Familial Handedness and Access to Words, Meaning, and Syntax during Sentence Comprehension

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We compared right-handed familial dextral (FS⁻) and familial sinistral (FS⁺) participants who were aged either 10–13 years (children) or 18–23 years (adults). In word probe and associative probe tasks, FS⁺ adults responded faster than all other groups and FS⁺ children responded more slowly than all other groups. In the word probe task, only the FS⁻ adults showed a significant effect of the serial position of the target word. We interpret these differences to support an analysis-by-synthesis model of comprehension in which individuals who differ in familial handedness and age emphasize different linguistic representations during comprehension. In general, FS⁺ individuals focus on words and meaning, while FS⁻ individuals focus on syntactic representations. In FS⁺ individuals, age-related experiences with language produce a shift in responding from compositional meaning to words and their associations. In FS⁻ individuals, age-related experiences with language produce a shift toward responding based more on detailed syntactic representations, including the serial order of words and possibly the structural roles of clauses. © 2001 Academic Press

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The most basic linguistic representations are words, meaning, and syntax. Representations of words include the sound properties of words and their associations to other words. Representations of meaning include thematic roles such as agent, action, patient, and so on. Syntactic representations specify the arrangement of words within a sentence, their organization into phrases, and the relationship of this organization of phrases to thematic roles and other aspects of meaning. There is an enduring ques-

tion about linguistic representations in sentence comprehension: How do the mind and brain organize the formation of representations of words, meaning, and syntax?

We have used several kinds of probe tasks to tap on-line access to different linguistic representations (e.g., Townsend, 1983; Townsend & Bever, 1978, 1989; Townsend, Ottaviano, & Bever, 1979; Townsend & Ravelo, 1981). For example, we can assess access to meaning by measuring response times to say whether a phrase probe such as *talking to a relative* is similar in meaning to part of the sentence fragment, as in (1).

(1) I liked calling up my aunt each night at [tone] . . . TALKING WITH A RELATIVE.

Example (1) shows the location of a timing tone in brackets and the probe item in capital letters. In this task, direct associations between *calling* and *talking* and between *aunt* and *relative* may elicit an overt judgment about meaning similarity. We expect that focusing on such overlearned habits will produce rapid responses. Alternatively, comprehenders may base their judgments on compositional meaning, which depends on the rule-governed syntactic relations between words in the sentence. For example, since *I* has the nominative case and is in the grammatical subject position before the verb, it is the agent of *liked.* In addition, the rule that allows deletion of an embedded subject noun phrase that is identical to the main subject noun phrase of verbs such as *liked* demands that *I* is agent of *calling up.* Similarly, *aunt* compositionally is patient of *calling up* by virtue of a rule that places the grammatical object immediately after the verb. Since compositional meaning depends on first determining these syntactic relations, responding to compositional meaning will produce relatively slow responses.

We can assess access to the words of speech by measuring response times to say whether the probe word *up* had occurred in a sentence fragment, as in (2) and (3).

(2) I liked calling *up* my aunt each night at [tone] . . . UP.
(3) I liked calling my aunt *up* each night at [tone] . . . UP.

A fast response time to (2) and (3) indicates that the comprehender focuses on the words of speech.

We can assess access to the syntactic arrangement of words in a sentence by determining how the serial position of the target in (2) versus (3) influences response time. The target *up* occurs early in the fragment in (2) but in (3), it occurs later. Large differences in response times to (2) and (3) indicate that the position of the target word influences response times and suggest that comprehenders focus on an ordered syntactic representation.

It is natural to assume that comprehenders access linguistic representations in the order words, syntax, and meaning. This assumption follows from the view that the meaning of a sentence depends on its syntactic structure (e.g., Frazier & Clifton, 1995). There is considerable recent evidence, however, that some aspects of meaning appear at the earliest stage of comprehension (e.g., Bever, Sanz, & Townsend, 1998; MacDonald, Pearlmutter, & Seidenberg, 1994; Townsend and Bever, 1991; Trueswell, Tanenhaus, & Garnsey, 1994). Townsend and Bever (1991) asked participants to make a judgment about the meaning of spoken discourse and to detect a word spoken by a different speaker. Increasing syntactic/semantic constraints on the target word decreased time to detect a change in speaker, but increasing the plausibility of the sentence in discourse *increased* time to detect a change in speaker. Such results imply that representations at different levels become available simultaneously, casting doubt on a model in which representations of within-sentence constraints precede representations of discourse meaning during comprehension. Townsend (1997) suggested two distinct mechanisms for comprehension, one in which ''computational''

processes determine syntactic structure and compositional meaning and one in which ''associative'' mechanisms use memorized pattern–meaning pairs. Finally, constraint-based theorists have argued that comprehenders do not access syntactic representations at all during comprehension (e.g., Tabor, Juliano, & Tanenhaus, 1997).

We have integrated structural and constraint-based approaches into an analysis-by-synthesis model of comprehension (Townsend & Bever, 2001). In this model, a preliminary analysis of statistically valid cues elicits an initial meaning/form hypothesis (see Fig. 1). These cues, or overlearned habits, include function words such as prepositions and determiners, word associations, and sentence templates that pair sequences such as noun + verb + noun with meaning relations such as actor + action + patient. The grammar uses the initial meaning/form hypothesis to synthesize a detailed syntactic structure, which is then compared with a memory representation of the speech signal. If the synthesized sequence matches the memorized speech signal, the corresponding compositional meaning of the sentence becomes integrated into conceptual memory. If the synthesized and memorized sequences do not match, over-learned habits again elicit a meaning/form hypothesis to begin another analysis-by-synthesis cycle.

The analysis-by-synthesis model maintains that attention to aspects of meaning and form fluctuates in cyclic fashion. For example, in the preliminary analysis there
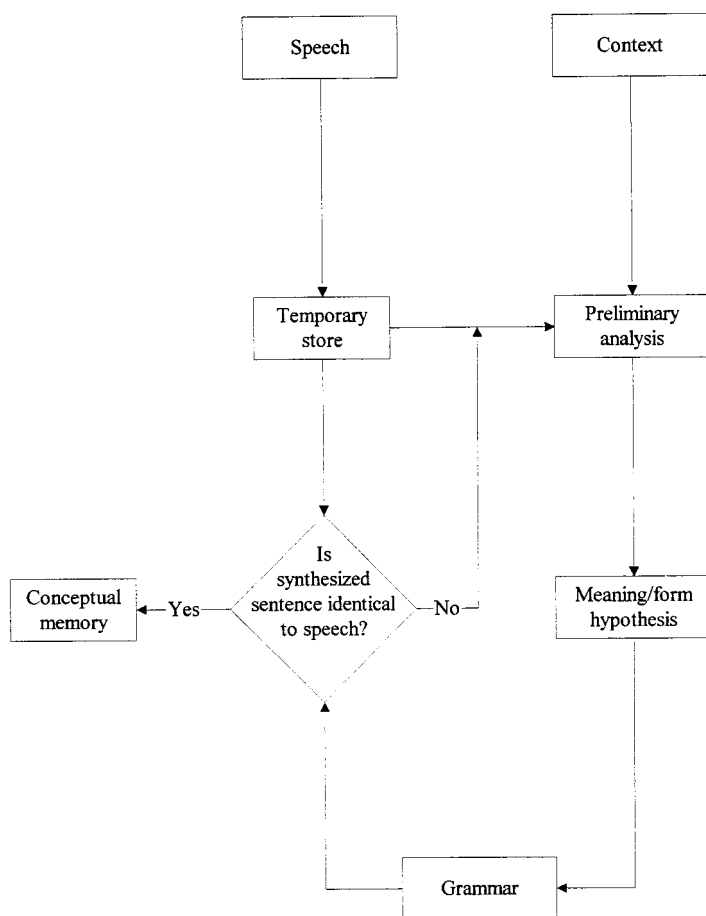

FIG. 1. An analysis-by-synthesis model of sentence comprehension. (Adapted from Townsend & Bever, 2001.)

is access to word meanings, low-level syntactic phrases, and sentence-level templates with their associated meanings. Later in a cycle, there is access to the order of words when the synthesized sequence is compared to a stored representation of speech. Finally, there is access to the compositional meaning of the sentence as it becomes integrated into conceptual memory.

