rvachew & Jamieson, 1989; Whitehill, Francis & Ching, 2003). However, it has proved problematic to determine whether deficits in production are the consequence of a primary perceptual deficit, or vice versa. The evidence collected from B is unique in featuring dissociation between perceptual and articulatory preferences, such that articulatory pressures prefer the realization of contrast in word-final contexts, whereas perceptual factors militate for maximal contrast in word-initial position. With the additional evidence offered by this dissociation, it was argued that the articulatory limitation is primary in a child like B, with perceptual deficits emerging as a side consequence of restrictions on production. A similar claim was made by Whitehill, Francis, & Ching (2003), who demonstrated that children with cleft lip and palate, whose phonological processes are likely to be articulatory in origin, exhibited patterns of perceptual difficulty that closely mirrored their errors in production. This section represents a preliminary effort at formalizing the interaction by which production-oriented pressures give rise to parallel deficits in perception. It will be proposed that this pattern can best be modeled on the assumption that a single set of markedness constraints applies over both the mapping from surface forms to lexical representations and from lexical representations to outputs, as suggested by Pater (2004). However, the model makes broad predictions for lexical and phonological learning that have not yet been examined in their entirety. It is hoped that the preliminary analysis offered here can serve as the basis for further investigation of an underexplored issue.

3.1 A single grammar for perception and production

Pater (1999, 2004) has proposed that separate production and perception mappings can be encoded in a single Optimality Theoretic grammar. While Smolensky (1996) offered a similar analysis, his model entailed that child grammar is characterized by highly constrained production together with fully adultlike comprehension. By contrast, Pater rejects the claim of a fully faithful mapping from acoustic input to lexical representations in the early stages of phonological development. Instead, he maintains that children's perceptual capacities develop over time, and they do so in a way that parallels later developments in production. Pater illustrated the parallel nature of constraints on production and perception with the example of early limitations on prosodic structure. It is well-established that young children's productions tend to be limited to a single trochaic foot, with truncation of the initial syllable of targets with an iambic stress pattern. Pater's examples, drawn from the productions of a single child between the ages of 1;9 and 1;10, are repeated in (1).

(1) a. Trochaic disyllables are realized faithfully

[ga:bɛ dʒ]	'garbage'
[wæ:dɪ t]	'rabbit'

b. Iambic disyllables undergo truncation[36]

[ga:dʒ]	'garage'
[wæ:f]	'giraffe'

Pater argues that similar prosodic constraints are active in the receptive competence of children at a younger stage of development. Using a headturn preference methodology, Jusczyk, Houston, & Newsome (1999) tested the influence of prosody on infants' ability to encode word shapes in memory without any assignation of meaning. One group of 7.5-month-old infants was familiarized with a set of trochaic words (e.g. *doctor*), while another group heard a set of iambic words (e.g. *guitar*). When they subsequently listened to samples of running speech that did or did not include those target words, the infants in the trochaic condition looked longer in response to the recording containing the familiarized targets, while the infants in the iambic condition exhibited no listening preference. 10-month-old infants tested with the same methodology exhibited longer listening times in response to both iambic and trochaic target words. Jusczyk et al. concluded that infants at the younger age encoded only trochaic wordforms in memory. There is thus parallelism in the order of emergence of structures across perception and production, although the timeframe on which children's mastery of iambic wordforms unfolds differs across the two domains.

To capture the similarities between developments in perception and production while permitting them to emerge on a different schedule, Pater proposed that a single set of markedness principles should constrain both perception and production, while the mapping from perception to lexical representations and the mapping from lexical representations to outputs are subject to separate constraints. Pater's FAITH(LS) constraints, which govern the mapping from lexical representations to surface forms, are equivalent to the input-output faithfulness constraints familiar from conventional models of production. A second type of faithfulness, FAITH(SL), is

[36] The identity of the onset consonant is determined by considerations of sonority that will not be discussed here.

posited to constrain the mapping from surface forms to lexical representations. Pater suggests that allowing markedness constraints to operate over the mapping from perception to lexical representation allows the child to minimize the complexity of the forms in his lexicon: "The role of the phonological grammar in the development of receptive competence is to regulate the structure, and therefore the complexity, of the representation(s) used in perception" (p. 10). Thus, in an early stage of development, constraints are ranked such that MARKEDNESS >> FAITH(LS), FAITH(SL), giving rise to simplification of lexical representations as well as output forms. A later stage is characterized by the promotion of only perceptual faithfulness above markedness, such that FAITH(SL) >> MARKEDNESS >> FAITH(LS). This gives rise to the perception-production gap that is frequently described in child phonology (Barton, 1976; Strange and Broen, 1980; Velleman, 1988). Finally, in a mature state of the grammar, FAITH(SL), FAITH(LS) >> MARKEDNESS. For illustration, Table 1 repeats Pater's examples of the simplification of iambic foot structure in the second stage of development, where production but not perception is constrained by markedness. Here, the relevant markedness principle is cast as a simplified WORDSIZE constraint, "A word is made up of a single trochee." Separate MAX constraints militate for the preservation of segments between the perceptual input and the lexical representation (MAX(SL)) and between the lexical representation and the output of production (MAX(LS)). In the perceptual mapping depicted in (a), the fully faithful candidate is preferred due to high-ranked MAX(SL). In the mapping from lexical forms to output, truncation occurs because the markedness constraint WORDSIZE dominates FAITH(LS). Note that in the mapping from perception to production forms, the competing candidates L_1 and L_2 are lexical representations; Pater posits that lexical representations can be specified for prosodic structure.

Table 1. FAITH(SL) >> WORDSIZE >> FAITH(LS): Perception-production gap (Pater, 2004, p. 13)

a. *Perception mapping*: An iambic disyllable is perceived faithfully.

S: gərádʒ	MAX(SL)	WORDSIZE	MAX(LS)
L_1 [[gádʒ]$_{Ft}$]$_{PrWd}$	**!		
☞L_2 [gə[rádʒ]$_{Ft}$]$_{PrWd}$		*	

b. *Production mapping*: An iambicdisyllable is produced with truncation.

L: [gə[rádʒ]$_{Ft}$]$_{PrWd}$	MAX(SL)	WORDSIZE	MAX(LS)
☞ S_1 [[gádʒ]$_{Ft}$]$_{PrWd}$			**
S_2 [gə[rádʒ]$_{Ft}$]$_{PrWd}$		*!	

By imposing the same markedness constraints on both perception and production mappings, Pater's model offers a straightforward means of modeling the parallel deficits in perception and production that were observed in B and have also been described in previous literature on phonological disorders. If the ranking of a given markedness constraint in a child's grammar is sufficiently high, dominating both FAITH(LS) and FAITH(SL), the child is expected to make parallel errors in perception and production. Table 2 illustrates how this model can derive both perception and production errors for a child with a process of positional velar fronting. To conform to the Harmonic Grammar framework used throughout the dissertation, the tableaux that follow make use of weighted constraints in place of the strict rankings presented in Pater (2004). As in our discussion of velar fronting in Chapter 4, the articulatory-oriented constraint MOVE-AS-UNIT is invoked as the motivation for velar fronting processes. Accordingly, the candidate with fronting, although perceived to have coronal place, is represented with a mid-

palatal stop to indicate undifferentiated lingual contact. Discussion of the complications posed by introducing this level of articulatory detail into the perception mapping will be deferred until the final section.

Table 2. Perception and production of word-initial velars

a. *Perception mapping:* An initial velar is perceived with fronted place.

S: kæt	MOVE-AS-UNIT	IDENT(SL)	IDENT(LS)	**TOTAL**
	2	1	1	
L_1 kæt	1	0	0	**2**
☞ L_2 cæt	0	1	0	**1**

b. *Production mapping:* An initial velar is produced with fronted place.

L: kæt	MOVE-AS-UNIT	IDENT(SL)	IDENT(LS)	**TOTAL**
	2	1	1	
S_1 kæt	1	0	0	**2**
☞ S_2 cæt	0	0	1	**1**

In Table 2, the candidate with fronting emerges as most harmonic in both perception and production mappings. This constitutes a first step toward modeling parallel neutralizations in perception and production as manifested in child speakers like B. However, the model has not yet engaged with the behavior of phonemic contrasts in word-final contexts, and additional assumptions will be needed for this purpose. We previously noted a puzzling dissociation between perception and production mappings in B's performance. In production, he exhibited preferential preservation of the coronal-velar place contrast in final position, while in the nonword discrimination task he distinguished word-initial coronal-velar pairs with equal or greater accuracy relative to word-final pairs. As it has been presented thus far, Pater's model will predict identical behavior across perception and production, including positional preferences expressed in these domains.

It will be important to recall, however, that perceptual preferences must be encoded in the grammar by some means other than the ranking of IDENT(SL) constraints relative to markedness constraints. We have seen extensive evidence of nonuniformity in adult perception, including the greater salience of cues in CV relative to VC transitions (Fujimura et al., 1978; Redford & Diehl, 1999), as well as differences in the discriminability of various feature contrasts (Benkí, 2003; Cutler et al., 2004). Since it is presumed that the scales of IDENT(SL) and IDENT(LS) constraints dominate most markedness constraints in adult speakers in Pater's model, these perceptual preferences must be expressed in some other way. A likely possibility is that there is ordering within the sets of IDENT constraints to reflect the relative perceptual prominence of various contrasts, in the manner of the P-map hypothesis (Steriade, 1999, 2001). This would indicate that in both perception and production mappings, deviations from faithfulness are penalized in proportion to the perceptual salience of the change. On the assumption that there is basic continuity between child and adult grammars, it is desirable to assume that these universal scales of perceptibility are also available to child speakers. This hypothesis is supported by the finding that B, despite his deviant pattern of production, exhibited an adultlike preference for word-initial over word-final contrasts in nonword discrimination. B's pattern of neutralization in

production can be understood on the assumption that the articulatory pressure to neutralize in strong position is weighted above both positional and general variants of the input-output faithfulness constraint. In fact, the approach to faithfulness that will be adopted in these analyses is slightly different from—although still compatible with—the framework proposed by Pater. The following section will present a revised perspective on faithfulness, with demonstrations that this approach enables to derive both divergent and convergent properties of perception and production in B's pattern of performance.

3.2 Perceptually-oriented versus gesturally-oriented faithfulness

In the analyses of child phonological processes pursued in this dissertation, it became necessary on several occasions to distinguish between perception-oriented and articulation-oriented constraints. The most illustrative example was seen in Chapter 6, where child consonant harmony was analyzed to involve simultaneous production of target and harmonizing gestures, adopting the articulatory model advocated by Pouplier and colleagues. Pouplier & Goldstein (2005) demonstrated that intrusive gestures have mixed perceptual consequences: an intrusive velar gesture during coronal articulation is generally perceived to be anomalous, whereas intrusive coronal gestures during a target velar typically go undetected. To encode the contrast between fully faithful productions and productions with a covert intrusive gesture, it was posited that the intrusive gesture violates an articulatory faithfulness constraint, DEP-gesture, which is insensitive to the perceptual consequences of the unfaithful gesture. A separate perceptually-oriented faithfulness constraint was violated only when the intrusive gesture had deviant perceptual consequences. Perceptually-oriented faithfulness constraints were also invoked in the analysis of velar fronting in Chapter 4, where undifferentiated lingual gestures were perceptually but not featurally unfaithful to a velar target. Lastly, a perceptually-oriented DEP-glide constraint was invoked to penalize the extended articulatory transition from an initial fricative to a nonhigh vowel, which was perceived as a glide even though a glide was never specified as a gestural target.