Research in cognitive neuroscience supports the notion of fluctuations of attention to meaning and syntax (see Townsend & Bever, 2001). This work reveals early access to basic aspects of phrase structure (preliminary analysis), later access to meaning (initial meaning/form hypothesis), and still later, access to a detailed representation of surface structure (synthesized string). For example, measures of evoked-response potentials (ERPs) demonstrate an early left anterior negative response (ELAN) to violations of basic aspects of phrase structure (Neville et al., 1991; Friederici et al., 1993). To illustrate, Neville, Nicol, Barss, Forster, and Garrett (1991) contrasted ERPs to the word *of* in sequences like (4) and (5):

(4) The man admired a sketch of the landscape.
(5) *The man admired Don's of sketch the landscape.

They found a rapid relative negativity in the front part of the left hemisphere at around 125 ms after presentation of the word /of/ in (5).

Somewhat later, the brain responds to violations of meaning (Kutas & Hillyard, 1983) and violations of common sentence-level templates (King & Kutas, 1995; Kutas, 1997; cf., Mecklinger et al., 1995; Neville et al., 1991). Neville et al. examined brain responses to semantic violations by comparing ERPs to *sketch* in (4) and *headache* in (6).

(6) *The man admired Don's *headache* of the landscape.

Around 400 ms after *headache* in (6), there was a widespread negativity in the brain. It is reasonable to interpret the effect as due to the oddness that *headache* introduces as patient of *admire.*

Still later, the brain responds to more global violations of grammatical structure (Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992). Osterhout and Holcomb (1992) described a late widespread positive shift that occurs when comprehenders must abandon the sentence template that noun + verb + noun corresponds to agent + action + patient. They examined ERPs in two types of sentences with a potential reduced relative clause. In one sentence the first verb (e.g., *persuaded*) may be a passive participle embedded in a reduced relative clause as in (7), but could be a main verb with an appropriate continuation (e.g., *the broker persuaded the buyer*):

(7) The broker (persuaded *to* sell the stock) was sent to jail.
(8) *The broker persuaded (*to* sell the stock).

In contrast, verbs such as *hoped* are more likely a main verb as in (10).

(9) *The broker (hoped *to* sell the stock) was sent to jail.
(10) The broker hoped (*to* sell the stock).

Osterhout and Holcomb (1992) found that the word *to* elicited a more positive wave in (7) than in (10). This increased positivity had its midpoint at about 600 ms after the onset of *to.* Since a sentence with *persuaded* may continue as the less preferred reduced relative structure (7), Osterhout and Holcomb proposed that the ''P600 effect'' occurs because of changing the assignment of *persuaded* from the preferred main verb to the less-preferred passive participle. In terms of the analysis-by-synthesis model, we can interpret the P600 effect to demonstrate a mismatch between

the synthesized sequence and the speech signal and recognition that there is no correct structure for the sequence in the main clause interpretation (8).

The research on ERPs suggests that brain responses to various linguistic representations fluctuate, as predicted by the analysis-by-synthesis model (Townsend & Bever, 2001). In the present research, we examine the question of whether individual differences in neural organization influence attention to words, meaning, and syntax. We contrast hypotheses based on biological factors, maturational factors, and the analysis-by-synthesis model. The *biological hypothesis* maintains that there is a strong relation between predispositions for hand preference, cerebral asymmetries, and attention to linguistic representations. Specifically, Bever, Carrithers, Cowart, and Townsend (1989) proposed that right-handed familial dextrals (FS$^-$), who have no left-handed family members, access syntactic information more readily than right-handed familial sinistrals (FS$^+$), who have at least one left-handed family member. Bever et al. (1989) argued that FS$^+$ individuals access words and meanings more readily than FS$^-$.

An extension of the biological hypothesis is the *maturational hypothesis.* The maturational hypothesis maintains that attention to words, meaning, and syntax depends on an interaction between biological predispositions for the cerebral organization of language and experience with language. In this view, genetically related differences in attention to linguistic representations become enhanced with age. Thus, older FS$^-$ individuals will access syntactic information more readily than younger FS$^-$, while older FS$^+$ individuals will access words and meanings more readily than younger FS$^+$.

We also consider biological and maturational factors in terms of the analysis-by-synthesis model (Townsend & Bever, 2001). This model proposes an initial meaning/form hypothesis based on habits and a later compositional meaning based on the application of grammatical rules. The model proposes that attention fluctuates between representations of form and representations of meaning. Early on, segmenting words into phrases focuses attention on form, and eliciting lexical associations and sentence-level templates focuses attention on meaning. Later, comparing the synthesized syntactic structure with a representation of the actual speech focuses attention on form, and integrating the syntactically derived meaning of a sentence into conceptual memory focuses attention again on meaning. We will return to a fuller discussion of the biological, maturational, and analysis-by-synthesis hypotheses after we consider evidence on individual differences in cerebral organization.

PATTERNS OF CEREBRAL ORGANIZATION

One of the most enduring results in cognitive neuroscience is that the left hemisphere participates in some aspects of language behavior more than the right (Finger, 1994). This generalization is stronger for those who are right-handers and for familial dextrals (FS$^-$). Kee, Bathurst, and Hellige (1983) found that solving word anagrams interferes with right-handed finger tapping more for right-handed familial dextrals than for right-handed familial sinistrals (FS$^+$). Since the left hemisphere controls the right hand, this research suggests familial handedness is related to variation in left hemisphere control of the processes used in solving anagram problems. It is difficult to specify the nature of anagram representations that vary with familial handedness since solving anagrams requires attention to both words and the sequence of letters within a word.

Familial handedness differences in language behavior may occur because the activities of the two cerebral hemispheres lead to different ''strategies'' for using language. Processing linguistic information with greater reliance on left hemisphere ac-

tivities may produce strategies that emphasize the syntactic relations between words, including their serial order. Relying on right hemisphere activities may produce strategies that are based more on words and meaning than on word order (Corballis, 1989; Dimond & Beaumont, 1974; Kinsbourne, 1978; Levy, 1974; Moscovitch, 1979; Semmes, 1968). In this view, FS^- and FS^+ do not differ in where or how they encode linguistic information, but in *attending* to the activities of one hemisphere or the other. For example, FS^- may attend more to the left hemisphere, which produces representations of sequence, while FS^+ may attend more to the right hemisphere, which produces representations of words and meaning. Alternatively, familial dextrals and familial sinistrals may differ in the extent of *encoding* linguistic information in the left versus the right hemisphere. For example, FS^- may encode linguistic information in the left hemisphere, which forms sequence representations, while FS^+ may encode it in the right, which emphasizes words and meaning. A variation of an encoding explanation is that FS^+ encode linguistic information similarly in the two hemispheres. If this is correct, FS^+ could use either hemisphere to perform a verbal task and therefore show little interference between anagram solving and finger tapping, as Kee et al. (1983) found.

Despite these uncertainties, it seems clear that the two cerebral hemispheres of the brain differ in structure and function. For example, the two hemispheres differ somewhat in size and shape (e.g., Geschwind & Levitsky, 1968; Witelson, 1985). In terms of hemispheric function, Dimond and Beaumont (1974) suggested that the left hemisphere specializes in determining the position of elements in serially ordered events, while the right hemisphere specializes in appositional, associative processing, as we noted above. In language processing, the left hemisphere performs better than the right on syntactic recognition, while the right hemisphere performs better than the left on maintaining alternate meanings of words and discourses. (For a review see Bradshaw, 1980; for recent demonstrations see Beeman, 1993; Brownell, Carroll, Rehak, & Wingfield, 1992, Burgess & Simpson, 1988, Chiarello, 1990, Chiarello, Burgess, Richards, & Pollock, 1990, Kaplan, Brownell, Jacobs, & Gardner, 1990, Lojek-Osiejuk, 1996, Rehak, Kaplan, & Gardner, 1992; for counterevidence see Faust, Kravetz, & Babkoff, 1993.)

This ''typical'' model of rule-governed sequence processing in the left and habit-based processing in the right appears most clearly in right-handed individuals. It is less clear among left-handers (Rasmussen & Milner, 1977) and among right-handers with FS^+ (Hardyck, 1977). These ''anomalies'' in hemispheric organization may involve a reversal of the typical functions of the two hemispheres, less cerebral specialization in the representation of cognitive functions, or reduced differences in attention to the activities of one hemisphere.

Researchers have proposed various explanations for individual differences in the cerebral representation of cognitive functions (e.g., Annett, 1985; Bryden, McManus, & Bulman-Fleming, 1994; Geschwind & Behan, 1984). For example, Geschwind and Behan (1984) suggest that during gestation, certain hormones may inhibit the growth of the left hemisphere and enhance the growth of the right hemisphere, leading to left-handedness and a different cerebral representation of language. Some researchers suggest that cerebral lateralization has a genetic source (Annett (1985; Levy & Nagylaki, 1972; McManus, 1995), while others propose that unusual lateralization arises out of birth complications (Bakan, 1971).

Aphasia

Damage to the left hemisphere is more likely to cause aphasia than is damage to the right hemisphere (Luria, 1970). This supports the basic claim that the left hemisphere generally is the primary center for linguistic ability, at least for the production of

ordered sequences of words. Damage to the left hemisphere disrupts language behavior more after puberty than before (Curtiss, 1989; Lenneberg, 1967).

FS^- individuals also are more likely than FS^+ individuals to suffer disorders of language comprehension and production following left hemisphere damage (Hecaen, De Agostini, & Monzon-Montes, 1981; Joanette, Lecours, Lepage, & Lamoureux, 1983; Luria, 1970). An encoding interpretation of the more favorable prognosis for FS^+ is that FS^+ encode linguistic information in both hemispheres. When there is damage to the left hemisphere, FS^+ can draw on the linguistic information of the right hemisphere to perform linguistic tasks. Alternatively, we can interpret these clinical studies in terms of attention: FS^+ and FS^- may not differ in how they encode linguistic information, but rather, both may encode habit-based linguistic information in the right hemisphere and rule-based linguistic information in the left. However, normal FS^+ and FS^- individuals may differ in how much they attend to the rule-based activities of the left hemisphere versus the associative activities of the right, so that left hemisphere damage in FS^+ individuals leaves them with their preferred habit-based mechanisms intact.

Certain patterns of linguistic ability among aphasic patients support a neurological distinction between rules and habits. For example, access to syntactic knowledge can be spared in Broca's aphasics even while access to the comprehension system is not (Caramazza & Zurif, 1976; Linebarger, Schwartz, & Saffran, 1980; Schwartz, Saffran, & Marin, 1980; but see Grodzinsky, 1986, for a different view). In addition, aphasic patients can lose only the semantic system while retaining the ability to check the grammaticality of sentences (Friederici, Hahne, & Cramon, 1998). Although these findings are controversial, they do suggest that the use of rules versus habits may involve distinct neurological sites.

Aptitude

Experimental studies of dichotic listening and visual recognition support the view that FS^+ and FS^- differ in the organization of functions within the brain. On letter recognition tasks, FS^- show an advantage for stimuli presented in the right visual field (McKeever, VanDeventer, & Suberi, 1973). On the other hand, more spatial tasks, such as reading a clock, produce a left visual field advantage for FS^- (Marino & McKeever, 1989), suggesting that the right hemisphere in FS^- individuals specializes in spatial processing. The size of the right ear advantage in dichotic listening studies typically is greater for FS^- than for FS^+ (Piazza, 1980). In dichotic listening as in spatial reasoning, however, familial handedness may interact with gender (McKeever & Hoff, 1982).

A byproduct of the possible bilateral representation of linguistic information in FS^+ is that linguistic abilities may ''crowd out'' the other functions of the right hemisphere. This leads to the prediction that FS^+ will have reduced ability for spatial reasoning. Several studies have established a relation between familial handedness and scores on aptitude tests. Unfortunately, different studies sometimes report contradictory results. Searleman, Herrmann, and Coventry (1984) and Briggs, Nebes, and Kinsbourne (1976) found that FS^- scored significantly higher on both verbal and mathematical achievement tests than did FS^+. This pattern held across various handedness groups. Casey, Brabeck, and Ludlow (1986) found that FS^+ were more likely to benefit from instructions on a mental rotation task, suggesting that their natural inclination is not favorable to spatial reasoning. On the other hand, van Strien and Bouma (1995; Burnett, Lane, & Dratt, 1982) found that left-handed FS^+ performed better than left-handed FS^- on spatial and numerical reasoning.

The contradictory results on the relation between familial handedness and aptitude

test scores may occur because of lack of control for variables that are related to aptitude. For example, McKeever, Seitz, Hoff, Marino, and Diehl (1983; McKeever, 1986; McKeever, Suter, & Rich, 1995) found that familial handedness was related to spatial visualization ability in different ways for males and females: for males, FS^+ was associated with superior performance, but for females, FS^- performed better. Thus, failing to control for gender can produce opposite results on the relation between familial handedness and spatial visualization. Other variables that may moderate the relation between familial handedness and spatial aptitude are consistency of hand preference (Snyder & Harris, 1993) and age (Harsham, Hampson, & Berenbaum, 1983; Kraft, 1984).

Three Hypotheses

We tested three hypotheses about how familial handedness is related to access to sequence-sensitive versus semantic/associative information during sentence comprehension. We assessed access to these alternative representations of speech with two tasks (Townsend & Bever, 1978). In one task, participants heard fragments of sentences, followed by a brief tone and a pause, and then a probe word, as in (2) and (3), which we repeat here.

(2) I liked calling up my aunt each night at [tone] . . . UP.
(3) I liked calling my aunt up each night at [tone] . . . UP.

Their task was to say whether the probe word had occurred in the sentence fragment. The target *up* appeared either early in the sentence fragment, as in (2), or late in the fragment, as in (3). We assumed that if comprehenders use a representation that encodes the position of the word in the sentence, response times will differ for early versus late targets. For example, searching an ordered representation of words from left to right until the target word is found will produce faster response times for early targets than for late targets (see Van Zandt & Townsend, 1993).

We also used an association task. In this task, participants again heard fragments of sentences followed by a brief tone and a pause, but now the probe item was a 2 to 4 word phrase, as in (1).

(1) I liked calling up my aunt each night at [tone] . . . TALKING WITH A RELATIVE.

Their task was to say whether the phrase was similar in meaning to any part of the sentence fragment. We assumed that this association task taps access to meaning in two ways. It may assess access to associations to the words in the sentence fragment. For example, *calling up* may elicit *talking* as an association, and *aunt* may elicit *relative.* On the other hand, responses on this task may be based on the complete compositional meaning of the fragment, which depends on determining the syntactic relations between words.

The biological hypothesis. According to the biological hypothesis, right-handed people with FS^- rely more on the rule-governed, sequence-sensitive processes of the left hemisphere. Their comprehension processes emphasize the order of words in a sentence and their syntactic relationships to other words in the sentence. Right-handed people with FS^+ rely more on the semantic/associative processes of the right hemisphere. These comprehension processes emphasize individual words and their associations. The biological hypothesis predicts that normal right-handed people who differ in familial handedness will perform differently on sentence processing tasks that emphasize sequence-sensitive processing versus semantic/associative processing. A number of studies support this claim for adults (Bever et al., 1989).

To test the biological hypothesis, we compared FS^- and FS^+ individuals. If FS^+

focus on individual words and their associations, they will respond faster than FS⁻ on both probe tasks. If FS⁻ comprehend by determining the syntactic relations between words within sentences, their response times on the word probe task will depend on the position of the target word in a sentence.

The maturational hypothesis.   A maturational version of the biological hypothesis emphasizes behavioral changes that occur over time. Greater experience with language will enhance biologically determined differences in cerebral organization. Since adults have had more experience with language than children, familial handedness differences will be greater in adults than in children. One relevant change between 13 and 18 years of age may be increases in vocabulary and knowledge of the contexts in which words occur (Miller, 1981). For example, by having experienced a word in a wider range of contexts, adults may have formed more associations to it. Therefore, adults have the potential for performing better on tasks that require extracting and attending to words and their associations. The maturational hypothesis, then, predicts that FS⁺ adults will respond faster than FS⁺ children to words and their associations.