Since a mapping between perceptual forms and underlying representations will be required for independent reasons, we can consider integrating this function with Pater's IDENT(SL) constraints to create a single set of perceptually-oriented faithfulness constraints. These constraints militate for identity between lexical representations and perceptually encoded forms. They are bidirectional in the sense that they apply whenever a speaker compares a perceptually encoded form against a lexical representation, whether the perceptually encoded form was his own output or that of another speaker. In children, the perceptually oriented faithfulness constraints are relatively low-ranked and can interact with markedness constraints. This can give rise to markedness-induced perceptual errors, as described by Pater, as well as productions whose perceptual consequences deviate from the lexical representation. In adults, the set of perceptually-oriented constraints dominates most markedness constraints. As a consequence, adult speakers typically do not exhibit deviant perceptual mappings, and the mapping from an adult's articulatory output to the corresponding perceptual consequences is typically one-to-one, without covert contrasts or covert errors.

The division of faithfulness constraints into separate IDENT(percept) and IDENT(gesture) scales has implications for the analysis of positional neutralization phenomena. Positional faithfulness effects are a natural consequence of perceptually-oriented faithfulness. If some featural change is carried out in a context with highly salient perceptual cues, such as word-initial position, the degree of deviance between the lexical representation and the perceptually

encoded form will be larger than it would be in a context with weak perceptual cues. Accordingly, an IDENT(percept) violation of greater magnitude will be recorded in the perceptually strong context. By contrast, the strength of perceptual cues has no place in the assessment of IDENT(gesture) constraints, although articulation has its own asymmetries, as we saw throughout the analyses pursued here.

3.3 Implementing the proposal for perception and production mappings

With these assumptions, we are prepared to create production and perception mappings to model positional neutralization in a child like B. To begin, Table 3 illustrates that the new set of constraints is sufficient to capture the basic positional asymmetry in B's production of velar place. Recall from Chapter 4 that the number of MOVE-AS-UNIT violations incurred by a candidate can be seen to vary with the height of the articulatory target, of which prosodic position is one conditioning factor. The larger and more forceful velar gesture produced in word-initial position incurs a larger number of violations of MOVE-AS-UNIT than the lower-amplitude gesture in the word-final context. A positional asymmetry is also encoded in the number of violations of IDENT(percept) incurred by a candidate, with deviations in the perceptually prominent word-initial context penalized more heavily than their counterparts in word-final position. To avoid duplicating the work of the markedness constraint, which is sensitive to positional variation in articulatory strength, the gestural faithfulness constraint IDENT(gesture) is penalized uniformly across positions. Note that both IDENT(gesture) and IDENT(percept) are violated by a deviation that is encoded in the articulatory plan and also has overt perceptual consequences, as in the examples below. Table 3(a) shows that a word-initial velar target will be produced with fronting, while Table 3(b) shows that faithful production is favored in word-final position. This is an accurate characterization of B's positional pattern of velar fronting

Table 3. Modeling velar production in initial and final contexts

a. *Production mapping:* A word-initial velar is fronted.

L: kæt "cat"	MOVE-AS-UNIT	IDENT(gesture)	IDENT(percept)	**TOTAL**
	2	1.5	1	
S_1 kæt	2	0	0	**4**
☞ S_2 cæt	0	1	2	**3.5**

b. *Production mapping:* A word-final velar is realized faithfully.

L: tæk "tack"	MOVE-AS-UNIT	IDENT(gesture)	IDENT(percept)	**TOTAL**
	2	1.5	1	
☞S_1 tæk	1	0	0	**2**
S_2 tæc	0	1	1	**2.5**

In Table 4 we turn to the perceptual mapping for initial and final velar targets. These tableaux differ from the preceding in that no violations of gestural faithfulness are incurred. Here we encounter the crucial asymmetry between perception and production mappings: while the speaker planning an utterance considers both perceptual and gestural aspects of his intended

production, only perceptually-oriented constraints are taken into account in the mapping from surface forms to lexical representations.

Table 4. Modeling velar perception in initial and final contexts

a. *Perception mapping:* A word-initial velar is perceived with fronted place.

S: kæt	MOVE-AS-UNIT	IDENT(gesture)	IDENT(percept)	**TOTAL**
	2	1.5	1	
L_1 kæt	2	0	0	**4**
☞ L_2 cæt	0	0	2	**2**

b. *Perception mapping:* A word-final velar is perceived with fronted place.

S: tæk	MOVE-AS-UNIT	IDENT(gesture)	IDENT(percept)	**TOTAL**
	2	1.5	1	
L_1 tæk	1	0	0	**2**
☞ L_2 tæc	0	0	1	**1**

With the constraint weightings violations assumed here, the unfaithful mapping to coronal place will be preferred for both initial and final velars. This is consistent with B's extremely low discrimination of coronal and velar pairs during the first testing session in the experiment reported in Chapter 3. The fact that this model gives rise to identical outcomes in both initial and final contexts is also consistent with the results of that experiment, since the percent accuracy with which B discriminated coronal-velar pairs did not differ significantly across initial and final contexts. However, a satisfactory model must also be able to encode the general advantage for word-initial over word-final contrasts in perception. Table 5 demonstrates that this preference emerges when the contrast in question is not associated with a high-weighted markedness violation, as in the case of the coronal-labial contrast. An ad hoc constraint *P is invoked to penalize occurrences of labial place. Again, there is parallelism with the results of the experimental investigation, since B's discrimination accuracy was significantly greater for coronal-labial pairs in initial than final position.

Table 5. Modeling labial perception in initial and final contexts

a. *Perception mapping:* A word-initial labial is perceived faithfully.

S: pæt	IDENT(gesture)	IDENT(percept)	*P	**TOTAL**
	1.5	1	1	
☞ L_1 pæt	0	0	2	**2**
L_2 tæt	0	2	0	**2**

b. *Perception mapping:* A word-final labial is perceived with variable place.

S: tæp	IDENT(gesture)	IDENT(percept)	*P	**TOTAL**
	1.5	1	1	

☞L_1 tæ p	0	0	1	**1**
☞L_2 tæ t	0	1	0	**1**

3.4 Issues for further consideration

Several questions are left unresolved by this preliminary analysis. Most notably, the system as it is laid out above suggests that the child's perception mapping in the context of a high-weighted markedness constraint will consistently be unfaithful. This is at odds with the assumption of a target-appropriate lexical representation in the production mapping. More importantly, it leaves unclear the mechanism by which the child will arrive at a veridical representation to motivate learning. We are thus in need of a mechanism by which a child can arrive at a correct representation of a contrast in spite of frequent misperceptions. This effect can be achieved on the assumption that some in some percentage of exposures to a word containing the problematic contrast, stochastic variation in the weighting of constraints will permit the child to perceive the correct target. Exposure to forms with exaggerated phonetic characteristics (as, for instance, in child-directed speech, or in a therapy setting) can be presumed to enhance the likelihood of accurate encoding. Over time, the accumulated weight of these exposures can persuade the child that the correct lexical representation contains an instance of the form he disfavors for markedness reasons. In the experiment reported in Chapter 3, because nonword targets were used, previous exposure could not play a role in B's perceptual judgment. Accordingly, his bias based on markedness tended to prevail, and discrimination accuracy was low.

A second question, alluded to previously, pertains to how markedness constraints that evaluate the well-formedness of articulatory gestures can be invoked in a mapping from acoustic forms to lexical representations. Without endorsing the entirety of the motor-theoretic notion that speakers perceive "in gestures," it is reasonable to suggest that phonological evaluation allows a motor plan to be formulated so that articulatory-oriented aspects of markedness can be evaluated. perceived forms are encoded with some level of articulatory phonetic detail. The exact mechanism for this assessment, along with the question of how phonetic detail, articulatory or otherwise, should be encoded in the lexicon, will be left outside of the scope of the present project.

The analyses offered here have espoused some rather unconventional notions regarding relationships among perception, production, and lexical representations. However, this is a case where the peculiarity of the analysis only mirrors the peculiarity of the empirical data. Recall that this analysis attempts to account for B's strange reversal of preferences across perception and production, where a perceptual advantage was maintained in initial position at the same time that articulatory neutralization preferentially affected the initial context. In the analyses pursued here, articulatory asymmetries were invoked to do most of the work of accounting for children's neutralizations in strong positions, and little role was afforded to perceptual asymmetries. However, it would be misguided to ignore the finding that B, like many other children described in the literature on child speech disorders, showed difficulty perceiving precisely those contrasts that he produced in error. This leads us to take the step of proposing that high-ranked markedness constraints can have an impact on perception, even if these constraints are rooted in principles of articulatory effort. Despite the counterintuitive nature of this assertion, it is supported by empirical findings that children who exhibit a primary deficit of speech-motor

control can typically be found to evince perceptual abnormalities as well. These include the children with cleft lip and palate described by Whitehill et al. (2003), in addition to children with apraxia of speech, described by Groenen, Maassen, Crul, & Thoonen (1996) and in the present investigation of B.

4. Conclusion

This dissertation explored the puzzle posed by child-specific phonological processes, notably processes of positional neutralization that preferentially preserve contrast in weak postvocalic positions. This is a surprising reversal of a cross-linguistic preference to neutralize contrasts in weak contexts, and as such, it has posed a significant challenge for efforts to model child processes using formalism borrowed directly from models of adult phonology. However, child-specific phonological processes can be more readily understood in the framework of phonetically-based phonology. If phonologies respond to low-level phonetic differences, and children and adults experience distinct phonetic pressures in one or more domains, some phonological differences between the two groups can be expected to occur. In this framework, the existence of child-specific constraints is neither logically nor formally problematic, since the child process will be eliminated as the developmental limitation influencing phonetic pressures is lifted over the course of maturation. Differences in speech-motor control were seen to play the dominant role in shaping child-specific phonological processes. It was argued that several common processes in child phonology reflect the influence of a pressure to produce ballistic gestures in which the entire articulatory complex moves in concert, formalized in the constraint MOVE-AS-UNIT. Further investigation is needed to determine what other child phonological processes might be amenable to analysis under this principle, with consideration for context-free processes as well as other instances of neutralization in strong position. Finally, it was emphasized throughout these studies that the realities of child articulation tend to be poorly reflected in impressionistic transcription. Thus, instrumental analyses are expected to play a key role in future elucidation of child processes of neutralization in strong contexts.

Works Cited

Adams, S. G., Weismer, G., & Kent, R. D. (1993). Speaking rate and speech movement velocity profiles. *Journal of Speech and Hearing Research*, 36, 41–54.

Ahn, S.-C. (1998). *An Introduction to Korean Phonology*. Seoul: Hanshin Publishing.

American Speech-Language-Hearing Association. (2007). Childhood Apraxia of Speech [Technical Report]. Available from www.asha.org/policy.

Amorosa, H., von Benda, E., Wagner, E. & Keck, A. (1985). Transcribing phonetic detail in the speech of unintelligible children: a comparison of procedures. *British Journal of Disorders of Communication*, 20, 281-287

Aram, D. (1984). Assessment and treatment of developmental apraxia. Seminars in Speech and Language, 5.

Aslin, R. (1999). Utterance-final bias in word recognition by 8-month-olds. Poster presented at the Society for Research in Child Development, Albuquerque.

Aslin, R., Woodward, J., LaMendola, N., & Bever, T. (1996). Models of word segmentation in fluent maternal speech to infants. In J. L. Morgan & K. Demuth, *Signal to syntax: Bootstrapping from speech to grammar in early acquisition* (pp. 117–134). Mahwah, NJ: Lawrence Erlbaum Associates.

Aungst, L. F. & Frick, J. V. (1964). Auditory discrimination ability and consistency of articulation of /r/. *Journal of Speech and Hearing Disorders*, 29, 76-85.