It seems unlikely that exposure to syntactic information differs much between the ages of 13 and 18 years. However, the processing efficiency of working memory, or at least its role in comprehension, may increase with age (cf. Engle, Carullo, & Collins, 1991). If we assume that the role of working memory in comprehension increases with age and that comprehenders determine syntactic structure before sentence meaning, we expect that adults will perform syntactic processing more efficiently than children. Thus, the maturational hypothesis predicts that FS⁻ children will show greater serial target position effects than FS⁻ adults on the word probe task. Alternatively, age-related improvements in access to syntactic information might appear as increased sensitivity to more subtle properties, such as the structural relations between clauses. The typical result of studies on the processing of main and subordinate clauses is that comprehenders access meaning more readily in main clauses. However, they access more superficial information, such as word order, more readily in subordinate than in main clauses (Bever & Townsend, 1979; Flores d'Arcais, 1978; Holmes, 1973; Townsend, 1983; Townsend & Bever, 1977). There is evidence that these differences are greater in adults than in children (Mazuka, 1998; Townsend, Ottaviano, & Bever, 1979; Townsend & Ravelo, 1980). To test the predictions of the maturational hypothesis, we compared FS⁻ and FS⁺ children aged 10–13 years and FS⁻ and FS⁺ adults aged 18–23 years.

The analysis-by-synthesis model.   According to the analysis-by-synthesis model, comprehenders access grammatical rules relatively late in comprehension (Townsend & Bever, 2001). As shown in Fig. 1, comprehension begins when preliminary analysis of function words, sentence-level templates, and other habits elicit an initial meaning/form hypothesis. The grammar uses the initial meaning/form hypothesis to synthesize a hypothetical sentence, which the system matches against a stored representation of the actual speech.

Biological and maturational factors may influence attention to different products of this architecture. Predictions about the role of familial handedness and age in accessing linguistic representations depend on three assumptions: (A) FS⁻ individuals access the grammar more readily than FS⁺, who rely more on words and meaning. (B) Adults are more proficient than children at accessing their preferred linguistic representation. (C) Comprehenders may use either word associations or compositional meaning in the association task. Since associations influence the initial meaning/form hypothesis and compositional meaning appears after synthesizing a detailed syntax, responding to associations will produce fast responses and to compositional meaning, slow responses.

In terms of Fig. 1, these assumptions lead to three predictions. First, FS$^+$ adults will respond fastest overall, since FS$^+$ individuals attend to words and meaning (assumption A), adults are more proficient than children in accessing their preferred linguistic representation (assumption B), and word associations become available more quickly than compositional meaning (assumption C). Second, FS$^-$ adults will show greater serial target position effects on the word probe task, compared to all other groups, since FS$^-$ readily access the grammar (assumption A) and adults are more proficient than children at accessing their preferred linguistic representation (assumption B). Third, FS$^+$ children will respond more slowly than other groups since FS$^+$ attend to words and meaning (assumption A), children are less proficient than adults at accessing their preferred linguistic information (assumption B), and compositional meaning appears later than associative meaning (assumption C).

METHOD

Participants

We tested 48 native English speakers. All participants were right-handed, defined as writing one's name with the right hand and a score above 95% on a reduced version of the Edinburgh Handedness Inventory (Oldfield, 1971).

Table 1 summarizes characteristics of the participants. Two groups of 24 college students were 18–23 years old, and two groups of 24 middle-school students were 10–13 years old.

Within each age group, there were 12 participants who had a left-handed family member and 12 who did not. For defining familial dextrality versus sinistrality, family members consisted of blood relatives who were siblings, parents, parents' siblings, and grandparents. The criterion for left-handedness among family members was that the participant reported a family member writing left-handed.

Half of each age–familial-handedness group was male and half was female. Participants in familial-handedness groups were matched for verbal achievement test scores (see Table 1). For children, the School Achievement Test yielded a measure of grades above current grade level; for adults, the Scholastic Aptitude Test yielded a standardized score on a scale from 200 to 800.

To determine whether the groups differed in comprehension skill, participants were given a text comprehension pretest. This test was adapted from study guides for verbal achievement tests. Passages were 200 words in length for children and 550 words in length for adults. Each participant heard two texts and each read two texts. Following each text, participants answered questions about the content of the text; there were 6 questions for each text for children and 12 for each text for adults. The pretest results (see Table 1) showed that the familial-handedness groups did not differ in the frequency with which they made errors on questions about the content of texts, $F < 1$.

Materials

There were two sets of materials. Each set contained six lists. Each list contained one instance of each combination of conjunction and target location in critical trials. Individual participants received a

TABLE 1
Characteristics of Familial Dextral (FS$^-$) and Familial Sinistral (FS$^+$) Participants

	Children		Adults	
	FS$^-$	FS$^+$	FS$^-$	FS$^+$
Handedness	Right	Right	Right	Right
Age (years)	10–13	10–13	18–23	18–23
Mean VSAT	0.93	0.92	570	577
Percentage of pretest error	22	20	25	22
Mean QSAT	0.96	0.93	549	638

Note. Children's SAT scores refer to grades above current grade level. Adults' SAT scores refer to the Scholastic Aptitude Test.

list from one set in the association task and a list from the other set in the word probe task. Across participants, each set of materials appeared on both the association task and the word probe task. Not counting introductory conjunctions, the critical sentence fragments were either 9 or 10 words long, with an average of 9.17 words.

For each task, there were 6 critical trials like those shown in (1)–(3). In these trials, the sentence fragment ended before the last word of an initial clause. The initial clause was either a main clause or a subordinate clause. For the critical subordinate clauses, the first word was either *if* or *though.* There were 18 filler trials. Six filler trials interrupted the second clause, 7 presented a complete two-clause sentence, 8 used conjunctions other than *if* or *though,* and 12 required a ''no'' response.

In the critical association trials, the phrase was similar in meaning to a part of the fragment. An independent group of college students ($N = 31$) rated the associative similarity of the test phrases and the fragments. On a five-point scale, the average ratings were 3.73 for positive trials that interrupted the initial clause, 3.57 for positive trials for which the phrase was related to the second clause, 1.24 for negative trials that interrupted the initial clause, and 1.22 for negative trials in which participants heard part or all of the second clause. Each list contained four test phrases that consisted of a subject–verb sequence such as *the teacher lecturing.* Each list contained 20 test phrases that consisted of a verb–object sequence such as *returning from work.*

In the critical word probe trials, each critical fragment contained a target word that occupied one of two different positions without changing the meaning of the fragment. At least 2 words separated the ''early'' and ''late'' positions of the target word; the average separation was 2.9 words (SD 1.0). Not counting introductory conjunctions, early targets were an average of 3.3 words from the start of the sentence in one set of lists and 3.2 words from the start in the other set of lists. The average position of late targets was 6.2 words from the start of the sentence in both sets of lists. Three target words were adverbs, 3 were verb particles, 4 were verbs, and 2 were nouns.

The 12 critical items in the two lists were rotated across the 12 combinations of task (word/association), clause (*if*/main/*though*), and target position (early/late). Within each group of participants, only one participant received an item with a particular combination of task, clause, and target position. Since participants were tested on a given item with different combinations of independent variables, statistical tests treat both participants and items as random effects (see Clark, 1973, p. 348). However, we report both F_1 and F_2 statistics.

Procedure

The 48 participants participated in the probe tasks immediately after taking the pretest. Half the participants received the association task before the word probe task, and half received the opposite ordering. Yoked participants received identical experimental materials, the same ear of presentation, and the identical ordering of the two probe tasks. Participants were tested individually in each task.

Participants listened to isolated sentences and fragments of sentences. Each fragment or sentence ended with an audible 50-ms 500-Hz tone that signaled the end of the stimulus material and triggered a Hunter millisecond timer. The auditory probe began 333 ms after the onset of the tone. For the association task, participants heard a sentence or sentence fragment followed by a phrase two to four words long. Their task was to classify the phrase as related or unrelated to the meaning of the sentence fragment. For the word probe task, the probe was a single syllable word, and the participant had to say whether it had occurred in the fragment or sentence.

A male speaker recorded the sentence fragments, and a female speaker recorded the probes. Copies of the original recordings were used for both probe tasks. Half the participants heard the materials in the right ear, and half heard them in the left ear.

Design

The basic design was a $2 \times 2 \times 2$. Age (adult vs. children) and familial handedness (FS⁻ vs. FS⁺) were participant variables, and task (word probe vs. association) was varied within participants. In the analysis of the word probe data, target position (early vs. late) was a within participant variable.

RESULTS

Errors occurred on 2.1% of the word probe trials and 2.4% of the association trials. Response times on these trials were replaced by the average response time for correct trials in the corresponding age, familial handedness, task, and target position cell.
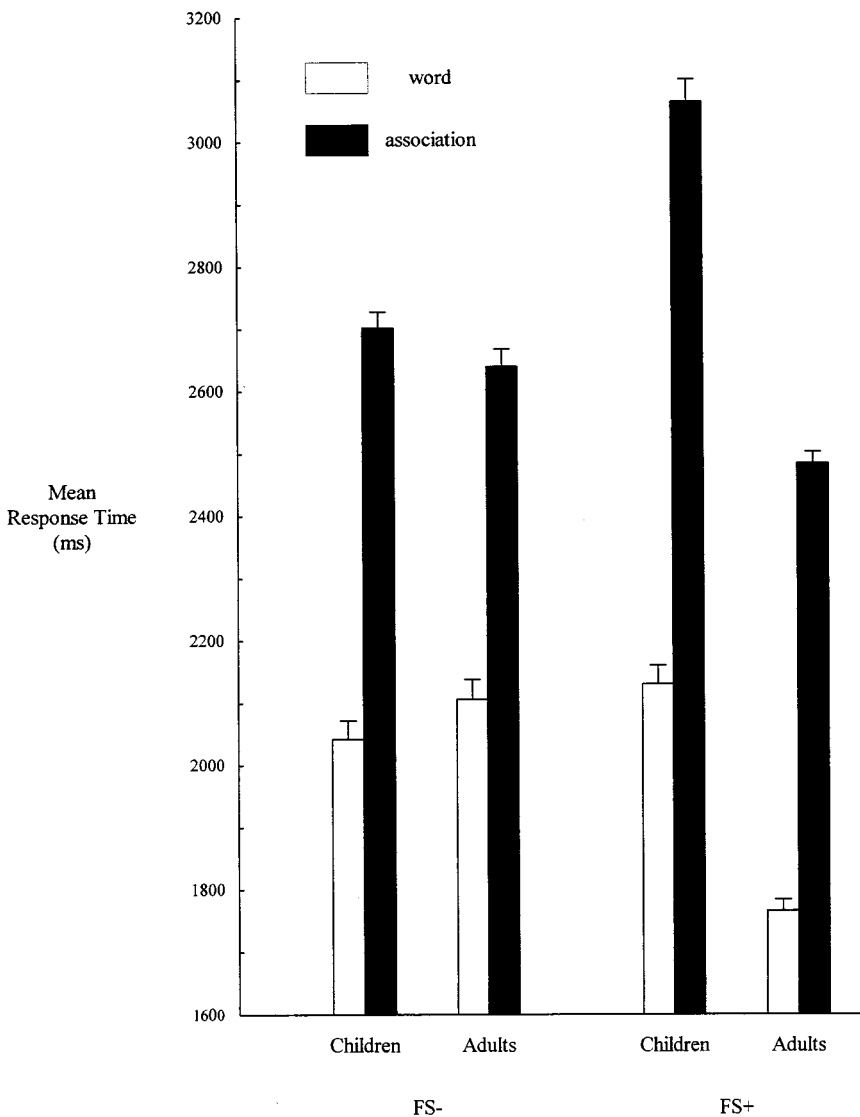
FIG. 2. Mean response times (ms) depending on task, age, and familial handedness. Empty bars indicate the word probe task, filled bars the association task. FS$^-$ refers to individuals with no left-handed family member, FS$^+$ to individuals with at least one left-handed family member. Error bars indicate standard error of the mean.

The mean overall response time was 2367 ms. Figure 2 shows the mean response times on each of the two tasks depending on age and familial handedness. The response time data initially were analyzed with task, age, and familial handedness as variables. The only significant effects in this analysis were (a) Response times were faster for the word probe task than for the association task. Mean response times were 2011 ms for the word probe task and 2721 ms for the association task, $F_1(1, 44) = 141.5$, $p < .0001$, $MS_e = 85,849$; $F_2(1, 11) = 168.0$, $p < .0001$, $MS_e = 150,917$. (b) Response times were faster for adults than for children. Mean response times were 2249 ms for adults and 2485 ms for children, $F_1(1, 44) = 5.56$, $p < .05$, $MS_e = 237,791$; $F_2(1, 11) = 31.3$, $p < .01$, $MS_e = 82,028$. (c) There was an interaction between age and familial handedness, $F_1(1, 44) = 5.67$, $p < .05$, $MS_e = 237,791$; $F_2(1, 11) = 15.6$, $p < .01$, $MS_e = 113,707$.

Inspection of Fig. 2 reveals the following apparent interaction effect: FS$^+$ adults responded faster than FS$^+$ children (2124 ms versus 2597 ms), but there was no age difference for FS$^-$ participants (2373 ms versus 2372 ms). Simple-effects tests confirmed this impression. Among FS$^+$ participants, adults responded faster than children, $F_1(1, 44) = 33.9$, $p < .01$, $F_2(1, 11) = 70.8$, $p < .01$. Among FS$^-$ participants there was no overall age difference, both $Fs < 1$.

The interaction between age and familial handedness was examined further. Figure 3 shows an obvious crossover interaction between these variables. Simple-effects tests revealed significant familial handedness differences at both ages. Among adults, the FS$^+$ participants (2124 ms) responded faster than the FS$^-$ participants (2373 ms), $F_1(1, 44) = 9.39$, $p < .01$, $F_2(1, 11) = 19.6$, $p < .01$. The opposite was found among children: the FS$^+$ participants (2597 ms) responded more slowly than the FS$^-$ participants (2372 ms), $F_1(1, 44) = 7.66$, $p < .01$, $F_2(1, 11) = 16.0$, $p < .01$.

The differences between the various groups on the two tasks were examined further with a Newman–Keuls test using all eight conditions (see Fig. 2). Since each group responded faster on the word probe task than every other group on the association task ($p < .01$ by participants and by items), we focus on the results of specific comparisons within tasks.

First, we present the Newman–Keuls analyses for the association task. Comparisons between groups on the association task produced the following conclusions: (a) The FS$^+$ adults responded faster than all other groups (2481 ms versus 2701 ms for FS$^-$ children, 2639 ms for FS$^-$ adults, and 3063 ms for FS$^+$ children) in the participant analysis ($p < .01$). All of these differences were significant as well at the .01 level in the item analyses, with the exception of the comparison between FS$^+$ adults and FS$^-$ adults, which was significant at $p < .05$. (b) The FS$^+$ children re-