Ayres, A. J. (1985). *Developmental dyspraxia and adult-onset apraxia*. Torrence, CA: Sensory Integration International.

Baayen, R. H., Piepenbrock, R., & van Rijn, H., eds. (1993). The CELEX Lexical Database [CD-ROM]. Linguistic Data Consortium, University of Pennsylvania.

Bach, E., & Harms, R. T. (1972). How Do Languages Get Crazy Rules? In R. P. Stockwell & R. K. S. Macauley (Eds.), *Linguistic Change and Generative Theory* (pp. 1-21). Bloomington, Indiana: Indiana University Press.

Bakovic, E. (2000). *Harmony, dominance, and control*. Doctoral dissertation, Rutgers

Barnes, J. (2006). *Strength and weakness at the interface: positional neutralization in phonetics and phonology*. Berlin and New York: Mouton de Gruyter.

Barton, D. (1976). *The Role of Perception in the Acquisition of Phonology*. Ph.D. dissertation, Stanford University. Distributed 1978, Indiana University Linguistics Club.

Bates, S. A. R., Watson, J. M. M. & Scobbie, J. M. (2002). Context conditioned error patterns in disordered systems. In M. Ball, & F. E. Gibbon (Eds.), *Vowel Disorders* (pp. 145-185). London: Butterworth Heinemann.

Beckman, J. (1997). Positional Faithfulness, Positional Neutralisation, and Shona Vowel Harmony. *Phonology,* 14, 1-46.

Beckman, M. E., Yoneyama, K., & Edwards, J. (2003). Language-specific and language-universal aspects of lingual obstruent productions in Japanese-acquiring children. *Journal of the Phonetic Society of Japan*, 7, 18-28.

Benkí, J. R. (2003). Analysis of English nonsense syllable recognition in noise. *Phonetica*, 60, 129-157.

Berg, T. (1995). Sound change in child language: A study of inter-word variation. *Language and Speech*, 38, 331–363.

Berkley, D. M. (2000). *Gradient OCP Effects*. Ph.D. dissertation, Northwestern University.

Bermúdez-Otero, R. (2007). *Diachronic phonology*. In P. de Lacy (Ed.), *The Cambridge handbook of phonology* (pp. 497-517). Cambridge: Cambridge University Press.

Bernhardt, B. & Stemberger, J. P. (1998). *Handbook of phonological development: From the perspective of constraint-based nonlinear phonology*. San Diego: Academic Press.

Bernhardt, B. & Stoel-Gammon, C. 1996. Underspecification and markedness in normal and disordered phonological development. In C. Johnson & J. H. V. Gilbert (Eds.), *Children's language (9)* (pp. 33-54). Mahwah, NJ: Lawrence Erlbaum Associates.

Betz, S. K. & Stoel-Gammon, C. (2005). Measuring articulatory inconsistency in children with developmental apraxia. *Clinical Linguistics & Phonetics*, 19, 53-66.

Bills, S., & Golston, C. (2002). Prosodic and linear licensing in English acquisition. In Carmichael, L., Huang, C.-H., & Samiian, V. (eds.), *Proceedings of the Western Conference on Linguistics*. Fresno: California State University, Fresno, 13–26.

Bleile, K. M. (2004). *Manual of articulation and phonological disorders. Second Edition. Infancy through Adulthood*. San Diego: Singular Publishing Group, Inc.

Blevins, J. (2004). *Evolutionary phonology: The emergence of sound patterns*. Cambridge: Cambridge University Press.

Boersma, P., & Weenink, D. (2008). Praat: doing phonetics by computer (Version 5.0.35) [computer program]. Retrieved September 23, 2008, from http://www.praat.org/

Boersma, Paul. 1998. *Functional Phonology: Formalizing the Interactions Between Articulatory and Perceptual Drives*. PhD dissertation. Amsterdam: University of Amsterdam.

Bosma, J. F. (1975). Anatomic and physiologic development of the speech apparatus. In D. B. Tower (Ed.), *The nervous system, part 3: Human communication and its disorders* (pp. 469-481). New York: Raven Press.

Broen, P. A., Strange, W., Doyle, S. S., & Heller, J. H. (1983). Perception and production of approximant consonants by normal and articulation-delayed preschool children. *Journal of Speech and Hearing Research*, 26, 601-608.

Brooks, P. J., & MacWhinney, B. (2000). Phonological priming in children's picture naming. *Journal of Child Language*, 27, 335-366.

Browman, C. P. and Goldstein, L. (1986). Towards an articulatory phonology. *Phonology Yearbook,* 3, 219-252.

Browman, C. P., & Goldstein, L. (1988). Some notes on syllable structure in Articulatory Phonology. *Phonetica*, 45, 140-155.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica*, 49, 155–180.

Browman, C. P. & Goldstein, L. (1995) Gestural syllable position effects in American English. In F. Bell-Berti & L. J. Raphael (Eds.), *Producing Speech: Contemporary Issues (for Kathering Safford Harris*) (pp. 19-33). Woodbury, NY: AIP Press.

Buder, E. H. (1996). Experimental phonology with acoustic phonetic methods: Formant measures from child speech. In B. Bernhardt, J. Gilbert, & D. Ingram (Eds.), *Proceedings of the UBC International Conference on Phonological Acquisition* (pp. 254–265). Somerville, MA: Cascadilla Press.

Byrd, D. (1992). Perception of assimilation in consonant clusters: A gestural model. *Phonetica*, 49, 1–24.

Byrd, D. (1995) C-Centers revisited. *Phonetica*, 52, 263-282.

Byrd, D. (1996). Influences on articulatory timing in consonant sequences. *Journal of Phonetics*, 24, 209-244.

Camerata, S., & Gandour, J. (1984). On describing idiosyncratic phonological systems. *Journal of Speech and Hearing Research*, 49, 262–266.

Carnegie Mellon University. (2007). Carnegie Mellon pronouncing dictionary [data file]. Retrieved September 10, 2008, from http://www.speech.cs.cmu.edu/cgi-bin/cmudict/

Chen, L. (2003). The origins in overlap of place assimilation. In G. Garding & M. Tsujimura (Eds.), *WCCFL 22. Proceedings of the XXIIth West Coast Conference on Formal Linguistics* (pp. 137–150). Somerville, MA: Cascadilla Press.

Chiat, S. (1983). Why Mikey's right and my key's wrong: The significance of stress and word boundaries in a child's output system. *Cognition*, 14, 275–300.

Cho, T. (1998). Intergestural overlap and timing in Korean palatalization: an Optimality Theoretic approach. In D. Silva (Ed.), *Japanese/Korean Linguistics* 8 (pp. 261-276). Stanford: CSLI.

Clements, G. N., & Osu, S. (2002). Explosives, implosives, and nonexplosives: the linguistic function of air pressure differences in stops. In C. Gussenhoven & N. Warner (Eds.), *Laboratory Phonology 7* (pp. 299-350). Berlin: Mouton de Gruyter.

Coady, J. A., & Aslin, R. N. (2004). Young children's sensitivity to probabilistic phonotactics in the developing lexicon. *Journal of Experimental Child Psychology*, 89, 183-213.

Cohen, J. H., & Diehl, C. F. (1963). Relation of speech-sound discrimination ability to articulation-type speech defects. *Journal of Speech and Hearing Disorders*, 28, 187–190.

Compton, A.J., & Streeter, M. (1977). Child Phonology: Data Collection and Preliminary Analyses. In *Papers and Reports on Child Language Development 7*. Palo Alto, CA: Stanford University.

Crary, M. A. (1984). Phonological characteristics of developmental verbal dyspraxia. *Seminars in Speech and Language*, 5, 71-83.

Crary, M. A. (1993). *Developmental motor speech disorders*. San Diego, CA: Singular Publishing Group.

Crelin, E. S. (1987). *The human vocal tract: Anatomy, function, development, and evolution*. New York: Vantage Press.

Cutler, A., Weber, A., Smits, R. & Cooper, N. (2004). Patterns of English phoneme confusions by native and non-native listeners. *Journal of the Acoustical Society of America*, 116, 3668-3678.

Dagenais, P. A., Critz-Crosby, P., & Adams, J. B. (1994). Defining and remediating persistent lateral lisps in children using electropalatography: Preliminary findings. *American Journal of Speech-Language Pathology*, 3, 67–76.

Davidson, L. (2003). *The Atoms of Phonological Representation: Gestures, Coordination and Perceptual Features in Consonant Cluster Phonotactics*. Ph D Dissertation, Johns Hopkins University.

Davis, B.L. & MacNeilage, P.F. (1994). Organization of babbling: A case study. *Language and Speech*, 37, 341–355.

Davis, B.L. & MacNeilage, P.F. (l995). The articulatory basis of babbling. *Journal of Speech and Hearing Research*, 38, 1199-1211.

Davis, B. L., Jakielski, K. J. and Marquardt, T. P. (1998). Developmental apraxia of speech: Determiners of differential diagnosis. *Clinical Linguistics and Phonetics*, 12, 25-45.

De Lacy, P. (2001). Markedness in prominent positions. In O. Matushansky, A. Costa, J. Martin-Gonzalez, L. Nathan, & A. Szczegielniak (Eds.), *HUMIT 2000, MIT Working Papers in Linguistics 40* (pp. 53-66). Cambridge, MA: MITWPL.

De Lacy, P. (2002). *The formal expression of markedness*. Doctoral dissertation, University of Massachusetts, Amherst.

Dell, G. (1984). Representation of serial order in speech: Evidence from the repeated phoneme effect in speech errors. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 10, 222–233.

Dell, G. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review*, 93, 283–321.

Dell, G., Burger, L., & Svec, W. (1997). Language production and serial order: a functional analysis and a model. *Psychological Review*, 104, 123–147.

Dell, G., Juliano, C., & Govindjee, A. (1993). Structure and content in language production: A theory of frame constraints in phonological speech errors. *Cognitive Science*, 17, 149-195.

Demuth, K., Culbertson, J. & Alter, J. (2006). Word-minimality, epenthesis, and coda licensing in the acquisition of English. *Language & Speech*, 49, 137-174.

Dinnsen, D. A. (1996). Context effects in the acquisition of fricatives. In B. Bernhardt, J. Gilbert, & D. Ingram (Eds.), *Proceedings of the UBC International Conference on Phonological Acquisition*. Somerville: Cascadilla Press.

Dinnsen, D. A. (1998). On the organization and specification of manner features. *Journal of Linguistics*, 34, 1-25.

Dinnsen, D. A., Chin, S. B., Elbert, M., & Powell, T. W. (1990). Some constraints on functionally disordered phonologies: Phonetic inventories and phonotactics. *Journal of Speech and Hearing Research*, 33, 28–37.

Dinnsen, D. A., & Eckman, F. R. (1977). Some substantive universals in atomic phonology. *Lingua*, 45, 1-14.

Dinnsen, D. A., & Farris-Trimble, A. W. (2008). The prominence paradox. In D. A. Dinnsen & J. A. Gierut (Eds.), *Optimality Theory, Phonological Acquisition and Disorders* (pp. 277-308). London: Equinox Publishing Ltd.

Dodd, B. & Mccormack, P. (1995). A model of speech processing for differential diagnosis of phonological disorders. In B. Dodd (Ed.), *Differential Diagnosis and Treatment of Children with Speech Disorders* (pp. 65–89). London: Whurr.

Dorman, M. F., Raphael, L. J., Liberman, A. M., & Repp, B. (1975). Some maskinglike phenomena in speech perception. *Haskins Laboratories Status Report on Speech Research*, SR-42/43, 265-276.