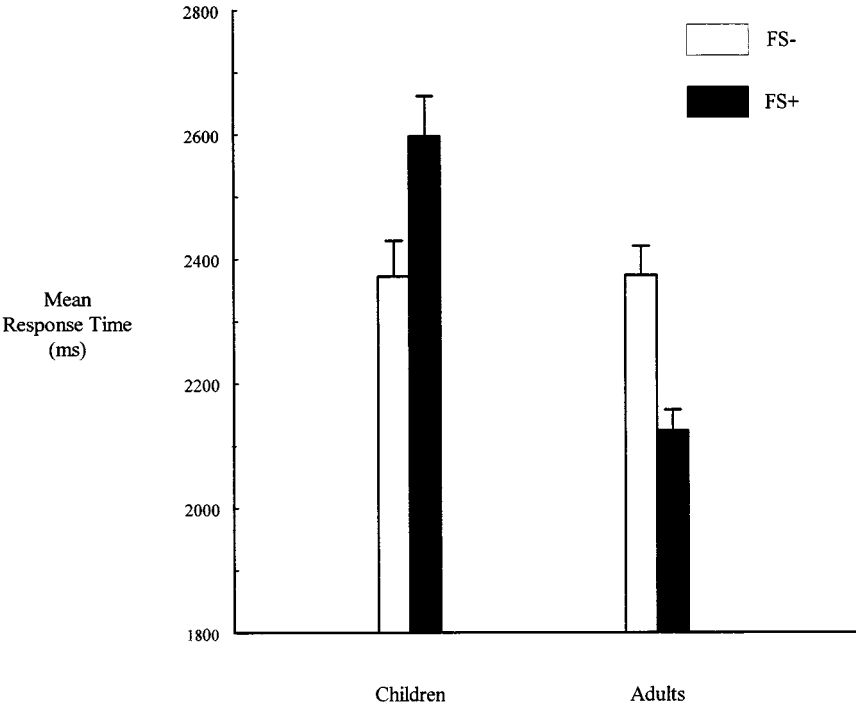**FIG. 3.** Mean response times (ms) depending on age and familial handedness. Empty bars indicate individuals with no left-handed family member (FS$^-$). Filled bars individuals with at least one left-handed family member (FS$^+$). Error bars indicate standard error of the mean.

sponded more slowly than all other groups in participant and item analyses of the association data ($p < .01$). (c) The two FS$^-$ groups did not differ on the association task ($p > .05$ by participants and by items).

Focusing on the word probe task, the Newman–Keuls analysis produced the following conclusions: (a) The FS$^+$ adults responded faster than every other group (1766 ms versus 2130 ms for FS$^+$ children, 2042 ms for FS$^-$ children, and 2106 ms for FS$^-$ adults) in both the participant analysis and the item analysis ($p < .01$). (b) There were no other significant differences between groups in either the participant analysis or the item analysis ($p > .05$).

Target Position

To examine serial target position effects in the word probe task, data from the word probe task were analyzed with target position, age, and familial handedness as variables.

Figure 4 shows mean response times for early versus late targets on the word probe task. There was a significant interaction between age, familial handedness, and target position, $F_1(1, 44) = 4.79, p < .05, MS_e = 34,960, F_2(1, 11) = 1.17, p > .05, MS_e = 72,775$. There were no other significant effects in the overall analysis of the target position data.

A Newman–Keuls test on the target position data showed the following results: (a) FS$^+$ adults responded faster to both early targets (1794 ms) and late targets (1738 ms) than any other group on either target position, all $ps < .01$ by participants and
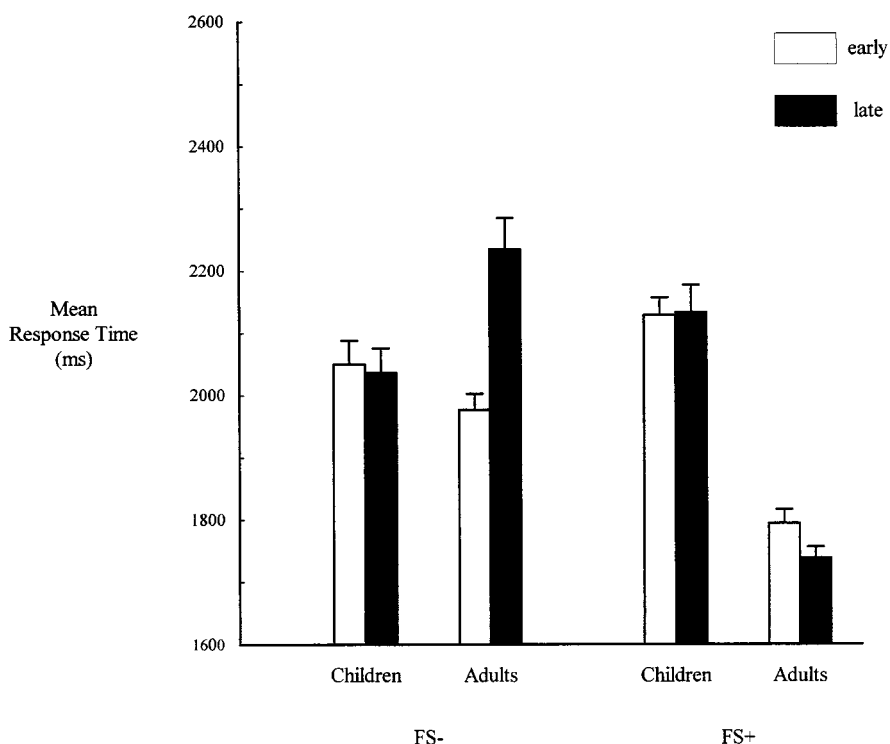

FIG. 4. Mean response times (ms) on the word probe task depending on target position, age, and familial handedness. Empty bars indicate early targets, filled bars late targets, FS$^-$ refers to individuals with no left-handed family members, FS$^+$ to individuals with at least one left-handed family member. Error bars indicate standard error of the mean.

by items. (b) FS$^-$ adults responded faster to early targets (1976 ms) than to late targets (2234 ms). This difference was significant by participants ($p < .01$) and by items ($p < .05$). (c) FS$^-$ adults responded faster to early targets than FS$^+$ children on both early targets (2127 ms) and late targets (2132 ms), $p < .01$ by participants but $p > .05$ by items. FS$^-$ adults' response times on early targets did not differ from those of FS$^-$ children on either early or late targets, all $ps > .05$. (d) FS$^-$ adults responded more slowly to late targets than FS$^-$ children on both early targets (2050 ms) and late targets (2036 ms), all $ps < .01$ by participants and by items. FS$^-$ adults' response times to late targets did not differ from response times for FS$^+$ children on either early or late targets, all $ps > .05$. (e) Besides FS$^-$ adults, no other group showed a significant difference in response times for early versus late targets, all $ps > .05$.

Clause Type

Table 2 presents the data from each task broken down by clause type. On the association task, the only groups that showed a numerical advantage for main clauses were FS$^-$ children and FS$^-$ adults, who responded faster to main clauses than to subordinate clauses by 67 and 3 ms, respectively. Analysis of variance of the association data using clause type, age, and familial handedness as variables, however, revealed no significant interactions with clause type, all $ps > .05$. Sign tests also showed no significant group difference in response times depending on clause type.

On the word probe task, the only group that showed larger target position effects in subordinate clauses was FS$^-$ adults, who responded 330 ms faster to early targets than to late targets in subordinate clauses but only 118 ms faster to early targets in main clauses. These results suggest that FS$^-$ adults accessed a representation that was more superficial for subordinate clauses than for main clauses. However, analysis of variance of the word probe data using clause type, target position, age, and familial handedness as variables revealed no significant interactions with clause type, all $ps > .05$. Examination of response times for individual participants revealed that for subordinate clauses, 10 out of the 12 FS$^-$ adults responded more slowly to late targets

TABLE 2
Response Times (ms) Depending on Clause Type

| | Association Task | | | |
| | FS$^-$ | | FS$^+$ | |
Clause type	Adults	Children	Adults	Children
Subordinate	2640	2723	2459	3008
Main	2637	2656	2547	3174
S–M	3	67	−88	−166
	Word task			
Subordinate				
Early	1992	2092	1816	2161
Late	2322	2052	1714	2082
L − E	330	−40	−102	−79
Main				
Early	1943	1965	1751	2058
Late	2061	2004	1785	2233
L − E	118	39	34	175

Note. S, subordinate clause; M, main clause; E, early target; L, late target.

than to early targets, $p < .05$ by sign test. No other group showed a significant target position effect by sign test in either subordinate or main clauses (all $ps > .05$).

DISCUSSION

We found several differences between participant groups. The major results were: (a) FS^+ adults responded faster than all other groups on both the word probe task and the association task. (b) FS^+ children responded more slowly than all other groups on both tasks. (c) Only FS^- adults showed a significant target position effect in the word probe task.

Some results supported the biological hypothesis, and some supported the maturational hypothesis. But more of the results supported the analysis-by-synthesis model, whose architecture requires fluctuations of attention between meaning and form. We first summarize the results in terms of these hypotheses and then discuss their implications for aphasia, modularity, and individual differences.

The Biological Hypothesis

The biological hypothesis states that FS^+ individuals comprehend by extracting individual words and their associations, while FS^- individuals comprehend by determining the syntactic relations between words within sentences. If we consider only the adult data, there was support for the biological hypothesis. Our results showed that FS^+ adults responded faster than FS^- adults on both the word probe task and the association task. This result confirms the prediction of the biological hypothesis that individuals with a stronger genetic tendency toward left-handedness attend more to words and their associations, which we presume to be the focus of right hemisphere language processing. In addition, we found that only FS^- adults showed a significant effect of serial target position in the word probe task, suggesting that these participants attend more to the specific sequence of words in the speech stimulus. This result also confirms the prediction of the biological hypothesis that individuals with a stronger genetic tendency toward right-handedness attend more to the syntactic arrangement of words in speech, which we presume to be the focus of left hemisphere language processing. The results for adult participants clearly support the biological hypothesis.

However, neither of the adult patterns occurred in the data for children. We found that FS^+ children responded more slowly than FS^- children on the association task. This result refutes the prediction of the biological hypothesis that individuals with a stronger genetic tendency toward left-handedness attend more to meaning. In addition, we found that FS^- children did not show a significant target position effect in the word probe task, refuting the prediction of the biological hypothesis that individuals with a stronger genetic tendency toward right-handedness attend more to the syntactic arrangement of words in speech. The results for children do not support the biological hypothesis.

The Maturational Hypothesis

The maturational hypothesis states that familial handedness differences in attention to linguistic representations become larger with age. Within the FS^+ group we did find that adults responded faster overall than children. This result may have occurred because adults have accumulated more associations to words or because they recognize words more efficiently. Within the FS^- group adults showed a significant target position effect on the word probe task, but children did not. Both results support the

maturational hypothesis. However, if we assume a syntax-first model of comprehension, the latter result does not support the maturational hypothesis. If comprehenders obtain syntactic structure before they obtain sentence meaning and if older comprehenders carry out these processes more efficiently, we expect that they will perform syntactic processing more quickly and, if anything, show smaller effects of target position. Since we found the opposite, there is no support for a maturational hypothesis based on a syntax-first model of sentence comprehension. Proponents of syntax-first models, of course, will point out that the word probe task is far too slow to produce an adequate test of the hypothesis that the initial stage of comprehension is the formation of a purely syntactic representation. For our purposes, however, the presence of serial target position effects in adults and their absence in children remains unexplained unless there is a late stage of comprehension in which there is access to the order of words in speech.

The Analysis-by-Synthesis Model

The analysis-by-synthesis model states that sentence comprehension involves an early stage in which word associations, function words, and sentence-level templates elicit an initial meaning/form hypothesis. The grammar uses the initial meaning/form hypothesis to synthesize a detailed syntactic structure, which is then compared to a representation of speech. If the synthesized string and the speech correspond, the compositional meaning becomes integrated into a conceptual representation of the sentence. Genetic factors may influence attention to words, syntax, and meaning. For example, FS^- may access the grammar more readily, while FS^+ may attend more to semantic/associative information. In this section, we consider the results for each of the four participant groups in terms of the analysis-by-synthesis model.

We found that FS^+ adults responded faster than all other groups on both the word probe task and the association task. In addition, FS^+ adults did not show a significant target position effect on the word probe task. These results suggest that FS^+ rely more on words and meaning than on syntactic word order. In terms of the analysis-by-synthesis model, FS^+ adults use the initial meaning/form hypothesis for their judgment. The faster response times overall for FS^+ adults than for FS^+ children may be due to the fact that adults have had experiences with words in a wider range of linguistic contexts. The FS^+ tendency to emphasize associative information during sentence comprehension may enable them to take advantage of these experiences, compared to FS^- groups.

FS^+ children responded more slowly than all other groups on both tasks. In addition, FS^+ children did not show a significant target position effect on the word probe task. The lack of a target position effect for FS^+ children suggests that they focus on information that does not contain sequence information. Their slower overall response times suggest that they respond to the compositional meaning of the sentence rather than to words or their associations. Since the compositional meaning depends on having synthesized a sentence, this meaning appears relatively late, making the FS^+ children's response times slow. The FS^+ children's use of compositional meaning for these tasks also explains their lack of a target position effect in the word probe task, since a representation of meaning would not contain information about the order of words (Sachs, 1967; Townsend & Bever, 1978).

FS^- adults responded faster on the word probe task to early targets than to late targets. This result indicates that these participants attend closely to the order of words in a sentence. The pattern of their response times on the word probe task suggests a left-to-right serial self-terminating search (see Sternberg, 1966, 1975; Bever & Townsend, 1979; Townsend, 1983; Townsend & Bever, 1978). We also found

that FS$^-$ adults responded to early targets more slowly than FS$^+$ adults on either target position. This result suggests that FS$^-$ adults initiate their search for the target word later than FS$^+$ adults. One interpretation of this result is that FS$^-$ adults use a representation for the word probe task that appears later during normal comprehension. According to the analysis-by-synthesis model, a late stage of comparing syntactic representations is a normal part of sentence comprehension, when the synthesized sentence is compared specifically to the speech signal. The results of FS$^-$ adults on the word probe task suggest that comparing the synthesized and stored sentences involves a serial, self-terminating process in which the system detects an error and initiates repair more quickly when the discrepancy between the two sentences appears early in the sentence.

FS$^-$ children overall responded faster than FS$^+$ children and more slowly than FS$^+$ adults. However, FS$^-$ children did not differ from FS$^-$ adults in overall response times, nor did they show the serial target position effects of FS$^-$ adults. FS$^-$ children cannot be accessing the same kind of representation as FS$^-$ adults with the same search procedure since FS$^-$ children did not show a serial target position effect on the word probe task.

There are several potential explanations for the pattern of results for the two FS$^-$ groups. None of these explanations is completely satisfactory, but the results do suggest that further investigations of the processing of structural properties of clauses may be fruitful. Consider first the view that both FS$^-$ groups access an ordered syntactic representation for the word probe task, but FS$^-$ children do not use a serial self-terminating search for identifying the target word. Since FS$^-$ children did not show a target position effect, we might suppose that they search the ordered representation in a serial exhaustive or parallel manner. In a serial exhaustive search, the comprehender examines every word one at a time before responding. In a parallel search, the comprehender examines all words simultaneously. The effects of set size, type of trial, and serial position on response time distinguish these types of search from a serial self-terminating search (see Van Zandt & Townsend, 1993, for a review). Since the serial exhaustive search and the parallel search both predict no serial target position effect, we can interpret the FS$^-$ children's data to support both types of search. Closer scrutiny, however, supports neither of these search processes. If FS$^-$ children used a serial exhaustive search, their response times will be closer to FS$^-$ adults' response times for late targets than to FS$^-$ adults' response times for early targets, since the FS$^-$ children will not respond to any target until they have examined all words. We found instead that the responses of FS$^-$ adults to late targets were significantly slower than the responses of FS$^-$ children to either target position, but that FS$^-$ adults' response times for early targets did not differ from the response times of FS$^-$ children to either target position. Thus, the data do not support the idea that FS$^-$ children use a serial exhaustive search. It seems plausible that FS$^-$ children use a parallel search if they searched a meaning representation, which does not encode serial order. If FS$^-$ children searched a meaning representation, their response times to the association task would be similar to those of FS$^+$ children. However, we found that FS$^-$ children responded faster than FS$^+$ children on the association task.

Another possibility is that all FS$^-$ participants use similar representations and search strategies, but children have reduced memory span. If this were true, FS$^-$ children may be unable to retain the entire sentence, giving the appearance that they do not use a self-terminating serial search (cf. Boswell, Sanders, & Young, 1974). If FS$^-$ children had reduced memory span, we would expect them to make more errors on targets that are beyond the range of their memory span. Since we found that the error rate was very low in both target positions, however, there is little support for this explanation.