Dressler, W., Dziubalska-Kolaczyk, K., Gagarina, N., & Kilani-Schoch, M. (2005). Reduplication in child language. In *Studies on Reduplication*, Mouton de Gruyter.

Duffy, J. R. (2005). *Motor speech disorders*. St. Louis: Mosby Year Book.

Dyson, A. T. (1988). Phonetic inventories of 2- and 3- year old children. *Journal of Speech and Hearing Disorders*, 53, 89-93.

Echols, C., & Newport, E. (1992). The role of stress and position in determining first words. *Language Acquisition*, 2, 189-220.

Edwards, M. L. (1979). Word position in fricative acquisition. *Papers and Reports in Child Language Development*, 16, 67- 75.

Edwards, M. L. (1996). Word position and the production of fricatives. In Bernhardt, B., Gilbert, J., & Ingram, D. (Eds.), *Proceedings of the UBC International Conference on Phonological Acquisition* (pp. 149-58). Somerville: Cascadilla Press.

Edwards, J., Beckman, M. E. & Fletcher, J. (1991). The articulatory kinematics of final lengthening. *Journal of the Acoustical Society of America*, 89, 369-82.

Edwards, J., Fourakis, M., Beckman, M. E., & Fox, R. A. (1999). Characterizing Knowledge Deficits in Phonological Disorders. *Journal of Speech, Language, and Hearing Research*, 42, 169–186.

Edwards, J., Fox, R. A., Rogers, C. L. (2002). Final consonant discrimination in children: Effects of phonological disorder, vocabulary size, and articulatory accuracy. *Journal of Speech, Language, and Hearing Research*, 45, 231-242.

Edwards, J., Gibbon, F., & Fourakis, M. (1997). On Discrete Changes in the Acquisition of the Alveolar/Velar Stop Consonant Contrast. *Language and Speech*, 40, 203-210.

Elbers, L. (1982). Operating principles in repetitive babbling: a cognitive continuity approach. *Cognition*, 12, 45-63.

Farwell, C. (1977). Some strategies in the early production of fricatives. *Papers and Reports on Child Language Development*, 12, 97-104.

Ferguson, C. A. & Farwell, C. B. (1975). Words and sounds in early language acquisition. *Language*, 51, 419-439.

Ferguson, C. A. (1975). Fricatives in child language acquisition. In *Proceedings of the Eleventh International Congress of Linguistics* (pp. 647-664). Bologna, Italy: Società editrice il Mulino.

Ferguson, C. A. (1978). Fricatives in child language acquisition. In V. Honsa & M. N. Hardman-Bautista (Eds.), *Papers on Linguistics and Child Language* (pp. 93-115). The Hague, Netherlands: Mouton.

Fikkert, P., Levelt, C. C., & van de Weijer, J. (To appear). Input, intake and phonological development: the case of consonant harmony. *Submitted to First Language*.

Flemming, E. (1995). Auditory Representations in Phonology, Phd Dissertation, UCLA. [Revised version published by Routledge, 2002]

Flemming, E. (2001). Scalar and categorical phenomena in a unified model of phonetics and phonology. *Phonology*, 7-44.

Flemming, E. (2003). The relationship between coronal place and vowel backness. *Phonology*, 20, 335–373.

Flemming, E. (2008). The grammar of coarticulation (draft). To appear in Embarki, M., & Dodane, C. (Eds.) *La Coarticulation: Indices, Direction et Representation*.

Fletcher, S. G. (1973). Maturation of the speech mechanism. *Folia Phoniatrica*, 25, 161-172.

Fletcher, S. G. (1989). Palatometric specification of stop, affricate, and sibilant sounds. *Journal of Speech and Hearing Research*, 32, 736–748.

Fletcher, S. G. (1992). *Articulation: A physiological approach*. San Diego, CA: Singular.

Forrest, K. (2003). Diagnostic criteria of developmental apraxia of speech used by clinical speech-language pathologists. *American Journal of Speech-Language Pathology*, 12, 376-380.

Forrest, K., Chin, S. B., Pisoni, D. B., & Barlow, J. N. (1995). Talker normalization in normally articulating and phonologically delayed children: Methodological considerations. In *Research on Spoken Language Processing, No. 19* (pp. 229-251). Bloomington: Indiana University Press, Department of Psychology.

Forrest, K., Weismer, G., Hodge, M., Dinnsen, D. A., & Elbert, M. (1990). Statistical analysis of word-initial /k/ and /t/ produced by normal and phonologically disordered children. *Clinical Linguistics and Phonetics*, 4, 327- 340.

Fougeron, C. (1996). Articulation of French nasal segments depending on their prosodic position. Presented at the January meeting of the Linguistic Society of America, San Diego.

Fougeron, C. (1998). *Variations articulatoires en début de constituants prosodiques de différents niveaux en français*. PhD dissertation, Université Paris III - Sorbonne Nouvelle.

Fougeron, C. (1999). Prosodically conditioned articulatory variations: A review. *UCLA Working Papers in Phonetics*, 97, 1–73.

Fougeron, C. (2001). Articulatory properties of initial segments in several prosodic constituents in French. *Journal of Phonetics*, 29, 109-135

Fougeron, C., & Keating, P. (1996). Articulatory strengthening in prosodic domain-initial position. *UCLA Working Papers in Phonetics*, 92, 61-87.

Fougeron, C., & Keating, P. (1997). Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustical Society of America*, 101, 3728-3740.

Fowler, C. A. (1987). Consonant-vowel cohesiveness in speech production as revealed by initial and final consonant exchanges. *Speech Communication*, 6, 231-244.

Frisch, S. (2004). Language processing and segmental OCP effects. In R. Hayes, R. Kirchner, & D. Steriade (Eds.), *Phonetically-based phonology* (pp. 346–371). Cambridge: Cambridge University Press.

Frisch, S., Pierrehumbert, J. & Broe, M. (2004) Similarity avoidance and the OCP. *Natural Language and Linguistic Theory*, 22, 179-228.

Frisch, S. & Wright, R. (2002). The phonetics of phonological speech errors: An acoustic analysis of slips of the tongue. *Journal of Phonetics*, 30, 139–162.

Fromkin, V. (1973). *Speech errors as linguistic evidence*. The Hague: Mouton.

Fujimura, O., Macchi, M. J., and Streeter, L. (1978). Perception of stop consonants with conflicting transitional cues: A cross-linguistic study. *Language and Speech*, 21, 337-346

Fujimura, O. & Miller, J. E. (1979). Mandible height and syllable-final tenseness. *Phonetica,* 36, 263-272.

Gafos, A. 1995. A-templatic reduplication. *Linguistic Inquiry*, 29, 515-527.

Gafos, A. (2002). A grammar of gestural coordination. *Natural Language and Linguistic Theory*, 20, 269–337.

Gallagher, G., & Coon, J. (In press). Distinguishing total and partial identity: evidence from Chol. To appear in *Natural Language and Linguistic Theory*.

Geudens, A., & Sandra, D. (2003). Beyond children's implicit phonological knowledge: No support for an onset-rime structure in children's explicit phonological awareness. *Journal of Memory and Language*, 49, 157-182.

Geumann, A., Kroos, C., & Tillmann, H. G. (1999). Are there compensatory effects in natural speech? In *Proceedings of the 14th International Congress in Phonetic Sciences*, *1* (pp. 399–402). San Francisco.

Gibbon, F. (1990). Lingual activity in two speech-disordered children's attempts to produce velar and alveolar stop consonants: Evidence from electropalatographic (EPG) data. *British Journal of Disorders of Communication*, 25, 329-340.

Gibbon, F. (1999). Undifferentiated Lingual Gestures in Children with Articulation/Phonological Disorders. *Journal of Speech, Language, and Hearing Research,* 42, 382–397.

Gibbon, F, Dent, H., & Hardcastle, W. (1993). Diagnosis and therapy of abnormal alveolar stops in a speech-disordered child using EPG. *Clinical Linguistics and Phonetics,* 7, 247-268.

Gibbon, F., & Hardcastle, W. (1987). Articulatory description and treatment of "lateral /s/" using electropalatography: A case study. *British Journal of Disorders of Communication,* 22, 203–217.

Gibbon, F., Hardcastle, B., & Dent, H. (1995). A study of obstruent sounds in school-age children with speech disorders using electropalatography. *European Journal of Disorders of Communication*, 30, 213–225.

Gibbon, F., Hardcastle W., & Moore, A. (1990). Modifying abnormal tongue patterns in an older child using electropalatography. *Child Language Teaching and Therapy*, 6, 227–245.

Gildersleeve-Neumann, C. E., Davis, B. L., & MacNeilage, P. F. (2000). Contingencies governing production of for fricatives, affricates and liquids in babbling. *Applied Psycholinguistics*, 21, 341-363.

Goad, H. (1997) Consonant harmony in child language: An optimality-theoretic account. In S.J. Hannahs & M. Young Scholten (Eds.), *Focus on phonological acquisition* (pp. 113-142). Amsterdam: John Benjamins.

Goad, H. (2004). Consonant harmony in early grammars revisited: Domains, licensing and directionality. In *Actes des/Proceedings of Journées d'Études Linguistiques (JEL) 2004: [Domain[e]s]*. Nantes: UFR Lettres et Langages.

Goffman, L. (2004). Kinematic differentiation of prosodic categories in normal and disordered language development. *Journal of Speech, Language, and Hearing Research*, 47, 1088–1102.

Goldman, R., & Fristoe, M. (1986). *The Goldman-Fristoe Test of Articulation*. Circle Pines, MN: American Guidance Services.

Goldrick, M., & Blumstein, S. (2006). Cascading activation from phonological planning to articulatory processes: Evidence from tongue twisters. *Language and Cognitive Processes*, 21, 649–683.

Goldsmith, J. (1979). *Autosegmental Phonology*. New York: Garland Press.

Goldstein, L., Pouplier, M., Chen, L., Saltzman, E., & Byrd, D. (2007). Dynamic action units slip in speech production errors. *Cognition*, 103, 386–412.

Gordeeva, O. B. (2007). Learnability of laryngeal abduction in voiceless fricatives: cross-linguistic evidence. In J. Trouvain & W.J. Barry (Eds.), *16th International Congress of Phonetic Sciences*. Saarbrücken: Universität des Saarlandes.

Gracco, V. L. (1994). 'Some organizational characteristics of speech movement control. *Journal of Speech and Hearing Research*, 37, 4–27.

Green, J. R., Moore, C. A., Reilly, K. J. (2002). The sequential development of jaw and lip control for speech. *Journal of Speech, Language, and Hearing Research*, 45, 66-79.

Groenen, P., Maassen, B., Crul, T., & Thoonen, G. (1996). The Specific Relation Between Perception and Production Errors for Place of Articulation in Developmental Apraxia of Speech. *Journal of Speech and Hearing Research*, 39, 468-482.

Grunwell, P. (1981). The Development of Phonology: A Descriptive Profile. *First Language*, 3, 161-191.

Haken, H., Peper, C. E., Beek, P. J., & Daffertshofer, A. (1996). A model for phase transitions in human hand movements during multifrequency tapping. *Physica*, 90, 179–196.

Hale, M. (2003). Neogrammarian sound change. In B. Joseph & R. Janda (Eds.), *Handbook of Historical Linguistics* (pp. 343-368). Oxford: Basil Blackwell.

Hale, M., & Reiss, C. (1998). Formal and Empirical Arguments concerning Phonological Acquisition. *Linguistic Inquiry*, 29, 656–683.

Hale, M. & Reiss, C. (2000). Phonology as cognition. In N. Burton-Roberts, P. Carr, & G. Doherty (Eds.), *Phonological Knowledge: Conceptual and Empirical Issues* (pp. 161-184). Oxford: Oxford University Press.

Hall, P. K. (2000). A letter to the parents of a child with developmental apraxia of speech. Part I. Speech characteristics of the disorder. *Language, Speech, and Hearing Services in Schools*, 31, 169-172.

Hall, P. K., Jordan, L. S., & Robin, D. A. (1993). *Developmental Apraxia of Speech*. Austin, TX: Pro-Ed.

Hamann, S., & Fuchs, S. (2008). How do voiced retroflex stops evolve? Evidence from typology and an articulatory study. In M. Żygis & S. Fuchs (Eds.), *ZAS Papers in Linguistics 49* (97-131).

Hansson, G. (2001). *Theoretical and typological issues in consonant harmony*. Doctoral dissertation, University of California, Berkeley.

Hardcastle, W. J., Morgan Barry, R. A., & Clark, C. J. (1987). An instrumental phonetic study of lingual activity in articulation-disordered children. *Journal of Speech and Hearing Research*, 30, 171–184.

Hayes, B. (1999). Phonetically-Driven Phonology: The Role of Optimality Theory and Inductive Grounding. In Darnell, M., Moravscik, E., Noonan, M., Newmeyer, F., and Wheatly, K., (Eds.), *Functionalism and Formalism in Linguistics, Volume I: General Papers* (pp. 243-285). Amsterdam: John Benjamins.

Hayes, B., Kirchner R., & Steriade, D. (Eds). (2004). Phonetically-Based Phonology. Cambridge: Cambridge University Press.

Hayes, B., & Stivers, T. (1996). A phonetic account of postnasal voicing. Ms., Department of Linguistics, UCLA.

Hertrich I, & Ackermann H. (1997). Articulatory control of phonological vowel length contrasts: Kinematic analysis of labial gestures. *Journal of the Acoustical Society of America*, 102, 523-536.

Hewlett, N., Gibbon, F., & Cohen-McKenzie, W. (1998). When is a velar an alveolar? Evidence supporting a revised psycholinguistic model of speech production in children. *International Journal of Language & Communication Disorders*, 33, 161-76.

Hillenbrand, J., Getty, L. A., Clark, M. J., & Wheeler, K. (1995). Acoustic characteristics of American English vowels. *Journal of the Acoustical Society of America*, 97, 3099–3111.

Hodge, M. M. (1989). *A comparison of spectral-temporal measures across speaker age: Implications for an acoustic characterization of speech maturation*. Unpublished doctoral dissertation, University of Wisconsin-Madison.

Hoffman, P. R., Daniloff, R. G., Bengoa, D., & Schuckers, G. H. (1985). Misarticulating and Normally Articulating Children's Identification and Discrimination of Synthetic [r] and [w]. *Journal of Speech and Hearing Disorders*, 50, 46-53.

Hoole, P. (1999). On the lingual organization of the German vowel system. *Journal of the Acoustical Society of America*, 106, 1020–1032.

Hoole, P., Munhall, K., & Mooshammer, C. (1998). Do airstream mechanisms influence tongue movement paths? *Phonetica*, 55, 131-146.

Houde, R. A. (1967). *A study of tongue body motion during selected speech sounds*. Ph.D. Dissertation, University of Michigan.

Howard, S. (1998). *Phonetic constraints on phonological systems: Combining perceptual and instrumental analysis in the investigation of speech disorders*. Unpublished doctoral thesis, University of Sheffield, UK.

Hyman, L. (1977). On the nature of linguistic stress. In L. Hyman (Ed.), *Studies in Stress and Accent* (pp. 37-82). University of Southern California.

Hyman, L. (2001). Privative tone in Bantu. In S. Kaji (Ed.), *Cross-linguistic studies of tonal phenomena* (pp. 237-257). Tokyo: Institute for the Study of Languages and Cultures.

Ingram, D. (l974). Fronting in child phonology. *Journal of Child Language*, 1, 233-241.

Inkelas, S., & Rose, Y. (2003) Velar Fronting Revisited. In B. Beachley, A. Brown, & F. Conlin (Eds.), *Proceedings of the 26th Annual Boston University Conference on Language Development* (pp. 334-345). Somerville, MA: Cascadilla Press.

Inkelas, S., & Rose, Y. (2008). Positional Neutralization: A Case Study from Child Language. *Language*, 83, 707-736.

Isshiki, N., & Ringel, R. (1964). Air flow during the production of selected consonants. *Journal of Speech and Hearing Research*, 7, 233-244.

Jacks, A., Marquardt, T. P., and Davis, B. L. (2006). Consonant and syllable structure patterns in childhood apraxia of speech: Developmental change in three children. *Journal of Communication Disorders*, 39, 424-441.

Jakobson, R. (1941/68). *Child language, aphasia, and phonological universals*. The Hague: Mouton. English trans. of *Kindersprache, aphasie und allgemeine lautgesetze*. Uppsala.

Johnson, K., Pisoni, D., & Bernacki, R. (1990). Do voice recordings reveal whether a person is intoxicated? A case study. *Phonetica*, 47, 215-237.

Jun, J. H. (1995). *Perceptual and Articulatory Factors in Place Assimilation: An Optimality Theoretic Approach*. PhD dissertation, UCLA.

Jun, J. H. (1996). Place assimilation is not the result of gestural overlap: Evidence from Korean and English. *Phonology*, 13, 377-407.

Jusczyk, P. (1997). *The discovery of spoken language*. London: MIT Press.

Jusczyk, P. W., Goodman, M., & Bauman, A. (1999). 9-month-olds' attention to sound similarities in syllables. *Journal of Memory and Language*, 40, 62-82.

Kager, R. (1995). Stem disyllabicity in Guugu Yimidhirr. Ms., OTS/RUU. ROA-70. Rutgers Optimality Archive, http://roa.rutgers.edu/.

Kager, R., Van der Feest, S.V. H., Fikkert, P., Kerkhoff, A. O., & Zamuner, T. S. (2007). Representations of [voice]: evidence from acquisition. In J. van der Weijer & E. J. van der Torre (Eds.), *Voicing in Dutch*. Current Issues in Linguistic Theory, 286 (pp. 41-80). Amsterdam: John Benjamins.

Keating, P. A. (1985). Universal phonetics and the organization of grammars. In V. Fromkin (Ed.), *Phonetic Linguistics* (pp. 115-132). Orlando: Academic Press.

Keating, P. (1995). Effects of prosodic position on /t,d/ tongue/palate contact. *Proceedings of the 13th International Congress of Phonetic Sciences*, 3, 432-435.

Keating, P. A. (1996). The Phonology-Phonetics Interface. In U. Kleinhenz (Ed.), *Interfaces in Phonology*. Studia grammatica 41 (pp. 262-278). Berlin: Akademie Verlag.

Keating, P. (2006). Phonetic Encoding of Prosodic Structure. In J. Harrington, & M. Tabain (Eds.), *Speech production: Models, phonetic processes, and techniques* (pp. 167-186). New York: Macquarie Monographs in Cognitive Science, Psychology Press.

Keating, P. A., Lindblom, B., Lubker, J., & Kreiman, J. (1994). Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics*, 22, 407–422.

Keating, P. A., Wright, R., & Zhang, J. (1999). Word-level asymmetries in consonant articulation. *UCLA Working Papers in Phonetics*, 97, 157-173.

Kehoe, M. M. & Stoel-Gammon, C. (1997). Truncation patterns in English-speaking children's word productions. *Journal of Speech, Language, and Hearing Research*, 40, 526-541.

Kent, R. D. (1981). Articulatory-acoustic perspective on speech development. In R. E. Start (Ed.), *Language behavior in infancy and early childhood* (pp. 105–26). New York: Elsevier.

Kent, R. D. (1983). The segmental organization of speech. In P. MacNeilage (Ed.), *The production of speech* (pp. 57-89). New York: Springer-Verlag.

Kent, R. D. (1992). The biology of phonological maturation. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological Development: Models, Research, Implications* (pp. 65-90). Timonium, MD: York Press.

Kent, R. D. (1997). Gestural phonology: Basic concepts and applications in speech-language pathology. In M. J. Ball, & R. D. Kent (Eds.), *The new phonologies: Developments in clinical linguistics* (pp. 247–268). London: Singular Press.

Kent, R. D. (2000). Research on speech motor control and its disorders: a review and prospective. *Journal of Communication Disorders*, 33, 391-427

Kent, R. D., & Bauer, H. R. (1985). Vocalizations of one-year olds. *Journal of Child Language*, 12, 491–526.

Kent, R. D. & Forner, L. L. (1980). Speech segment durations in sentence recitations by children and adults. *Journal of Phonetics*, 8, 157-168.

Kent, R. D., & Moll, K. L. (1969). Vocal-tract characteristics of the stop cognates. *Journal of the Acoustical Society of America*, 46, 1549-1555.

Khan, L., & Lewis, N. (2002). *Khan-Lewis Phonological Analysis-2*. Circle Pines, MN: American Guidance Service.

Kilpatrick, C., Barlow, J., and Cragg, S. (2007). Reduplication in child phonology: A structural markedness account. Paper presented at the Annual Meeting of the Linguistic Society of America, 4-7 Jan 2007, Anaheim, CA.

Kingston, J. (1990). Articulatory binding. In J. Kingston and M. E. Beckman (Eds.), *Papers in Laboratory Phonology I. Between the Grammar and Physics of Speech* (pp. 406-434). Cambridge: Cambridge University Press.

Kiparsky, P. (1994). Remarks on markedness. Paper presented at TREND 2, Stanford.

Kiparsky, P., and Menn, L. (1977). On the Acquisition of Phonology. In J. Macnamara (Ed.), *Language Learning and Thought* (pp. 47-78). Academic Press, New York.

Kirchner, R. (1997). Contrastiveness and Faithfulness. *Phonology*, 14, 83-111.

Kirchner, R. (1998). *An effort-based approach to consonant lenition*. Doctoral Dissertation. UCLA. Reprinted (2001) by Routledge.

Kirk, C. & Demuth, K. (2003). Onset/coda asymmetries in the acquisition of clusters. In B. Beachley, A. Brown, & F. Conlin, *Proceedings of the 27th Annual Boston University Conference on Language Development* (pp. 437-448). Somerville, MA: Cascadilla Press.

Kochetov, A., & Radišić, M. (2008). Latent consonant harmony in Russian: Experimental evidence for Agreement by Correspondence. Paper presented at the 17th meeting of Formal Approaches to Slavic Linguistics, Yale University.

Krakow, R. A. (1999). Physiological organization of syllables: a review. *Journal of Phonetics*, 27, 23-54.

Ladefoged, P. (1967). *Three areas of experimental phonetics*. London: Oxford University Press

Ladefoged, P., & Loeb. G. (2002). Preliminary experiments on respiratory activity in speech. *UCLA Working Papers in Phonetics*, 101, 50-60.

Ladefoged, P., & Maddieson, I. (1996). *The sounds of the world's languages*. Oxford: Blackwell.

Lavoie, L. (2001). *Consonant Strength: Phonological Patterns and Phonetic Manifestations*. New York: Garland.

Leeper, H. A. (1969). *Pressure measurements of articulatory behavior during alterations of vocal effort*. Doctoral dissertation, Purdue University.

Lehiste, I. (1960). An acoustic-phonetic study of internal open juncture. Supplement to *Phonetics*, 5.

Lehiste, I. (1961). Acoustic studies of boundary signals. In A. Sovijarvi & P. Aalto, *Proceedings of the 4th International Congress of Phonetic Science* (pp. 178-187). The Hague: Mouton.