A third possible explanation of the FS^- results is that children and adults use similar representations and search strategies, but FS^- children search at a slower rate. There is evidence for developmental differences in the rate of searching nonlinguistic stimuli (Herrmann & Landis, 1977; Keating & Bobbitt, 1978; Keating, Keniston, Manis, & Bobbitt, 1980). If this explanation were correct, however, the serial target position effect would be larger for FS^- children than for FS^- adults, not smaller, as we found.

It may be that FS^- children adopt a mixture of search strategies. Some FS^- children may use self-terminating search, some exhaustive search, and some parallel search. This could have the effect of obscuring the serial target position effects in the group of FS^- children. However, the fact that the standard errors for FS^- children on the word probe task were small appears to rule out this explanation.

FS^- children may have poorer access than FS^- adults to the full grammatical representation of sentences, including the distinction between main and subordinate clause. There is evidence from probe tasks that response time differences between main and subordinate clauses are relatively greater for adults than for preschool children (Townsend, Ottaviano, & Bever, 1979; Townsend & Ravelo, 1980). In the present study, we did not find any significant overall differences due to structural role. The failure to find a significant effect in the overall analysis may be due to an insufficient number of observations in the clause type by target position cells (for main clauses each participant received only one trial for each target position). FS^- adults did show a serial target position effect in subordinate clauses when examined by sign test. If additional testing shows that this trend is reliable, it would suggest that FS^- adults access grammatical details more effectively than FS^- children. We would expect such a difference if the initial meaning/form hypothesis of FS^- adults differentiates main and subordinate clauses. For example, for FS^- adults, main clauses may elicit a meaning/form hypothesis more readily than subordinate clauses, providing quicker completion of an analysis-by-synthesis cycle for main clauses. On the other hand, if main and subordinate clauses do not differ in eliciting an initial meaning/form hypothesis for FS^- children, we would not expect a difference in the rate of completing an analysis-by-synthesis cycle for main versus subordinate clauses. Future research that specifically tests for the role of clause structure and sentence length may clarify the implementation of the analysis-by-synthesis architecture throughout development.

Implications

We have proposed an architecture for sentence comprehension in which linguistic habits elicit an initial meaning/form hypothesis. These habits include word associations, function word cues to phrase boundaries, and sentence-level templates. The grammar uses the initial meaning/form hypothesis to generate a detailed surface structure, which is compared to a stored representation of the linguistic stimulus. If the two match, the compositional meaning becomes integrated into permanent memory.

The analysis-by-synthesis model has characteristics of both interactive and modular models of sentence comprehension. Modularity is the proposal that, for example, semantic information cannot inform ongoing syntactic processes (Fodor, 1983). Since preliminary analysis freely uses syntactic and semantic information to form the initial meaning/form hypothesis, this aspect of comprehension is interactive. When the initial meaning/form hypothesis becomes available, however, the grammar uses only syntactic knowledge to synthesize a detailed syntax. Thus, once synthesis has begun, the system is modular in the sense that it operates without influence from nonsyntactic

information. A system may be modular for informational reasons or for architectural reasons (Townsend & Bever, 1991). If the computational languages of two systems differ, one cannot affect the internal operation of the other. For example, the language of the meaning system may differ from the language of the syntactic system and therefore be unable to influence the operation of the syntactic system. On the other hand, a system may not be able to influence the internal operation of another because the two systems are physically segregated and therefore physically unable to communicate during ongoing processing.

Our results are consistent with our general understanding of the biological bases of language comprehension. Among adults at least, those individuals who lateralize language functions more strongly in the left hemisphere, namely, FS$^-$ adults, show greater sensitivity to sequential properties of the linguistic stimulus. Those who show relatively less lateralization of linguistic functions in the left hemisphere, namely, FS$^+$ adults, show greater sensitivity to lexical-associative properties of the linguistic stimulus.

Our results have implications for understanding the nature of deficits in aphasia. Two general deficits follow from the analysis-by-synthesis model. If the comprehension system has the analysis-by-synthesis architecture, we expect that brain damage could cause a loss of access to sentence templates. In this case, the patient would have difficulty obtaining an initial meaning/form hypothesis, but retain access to the grammar. Alternatively, we expect that brain damage could produce an inability to access the grammar and synthesize a detailed syntactic structure. In this case, the patient would retain access to sentence templates. As we noted earlier, there is evidence to support the first of these possibilities, that brain damage can interfere with the ability to understand sentences while preserving the ability to make grammaticality judgments about them. In addition, brain damage is less likely to disrupt comprehension in FS$^+$ than in FS$^-$. The analysis-by-synthesis model predicts this result if we assume that FS$^+$ represent sentence templates more broadly across the two hemispheres. If this is true, then both modular and interactive properties of the language comprehension system fall out of the analysis-by-synthesis architecture.

It is important to note that all our participants are skilled comprehenders. The performance differences we observed are small and apparently have little consequence for verbal achievement. These observations suggest that there is a single architecture for sentence comprehension and that familial handedness differences are due to subtle differences in which aspect of analysis-by-synthesis processes participants focus on more. It seems unlikely that differences in working memory capacity could account for our results. Our two age groups may well have differed in working memory capacity, but since the familial handedness groups within ages were matched for verbal achievement, explanations of familial handedness differences in terms of working memory capacity do not appear promising. The fact that we found familial handedness differences within age groups despite our controls for verbal achievement suggests that familial handedness groups differ in their reliance on distinct but interacting systems of linguistic habits and rules.

APPENDIX

Test sentence fragments appear below. Early targets in the word probe task appear in (a), late targets in (b). Probe items are capitalized. Word probes appear first followed by associative probes in parentheses. Fragments began with *if, though,* or no conjunction.

  1a. Pete will soon come home from his job at . . . SOON (RETURNING FROM WORK).
  1b. Pete will come home soon from his job at . . . SOON (RETURNING FROM WORK).
  2a. French chef fried eggs, boiled ham, and sliced . . . BOILED (PREPARING A MEAL).

2b. The French chef boiled ham, fried eggs, and sliced . . . BOILED (PREPARING A MEAL).
3a. I liked calling up my aunt each night at . . . UP (TALKING TO A RELATIVE).
3b. I liked calling my aunt up each night at . . . UP (TALKING TO A RELATIVE).
4a. Tom has poured the red wine and served the iced . . . POURED (FILLING THE GLASSES).
4b. Tom has served the red wine and poured the iced . . . POURED (FILLING THE GLASSES).
5a. Jim bought some nails, some long boards, and light . . . NAILS (PURCHASING SUPPLIES).
5b. Jim bought some boards, some long nails, and light . . . NAILS (PURCHASING SUPPLIES).
6a. Bill swept, cleaned, and mopped the floor of the . . . SWEPT (USING A BROOM).
6b. Bill mopped, cleaned, and swept the floor of the . . . SWEPT (USING A BROOM).
7a. The trains miss their stops, run late, and break . . . MISS (FOULING UP THE SCHEDULE).
7b. The trains run late, miss their stops, and break . . . MISS (FOULING UP THE SCHEDULE).
8a. Bob did put down some new tiles in the . . . DOWN (COVERING A FLOOR).
8b. Bob did put some new tiles down in the . . . DOWN (COVERING A FLOOR).
9a. The high food costs will stay as they are . . . HIGH (KEEPING INFLATION DOWN).
9b. The food costs will stay high as they are . . . HIGH (KEEPING INFLATION DOWN).
10a. The large chair or the small couch must be . . . CHAIR (REARRANGING FURNITURE).
10b. The large couch or the small chair must be . . . CHAIR (REARRANGING FURNITURE).
11a. Miss Jones lets out the whole class too late for . . . OUT (DISMISSING PEOPLE).
11b. Miss Jones lets the whole class out too late for . . . OUT (DISMISSING PEOPLE).
12a. Teams play there a lot at the end of . . . THERE (PRACTICING FOOTBALL).
12b. Teams play a lot there at the end of . . . THERE (PRACTICING FOOTBALL).

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