Lehiste, I. (1964). Juncture. In E. Zwirner and W. Bethge (Eds.), *Proceedings of the Fifth International Congress of Phonetic Sciences* (pp. 172-200). Basel: Karger.

Levelt, C., Schiller, N., & Levelt, W. (2000). The acquisition of syllable types. *Language. Acquisition*, 8, 237-264.

Lewis, B. A., Freebairn, L. A., Hansen, A. J., Iyengar, S. K., & Taylor, H. G. (2004). School-age follow-up of children with childhood apraxia of speech. *Language, Speech, and Hearing Services in Schools*, 35, 122- 40.

Li, F. (2008). *The phonetic development of voiceless sibilant fricatives in children speaking English, Japanese and Mandarin Chinese*. Doctoral Dissertation, Ohio State University.

Li, F., Edwards, J., & Beckman, M. E. (2009). Contrast and covert contrast: The phonetic development of voiceless sibilant fricatives in English and Japanese toddlers. *Journal of Phonetics*, 37, 111-124.

Liberman, A. M., Cooper, F. S., Shankweiler, D. P., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review*, 74, 431-461.

Lindblom, B. (1963). Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America*, 35, 1773-1781.

Lindblom, B. (1983). Economy of speech gestures. In P. F. MacNeilage (Ed.), *The Production of Speech* (pp. 217-246). New York: Springer-Verlag.

Lleó, C. & Prinz, M. (1996). Consonant clusters in child phonology and the directionality of syllable structure assignment. *Journal of Child Language*, 23, 31-56.

Locke, J. L. (1980). The inference of speech perception in the phonologically disordered child. Part II. Some clinically novel procedures, their use, some findings. *Journal of Speech and Hearing Disorders*, 45, 445-468.

Locke, J. L. (1983). *Phonological acquisition and change*. New York: Academic Press.

Lombardi, L. (1999). Positional faithfulness and voicing assimilation in Optimality Theory. *Natural Language and Linguistic Theory*, 17, 267-302.

Lowe, R. J., Knutson, P. J., & Monson, M. A. (1985). Incidence of fronting in preschool children. *Language, Speech, and Hearing Services in Schools*, 16, 119-123.

Luce, R. D. (1963). Detection and recognition. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of Mathematical Psychology* (pp. 103-187). New York: Wiley.

MacKay, D. (1970). Spoonerisms: the structure of errors in the serial order of speech. *Neuropsychologia*, 8, 323-350.

MacKenzie, C. L., Marteniuk, R. G., Dugas, C., Liske, D. & Eickmeier, B. (1987). Three-dimensional movement trajectories in Fitts' task: Implications for control. *Quarterly Journal of Experimental Psychology*, 39, 629-647.

Macnamara, J. (1982). *Names for things: A study of child language*. Cambridge, MA: Bradford Books/MIT Press.

MacNeilage, P. F., & Davis, B. L. (1990). Acquisition of speech production: Frames, then content. In M. Jeannerod (Ed.), *Attention and performance: Vol. 13, Motor representation and control* (pp. 453-475). Hillsdale, N.J.: Erlbaum.

Maddieson, I., & Precoda, K. (1990). Updating UPSID. *UCLA Working Papers in Phonetics*, 74, 104-114.

Malécot, A. (1955). The force of articulation of American stops and fricatives as a function of position. *Phonetica*, 18, 95-102.

Marshall, C., & Chiat, S. (2003). A foot domain account of prosodically-conditioned substitutions. *Clinical Linguistics and Phonetics*, 17, 645–57.

Maxwell, E. M., & Weismer, G. (1982). The contribution of phonological, acoustic, and perceptual techniques to the characterization of a misarticulating child's voice contrast for stops, *Applied Psycholinguistics*, 3, 29-43.

McCarthy, J. J. (1986). OCP Effects: Gemination and Antigemination. *Linguistic Inquiry*, 17, 207–263.

McCarthy, J. J. (1994). The Phonetics and Phonology of Semitic Pharyngeals. In P. Keating (Ed.), *Papers in Laboratory Phonology III* (pp. 191-283). Cambridge: Cambridge University Press.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of Basic Findings. *Psychological Review*, 88, 375-407.

McGlone, R. E., & Shipp, T. (1972). Comparison of subglottal air pressures associated with /p/ and /b/. *Journal of the Acoustical Society of America*, 51, 664.

McReynolds, L. V., Kohn, J., & Williams, G. C. (1975). Articulatory-defective children's discrimination of their production errors. *Journal of Speech and Hearing Disorders*, 40, 327-338.

Menn, L. (1971). Phonotactic rules in beginning speech. *Lingua*, 26, 225-51.

Meyer, A. (1992). Investigation of phonological encoding through speech error analyses: Achievements, limitations, and alternatives. *Cognition*, 42, 181-211.

Miller, G. A., & Nicely, P. (1955). An analysis of perceptual confusions among some English consonants. *Journal of the Acoustical Society of America*, 27, 338-352.

Mitchell, P. R., & Kent, R. D. (l990). Phonetic variation in multisyllabic babbling. *Journal of Child Language*, 17, 247-265.

Moen, I., & Simonsen, H. G. (1997). Effects of voicing on /t, d/ tongue/palate contact in English and Norwegian. Paper presented at the 5th European Conference on Speech Communication and Technology. Rhodes.

Monnin, L. M., & Huntington, D.A. (1974). Relationship of articulatory defects to speech-sound identification. *Journal of Speech and Hearing Research*, 17, 352-366.

Mooshammer, C., Hoole, P., Geuman, A. (2006). Interarticulator cohesion within coronal consonant production. *Journal of the Acoustical Society of America*, 120, 1028-1039.

Mooshammer, C., Hoole, P. & Geumann, A. (2007). Jaw and order. *Language & Speech*, 50, 145-176.

Mooshammer, C.; Hoole, P.; Kühnert, B. (1995). On loops. *Journal of Phonetics*, 23, 3-21.

Morisette, M. L., Dinnsen, D. A., & Gierut, J. A. (2003). Markedness and Context Effects in the Acquisition of Place Features. *Canadian Journal of Linguistics*, 48, 329-355.

Motley, M. T., & Baars, B. J. (1975). Encoding sensitivities to phonological markedness and transition probability: Evidence from spoonerisms. *Human Communication Research*, 2, 351-361.

Munhall, K. G., Flanagan, J. R., & Ostry, D. J. (1991). Sensorimotor transformations and control strategies in speech In Y. Tohkura, Y. Sagisaka, & E. Vatiokis-Bateson (Eds.), *Speech perception, production and linguistic structure*. Tokyo: OHM Publishing.

Munson, B., Bjorum, E., & Windsor, J. (2003). Acoustic and perceptual correlates of stress in nonwords produced by children with suspected developmental apraxia of speech and children with phonological impairments. *Journal of Speech, Language, and Hearing Research*, 46, 189-202.

Nathani, S., Oller, D. K., & Cobo-Lewis, A. B. (2003). Final Syllable Lengthening (FSL) in Infant Vocalizations. *Journal of Child Language*, 30, 3-25.

Ní Chiosáin, M., & Padgett, J. (2001). Markedness, Segment Realization and Locality in Spreading. In L. Lombardi (Ed.), *Constraints and representations: segmental phonology in Optimality Theory*. Cambridge: Cambridge University Press.

Nicolaidis, K., Edwards, J., Beckman, M., & Tserdanelis, G. (2003). Acquisition of lingual obstruents in Greek. Paper presented at the 6th International Conference of Greek Linguistics, Rethymno, Crete.

Nittrouer, S. (1993). The Emergence of Mature Gestural Patterns Is Not Uniform – Evidence from an Acoustic Study. *Journal of Speech and Hearing Research*, 36, 959-972.

Nittrouer, S., & Studdert-Kennedy, M. (1987). The Role of Coarticulatory Effects in the Perception of Fricatives by Children and Adults. *Journal of Speech and Hearing Research*, 30, 319-329.

Nittrouer, S., Studdert-Kennedy, M., & McGowan, R. (1989). The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults. *Journal of Speech and Hearing Research*, 32, 120-132.

Ohala, J. J., & Kawasaki, H. (1984). Prosodic phonology and phonetics. *Phonology Yearbook*, 1, 113-127.

Ohala, J. J. (1981). The listener as a source of sound change. In C. S. Masek, R. A. Hendrick, & M. F. Miller (Eds.), *Papers from the Parasession on Language and Behavior* (pp. 178-203). Chicago: Chicago Linguistic Society.

Ohala, J. J. (1983). The origin of sound patterns in vocal tract constraints. In P.F. MacNeilage (Ed.), *The production of speech* (pp. 189-216). New York: Springer-Verlag.

Ohala, J. J. (1990). The phonetics and phonology of aspects of assimilation. In J. Kingston & M. Beckman (Eds.), *Papers in Laboratory Phonology I: Between the grammar and the physics of speech* (pp. 258-275). Cambridge: Cambridge University Press.

Ohala, J. J. (1993). The phonetics of sound change. In C. Jones (Ed.), *Historical linguistics: problems and perspective*s (pp. 237-278). London: Longman.

Oller, D. K., & Eilers, R. E. (1982). Similarity of babbling in Spanish-leaning and English-learning babies. *Journal of Child Language*, 9, 565-577.

Oller, K., Wieman, L., Doyle, W., & Ross, C. (1976). Infant babbling and speech. *Journal of Child Language*, 3, 1-11.

Pater, J. (1997). Minimal Violation and Phonological Development. *Language Acquisition*, 6, 201-253.

Pater, J. (1999). The comprehension/production dilemma and the development of receptive competence. Ms., University of Alberta.

Pater, J. (2002). Form and Substance in Phonological Development. In L. Mikkelson and C. Potts, (Eds.), *WCCFL 21* (pp. 348-372). Somerville, MA: Cascadilla Press.

Pater, J. (2004) Bridging the gap between receptive and productive development with minimally violable constraints. In R. Kager, J. Pater & W. Zonneveld (Eds.), *Constraints in phonological acquisition* (pp. 219-244). Cambridge: Cambridge University Press.

Pater, J., & Werle, A. (2001). Typology and variation in child consonant harmony. In ed. by C. Féry, A. D. Green, & R. van de Vijver (Eds.), *Proceedings of HILP5* (pp. 119-39). University of Potsdam.

Pater, J. & Werle, A. (2003) Direction of assimilation in child consonant harmony. *Canadian Journal of Linguistics*, 48, 385-408.

Peper, C. E., Beek, P. J., & van Wieringen, P. C. W. (1995). Multifrequency coordination in bimanual tapping: asymmetric coupling and signs of supercriticality. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1117-1138

Pepinsky, T., Demuth, K., & Roark, B. (2001). The status of 'filler syllables' in children's early speech. In A. H.-J. Do, L. Domínguez, & A. Johansen (Eds.), *Proceedings of the 25th Annual Boston University Conference on Language Development* (pp.575-586). Somerville, MA: Cascadilla Press.

Perkell, J. S. (1969). Physiology of Speech Production: Results and Implications of a Quantitative Cineradiographic Study. *Research Monograph No. 53*. Cambridge, MA: MIT Press.

Peterson, G. & Barney, H. (1952). Control methods used in the study of vowels. *Journal of the Acoustical Society of America*, 24, 175-184.

Pierrehumbert, J. (1993). Prosody, Intonation, and Speech Technology. In M. Bates & R. Weischedel (Eds.), *Challenges in Natural Language Processing* (pp. 257-282). Cambridge: Cambridge University Press.

Pinker, S. (1984). *Language learnability and language development*. Cambridge, MA: Harvard University Press.

Pollock, K. E., & Hall, P. K. (1991). An analysis of the vowel misarticulations of five children with developmental apraxia of speech. *Clinical Linguistics and Phonetics*, 5, 207-224.

Pouplier, M. (2003). The dynamics of error. In M.-J. Solé, D. Recasens, & J. Romero, (Eds.), *Proceedings of the 15th International Congress of the Phonetic Sciences* (pp. 2245-2248). Rundle Mall: Causal Productions.

Pouplier, M. (2008). The role of a coda consonant as error trigger in repetition tasks. *Journal of Phonetics*, 36, 114–140.

Pouplier, M. & Goldstein, L. (2005). Asymmetries in the perception of speech production errors. *Journal of Phonetics*, 33, 47–75.

Pouplier, M. & Hardcastle, W. (2005). A re-evaluation of the nature of speech errors in normal and disordered speakers. *Phonetica*, 62, 227-243.

Pozdniakov, K. & Segerer, G. (2007). Similar place avoidance: A statistical universal. *Linguistic Typology*, 11, 307-348.

Prince, A., and Tesar, B. (2004). Learning phonotactic distributions. In R. Kager, J. Pater & W. Zonneveld (Eds.), *Constraints in phonological acquisition* (pp. 245-291). Cambridge: Cambridge University Press.

Raaymakers, E., & Crul, T. (1988). Perception and production of the final /s-ts/ contrast in Dutch by misarticulating children. *Journal of Speech and Hearing Disorders* 53, 262–270.

Redford, M. A., & Diehl , R. L. (1999). The relative distinctiveness of initial and final consonants in CVC syllables. *Journal of the Acoustic Society of America*, 106, 1555-1565.

Redford, M. L., MacNeilage, P. F. & Davis, B. L. (1997). Perceptual and motor influences on final consonant inventories in babbling. *Phonetica*, 54, 172-186.

Reich, P. A. (1977). Evidence for a stratal boundary from slips of the tongue. *Forum Linguisticum*, 2, 211-217.

Rochet-Capellan, A., & Schwartz, J.-L. (2005). The labial-coronal effect and CVCV stability during reiterant speech production: An articulatory analysis. In *Proceedings of INTERSPEECH 2005* (pp. 1013–1016).

Rose,Y. (2000). *Headedness and Prosodic Licensing in the L1 Acquisition of Phonology*. Ph.D. dissertation, McGill University.

Rose, S. & Walker, R. (2004). A typology of consonant agreement as correspondence. *Language*, 80, 475–531.

Rvachew, S. & Andrews, E. (2002). The influence of syllable position on children's production of consonants. *Clinical Linguistics and Phonetics*, 16, 183–98.

Rvachew, S., & Jamieson, D. G. (1989). Perception of voiceless fricatives by children with a functional articulation disorder. *Journal of Speech and Hearing Research*, 54, 193–208.

Sander, E. (1972). When are speech sounds learned? *Journal of Speech and Hearing Disorders*, 37, 55-63.

Schellekens, J. M. H., Kalverboer, A. F., Scholten, C. A. (1984). The Micro-Structure of Tapping Movements in Children. *Journal of Motor Behavior*, 16, 20-39.

Schwartz, M. F., Saffran, E. M., Bloch, D. E., & Dell, G. S. (1994). Disordered speech production in aphasic and normal speakers. *Brain and Language*, 47, 52-88.

Scobbie, J. M. (1998) Interactions between the acquisition of phonetics and phonology. In M. C. Gruber, D. Higgins, K. Olson, & T. Wysocki (Eds.) *Papers from the 34th Annual Regional Meeting of the Chicago Linguistic Society, Volume II: The Panels* (pp. 343-358). Chicago: Chicago Linguistics Society.

Scobbie, J. M., Gibbon, F., Hardcastle, W. J. & Fletcher, P. (1998) Covert contrast and the acquisition of phonetics and phonology. In W. Ziegler & K. Deger (Eds.), *Clinical Phonetics and Linguistics* (p. 147-156). London: Whurr Publishers.

Scobbie, J., Gibbon, F., Hardcastle, W., & Fletcher, P. (2000). Covert contrast as a stage in the acquisition of phonetics and phonology. In M. Broe & J. Pierrehumbert (Eds.), *Papers in Laboratory Phonology V* (pp. 194-207). Cambridge, MA: Cambridge University Press.

Sharkey, S. G. & Folkins, J. W. (1985). Variability of lip and jaw movements in children and adults: implications for the development of speech motor control. *Journal of Speech and Hearing Research*, 28, 8-15.

Shattuck-Hufnagel, S. (1983). Sublexical units and suprasegmental structure in speech production planning. In P. F. MacNeilage (Ed.), *The production of speech* (pp. 109-136). New York: Springer.

Shattuck-Hufnagel, S. (1992). The role of word structure in segmental serial ordering. *Cognition*, 42, 213–259.

Shattuck-Hufnagel, S. & Klatt, D. H. (1979). The limited use of distinctive features and markedness in speech production: Evidence from speech errors. *Journal of Verbal Learning and Verbal Behaviour*, 18, 41–55.

Sherman, D., & Geith, A. (1967). Speech sound discrimination and articulation skill. *Journal of Speech and Hearing Research* 10, 277–280.

Shriberg, L. D., Aram, D. M. & Kwiatkowski, J. K. (1997). Developmental apraxia of speech: II. Toward a diagnostic marker. *Journal of Speech, Language, and Hearing Research*, 40, 286-312.

Shriberg, L. D., Green, J. R., Campbell, T. F., McSweeny, J. L., & Scheer, A. (2003). A diagnostic marker for childhood apraxia of speech: The coefficient of variation ratio. *Clinical Linguistics and Phonetics*, 17, 575-595.

Silverman, D. (2003). On the Rarity of Pre-Aspirated Stops. *Journal of Linguistics*, 39, 575–598.

Skinder, A., Strand, E. A., & Mignerey, M. (1999). Perceptual and acoustic analysis of the lexical and sentential stress in children with developmental apraxia of speech. *Journal of Medical Speech-Language Pathology*, 7, 133-144.

Slobin, D. (1973). Cognitive prerequisites for the development of grammar. In C. Ferguson & D. Slobin (Eds.), *Studies of child language development*. New York: Holt.

Smit, A. B. (1993). Phonologic error distributions in the Iowa-Nebraska articulation norms project: Consonant singletons. *Journal of Speech and Hearing Research*, 36, 533-547.

Smit, A. B., Hand, L., Frelinger, J. J., Bernthal, J. E., & Bird, A. (1990). The Iowa articulation norms project and its Nebraska replication. *Journal of Speech and Hearing Disorders*, 55, 779-798.

Smith, B.L. (1977). Developmental aspects of English segment duration. Paper presented at the Stanford Child Language Forum, Stanford, California.

Smith, J. (2000). Prominence, augmentation, and neutralization in phonology. In L. Conathan, J. Good, D. Kavitskaya, A. Wulf, & A. Yu (Eds.), *Proceedings of BLS 26* (pp. 247-257). Berkeley, CA: Berkeley Linguistics Society. [Published version has formatting errors; corrected version available as Rutgers Optimality Archive #727 (2005).]

Smith, J. (2002). *Phonological augmentation in prominent positions*. Doctoral dissertation, University of Massachusetts, Amherst.

Smith, N. (1973). *The Acquisition of Phonology: A Case Study*. Cambridge: Cambridge University Press.

Smith, A., & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research*, 41, 18-30.

Smolensky, P. (1996). On the comprehension/production dilemma in child language. *Linguistic Inquiry*, 27, 720-31.

Snow, D. (1997). Children's acquisition of speech timing in English: a comparative study of voice onset time and final syllable vowel lengthening. *Journal of Child Language*, 4, 35-56.

Stackhouse, J. (1992). Developmental verbal dyspraxia. I: A review and critique. *European Journal of Disorders of Communication: The Journal of the College of Speech and Language Therapists, London*, 27, 19-34.

Stark, R. E. (1980). Stages of speech development in the first year of life. In G. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child Phonology: Vol. 1. Production* (pp.93-112). New York: Academic Press.

Stemberger, J. P. (1991). Apparent anti-frequency effects in language production: The addition bias and phonological underspecification. *Journal of Memory and Language*, 30, 161-185.

Stemberger, J. (1992). The reliability and replicability of naturalistic speech error data. A comparison with experimentally induced errors. In B. J. Baars (Ed.), *Experimental slips and human error: Exploring the architecture of volition* (pp. 195–215). New York: Plenum Press.

Stemberger, J., & Treiman, R. (1986). The internal structure of word-initial consonant clusters. *Journal of Memory and Language*, 25, 163–180.

Steriade, D. (1995) Positional neutralisation. Ms., Department of Linguistics, UCLA. [http://www.linguistics.ucla.edu/people/steriade/papers/PositionalNeutralisation.pdf]

Steriade, D. (1999). Phonetics in phonology: The case of laryngeal neutralization. *UCLA Working Papers in Linguistics*, 2, 25-146.

Steriade, D. (2001) Directional asymmetries in place assimilation: A perceptual account. In E. Hume & K. Johnson (Eds.), *The Role of Speech Perception in Phonology* (pp. 219-50). New York: Academic Press.

Stetson, R.M. 1928. Motor Phonetics, a study of speech movements in action. *Archives Néerlandaises de Phonétique Expérimentale 3*.

Stites, J., Demuth, K., & Kirk, C. (2004). Markedness versus frequency effects in coda acquisition. In A. Brugos, L. Micciulla, & C. E. Smith (Eds.), *Proceedings of the 28th Annual Boston University Conference on Language Development* (pp. 565-576). Somerville, MA: Cascadilla Press.

Stoel-Gammon, C. (1985). Phonetic inventories, 15-24 months: a longitudinal study. *Journal of Speech and Hearing Research*, 18, 505-512.

Stoel-Gammon, C. (1996). On the acquisition of velars in English. In B. Bernhardt, J. Gilbert, & D. Ingram (Eds.), *Proceedings of the UBC International Conference on Phonological Acquisition* (pp. 201-214). Somerville, MA: Cascadilla Press.

Stoel-Gammon, C., &. Dunn, C. (1985). *Normal and Disordered Phonology in Children*. Austin, TX: Pro-Ed.

Stoel-Gammon, C. & Stemberger, J. (1994) Consonant harmony and phonological underspecification in child speech. In M. Yavas (Ed.), *First and Second Language Phonology* (pp. 63-80). San Diego, CA: Singular Press.

Stone, M., Faber, A., Raphael, L., & Shawker, T. (1992). Cross-sectional tongue shape and lingua-palatal contact patterns in [s], [k], and [l]. *Journal of Phonetics*, 20, 253-270.

Strange, W. & Broen, P. A. (1980). Perception and production of approximant consonants by 3-year-olds: a first study. In G. H. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child Phonology, Volume 2* (pp. 117-154). New York: Academic Press.

Strogatz, S. H., & Stewart, I. (1993). Coupled oscillators and biological synchronization. *Scientific American*, 269, 102–109.

Studdert-Kennedy, M., & Goodell, E. W. (1995). Gestures, features and segments in early child speech. In B. De Gelder & J. Morais (Eds.), *Speech and reading* (pp. 65–88). London: Erlbaum, Taylor, and Francis.

Sussman, H. M., Hoemeke, K. A., & McCaffrey, H.A. (1992). Locus equations as an index of coarticulation for place of articulation distinctions in children. *Journal of Speech and Hearing Research*, 35, 769-781.

Swingley, D., & Aslin, R. N. (2007). Lexical competition in young children's word learning. *Cognitive Psychology*, 54, 99-132.

Tesar, B., & Smolensky, P. (1996). Learnability in Optimality Theory (long version). Technical Report 96-3, Department of Cognitive Science, Johns Hopkins University, Baltimore. Available as Rutgers Optimality Archive 156, http://ruccs.rutgers.edu/roa.html

Toro, J. M., Bonatti, L., Nespor, M., & Mehler, J. (2008). Finding words and rules in a speech stream: functional differences between vowels and consonants. *Psychological Science*, 19, 137-144.

Troubetzkoy, N. S. (1971). *Principles of Phonology*. Translated from *Grundzüge der Phonologie*, 3rd edition, 1962, by C. A. M. Baltaxe. Los Angeles: University of California Press.

Turvey, M. T., Fitch, H. L. & Tuller, B. (1982). The Bernstein perspective: I. The problems of degrees of freedom and context-conditioned variability. In J. A. S. Kelso (Ed.), *Human motor behavior: An introduction* (pp. 239-252). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Tyler, A. A., Figurski G. R., & Langsdale, T. (1993). Relationships between acoustically determined knowledge of stop place and voicing contrasts and phonological treatment progress. *Journal of Speech and Hearing Research*, 36, 746-759.

Tyler, A. A., Edwards, M. L., & Saxman, J. H. (1990). Acoustic validation of phonological knowledge and its relationship to treatment. *Journal of Speech and Hearing Disorders*, 55, 251-261.

Vatikiotis-Bateson, E., & Kelso, J. A. S. (1993). Rhythm type and articulatory dynamics in English, French and Japanese. *Journal of Phonetics*, 21, 231-265.

Velleman, S. L. (1988). The role of linguistic perception in later phonological development. *Applied Psycholinguistics*, 9, 221–236.

Velleman, S. L. (1996). Metathesis highlights feature-by-position constraints. In B. Bernhardt, J. Gilbert, & D. Ingram (Eds.), *Proceedings of the UBC International Conference on Phonological Acquisition* (pp. 173-186). Somerville, MA: Cascadilla Press.

Velleman, S. L., & Shriberg, L. D. (1999). Metrical analysis of the speech of children with suspected developmental apraxia of speech. *Journal of Speech, Language, and Hearing Research*, 42, 1444-1460.

Velleman, S. L., & Strand, K. (1994). Developmental Verbal Dyspraxia. In J. Bernthal & N. Bankson (Eds.), *Child Phonology: Characteristics, Assessment, and Intervention with Special Populations* (pp. 110-139). New York: Thieme Medical Publishers.

Vihman, M. M., Macken, M. A., Miller, R., Simmons, H., & Miller, J. (1985). From babbling to speech: A re-assessment of the continuity issue. *Language*, 61, 397-445.

Vousden, J. I., Brown, G. D. A., & Harley, T. A. (2000). Serial control of phonology in speech production: a hierarchical model. *Cognitive Psychology,* 41, 101-175.

Wakumoto, M., Masaki, S., Honda, K. & Ohue, T. (1998). A pressure sensitive palatography: application of new pressure sensitive sheet for measuring tongue-palatal contact pressure. In *Proceedings of the 5rd International Conference on Spoken Language Processing* (pp. 3151-3154). Sydney.

Waldman, F. R., Singh, S., & Hayden, M. E. (1978). A comparison of speech-sound production and discrimination in children with functional articulation disorders. *Language and Speech*, 21, 205–220.

Walker, R. (2000). Long-distance consonantal identity effects. In R. Billerey & B. Lillehaugen (Eds.), *WCCFL 19* (pp. 532-545). Somerville, MA: Cascadilla Press.

Walter, M. A. (2007). *Repetition avoidance in human language*. Doctoral Dissertation, Massachusetts Institute of Technology.

Wang, M. D., & Bilger, R. C. (1973). Consonant confusions in noise: a study of perceptual features. *Journal of the Acoustical Society of America*, 54, 1248-1266.

Weismer, G. (1984). Acoustic analysis strategies for the refinement of phonological analysis. In M. Elbert, D. A. Dinnsen, & G. Weismer (Eds.), *Phonological theory and the misarticulating child*. ASHA Monographs 22 (pp. 30-52). Rockville, MD: ASHA.

Weismer, G., Dinnsen, D. A., & Elbert, M. (1981). A study of the voicing distinction associated with omitted word-final stops. *Journal of Speech and Hearing Disorders*, 46, 320-327.

Weismer, G., Martin, R., Kent, R., & Kent, J. (1992). Formant trajectory characteristics of males with ALS. *Journal of the Acoustical Society of America*, 91, 1085-1098.

Wells, R. (1951). Predicting slips of the tongue. *Yale Scientific Magazine*, 26, 9-30.

Westbury, J. R., & Keating, P. A. (1986). On the naturalness of stop consonant voicing. *Journal of Linguistics*, 22, 145-166.

White, D. (2001). Covert contrast, merger, and substitution in children's productions of /k/ and /t/. MA Thesis, Ohio State University.

Whitehill, T. L., Francis, A. L., & Ching, C. K-Y. (2003). Perception of place of articulation by children with cleft palate and posterior placement. *Journal of Speech, Language, and Hearing Research*, 46, 451-461.

Wijnen, F. (1992). Incidental word and sound errors in young speakers. *Journal of Memory and Language*, 31, 734-755.

Williams, A. L., & Dinnsen, D. A. (1987). A problem of allophonic variation in a speech disordered child. *Innovations in Linguistic Education*, 5, 85-90.

Yip, M. (1989). Feature geometry and cooccurrence restrictions. *Phonology*, 6, 349-74.

Yoss, K. A., & Darley, F. L. (1974). Developmental apraxia of speech in children. *Journal of Speech and Hearing Research*, 17, 399-416.

Young, E. C. & Gilbert, H.R. (1988). An analysis of stops produced by normal children and children who exhibit velar fronting. *Journal of Phonetics*, 16, 243-246.

Zamuner, T. S. (2006). Sensitivity to word-final phonotactics in 9- to 16-month-old infants. *Infancy*, 10, 77-95.

Zoll, C. (1998) Positional asymmetries and licensing. Ms. of paper presented at the annual meeting of the LSA, New York, January 1998. [ROA-282-0098]

Appendix A. Experimental Stimuli for Nonword Discrimination Task

#	Stimuli	Vowel	Place Contrast	Position	Voicing	Harmony
1	bape—dape	[eɪ]	Labial-Coronal	Initial	Voiced	Y
2	beng—deng	[ɛ]	Labial-Coronal	Initial	Voiced	Y
3	toab—poab	[oʊ]	Labial-Coronal	Initial	Voiced	Y
4	tep—pep	[ɛ]	Labial-Coronal	Initial	Voiceless	Y
5	gud—gub	[ʌ]	Labial-Coronal	Final	Voiced	Y
6	joot—joop	[uw]	Labial-Coronal	Final	Voiceless	N
7	koip—koit	[ɔ i]	Labial-Coronal	Final	Voiceless	Y
8	woad—woab	[oʊ]	Labial-Coronal	Final	Voiced	N
9	ched—cheb	[ɛ]	Labial-Coronal	Final	Voiced	N
10	dack—gack	[æ]	Coronal-Velar	Initial	Voiced	Y
11	dape—gape	[eɪ]	Coronal-Velar	Initial	Voiced	N
12	diz—giz	[ɪ]	Coronal-Velar	Initial	Voiced	N
13	geng—deng	[ɛ]	Coronal-Velar	Initial	Voiced	Y
14	geyg—deyg	[eɪ]	Coronal-Velar	Initial	Voiced	Y
15	kang—tang	[æ]	Coronal-Velar	Initial	Voiceless	Y
16	kuv—tuv	[ʌ]	Coronal-Velar	Initial	Voiceless	N
17	teeg—keeg	[ij]	Coronal-Velar	Initial	Voiceless	Y
18	tep—kep	[ɛ]	Coronal-Velar	Initial	Voiceless	N
19	koab—toab	[oʊ]	Coronal-Velar	Initial	Voiceless	N
20	ched—cheg	[ɛ]	Coronal-Velar	Final	Voiced	N
21	gig—gid	[ɪ]	Coronal-Velar	Final	Voiced	Y
22	gowd—gowg	[au]	Coronal-Velar	Final	Voiced	Y
23	gud—gug	[ʌ]	Coronal-Velar	Final	Voiced	Y
24	kug—kud	[ʌ]	Coronal-Velar	Final	Voiced	Y
25	woad—woag	[oʊ]	Coronal-Velar	Final	Voiced	N
26	jook—joot	[uw]	Coronal-Velar	Final	Voiceless	N
27	koit—koik	[ɔ i]	Coronal-Velar	Final	Voiceless	Y
28	yake—yate	[eɪ]	Coronal-Velar	Final	Voiceless	N
29	zuke—zute	[uw]	Coronal-Velar	Final	Voiceless	N
30	yaze—zaze	[eɪ]	Fricative-Glide	Initial	Voiced	Y
31	yish—zish	[ɪ]	Fricative-Glide	Initial	Voiced	Y
32	yoaz—zoaz	[oʊ]	Fricative-Glide	Initial	Voiced	Y
33	zoin—yoin	[ɔ i]	Fricative-Glide	Initial	Voiced	N
34	zug—yug	[ʌ]	Fricative-Glide	Initial	Voiced	N
35	sowz—yowz	[au]	Fricative-Glide	Initial	Voiceless	Y
36	suke—yuke	[uw]	Fricative-Glide	Initial	Voiceless	N
37	sush—yush	[ʌ]	Fricative-Glide	Initial	Voiceless	Y
38	yal—sal	[æ]	Fricative-Glide	Initial	Voiceless	N
39	yop—sop	[a]	Fricative-Glide	Initial	Voiceless	N

Appendix B. Control Stimuli for Nonword Discrimination Task

#	Stimuli	Vowel	Controls For
1	zep—zep	[ɛ]	Fricative-Glide; Labial-Coronal
2	yom—yom	[a]	Fricative-Glide
3	lig—lig	[ɪ]	Coronal-Velar
4	gom—gom	[a]	Coronal-Velar
5	vug—vug	[ʌ]	Coronal-Velar
6	yoop—yoop	[uw]	Fricative-Glide; Labial-Coronal
7	yil—yil	[ɪ]	Fricative-Glide
8	gaff—gaff	[æ]	Coronal-Velar
9	koov—koov	[uw]	Coronal-Velar
10	tud—tud	[ʌ]	Coronal-Velar; Labial-Coronal
11	ying—ying	[ɪ]	Fricative-Glide
12	keb—keb	[ɛ]	Coronal-Velar; Labial-Coronal
13	zoid—zoid	[ɔ i]	Fricative-Glide; Coronal-Velar; Labial-Coronal
14	choat—choat	[oʊ]	Coronal-Velar; Labial-Coronal
15	deek—deek	[ij]	Coronal-Velar; Labial-Coronal
16	yub—yub	[ʌ]	Fricative-Glide; Labial-Coronal
17	zote—zote	[oʊ]	Fricative-Glide; Coronal-Velar; Labial-Coronal
18	tull—tull	[ʌ]	Coronal-Velar; Labial-Coronal
19	rowt—rowt	[au]	Coronal-Velar; Labial-Coronal
20	gatch—gatch	[æ]	Coronal-Velar
21	doke—doke	[oʊ]	Coronal-Velar; Labial-Coronal
22	weck—weck	[ɛ]	Coronal-Velar
23	zuch—zuch	[ʌ]	Fricative-Glide
24	teeb—teeb	[ij]	Coronal-Velar; Labial-Coronal
25	dabe—dabe	[eɪ]	Coronal-Velar; Labial-Coronal