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Spatial Audiometry: Detection of Spondaic Words in Noise

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Abstract

It is important to select appropriate stimuli and test conditions for developing standardized spatial audiometric tests. In three experiments, binaural detection thresholds (BDTs) for a target signal, located at either 0, 45, 90, 135, 180, 225, 270, or 315° azimuth, were measured in the presence of a masker positioned at one of these eight locations. Target signals included spondaic words from the CID W-1 list. The masker was speech spectrum noise (SSN) or multitalker noise (MTN) presented at a constant level (65 dBA). Bekesy tracking was used to measure BDTs in listeners with normal hearing. Results indicate that BDTs are significantly influenced by the (a) angular separation between the target and noise source and (b) choice of spondaic words used as target stimuli. BDTs for various spondaic words differed as much as 13 dB for a given angular separation. BDTs measured in SSN and MTN for otherwise identical test conditions differed less than 3 dB. A single spondaic word appears to be appropriate for spatial audiometric tests of detection. Nonsignificant differences between masked BDTs obtained for SSN and MTN noises indicate that for spatial detection, the masking effects of these noises are comparable. These results indicate that the development of a clinical test of spatial detection should include the use of SSN and a single spondaic word, with detection being measured for a set of four or five signal and noise source configurations.

Key Words: Binaural detection threshold, directional noise, spatial audiometry, spondaic words

Abbreviations: ANOVA = analysis of variance, CID = Central Institute for the Deaf, BDT = binaural detection threshold, KEMAR = Knowles Electronic Manikin for Acoustic Research, MLD = masking level difference, MTN = multitalker noise, SSN = speech spectrum noise, VAD = virtual audio display

It has been well documented that individuals with impaired hearing have difficulty with binaural processing tasks, especially in the presence of background noise and excessive reverberation (e.g., Nabelek and Letowski, 1985, 1988, 1989; Letowski and Poch, 1995, 1996; Abouchacra et al, 1997; Besing et al, 1997a, b; Koehnke and Besing, 1997a; Roberts et al, 1997; Vaughan and Letowski, 1997). In addition, it has been demonstrated that performance on binaural processing tasks cannot be predicted based on audiometric sensitivity alone (e.g., Hausler et al, 1983; Koehnke et al, 1995; Roberts et al, 1997). Rather, it usually requires a battery of tests to obtain information about an individual's binaural processing capacity (Gabriel et al, 1992; Koehnke et al, 1995; Bellis, 1996). The tests presently used in routine audiometric evaluations do not enable the audiologist to assess performance on binaural tasks in general, and in particular, binaural tasks typically encountered in everyday activities. Therefore, in the past few years we have been involved in the development of some clinical tests designed to measure performance in everyday listening

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situations (Smith-Abouchacra, 1993; Besing and Koehnke, 1995; Koehnke and Besing, 1996; Abouchacra et al, 1998; Besing et al, 1998). Although these tests are used to evaluate performance on a number of different listening tasks, we refer to them collectively as spatial audiometry because they involve (a) the presentation of test stimuli from different locations in a real or virtual acoustic space and (b) the measurement of an individual's spatial awareness. The clinical importance of spatial audiometry lies in the fact that it is a simple and natural method for assessing the integrity of the binaural auditory system; it would also enable the audiologist to determine the performance of their clients on everyday listening tasks that are not included in the diagnostic test battery used today.

Spatial audiometric tests can provide information about an individual's ability to do a number of tasks that are essential for communication and safety in everyday activities. For example, tests evaluating a listener's ability to (1) detect signals in quiet and in noise from different spatial locations, (2) localize sound sources in quiet and in noise, and (3) understand speech in noise in various listening situations (with one or more interfering noise sources) can provide the clinician with valuable baseline performance information. Results of such spatial audiometric tests can then be used to select hearing aids and other assistive listening devices that influence spatial perception because amplification affects spatial orientation cues and audibility of the target signal. Additionally, these test results can help clinicians develop appropriate remediation strategies for individuals with hearing loss. Such strategies will improve the individual's ability to communicate in their everyday activities.

To date, most efforts in the development of spatial audiometric tests have focused on sound source localization and speech recognition tasks (Bergman, 1957; Sanchez-Longo et al, 1957; Link and Lenhardt, 1966; Kuyper and de Boer, 1969; Tonning, 1970; Bienvenue and Siegenthaler, 1974; Zera et al, 1982; Smith-Abouchacra, 1993; Besing and Koehnke, 1995; Koehnke and Besing, 1996, 1997a, b; Roberts et al, 1997). Results obtained with these tests indicate that they are relatively easy to administer and score and are sensitive to the influence of hearing loss and amplification on spatial perception. As demonstrated in various clinical studies (e.g., Letowski et al, 1992), detection thresholds are highly reliable, can be measured rapidly, and the task requires minimal training for the listener. However, the need still exists for a spatial audiometric test designed to measure detection of signals in the presence of background noise or other acoustic signals. Such a test would provide the audiologist with important information concerning an individual's spatial acuity in a typical, noisy listening environment. If a person cannot detect speech in noise, she/he will almost certainly have difficulty localizing and understanding speech in noise.

The purpose of the present study was to evaluate stimuli and test conditions for use in the development of spatial audiometric tests of detection. Specifically, detection thresholds for standard spondaic words presented in directional noise were measured in an anechoic environment. The signal and noise were presented from actual sound sources positioned at various locations in the horizontal plane. Three experiments were conducted to determine (1) the effect of sound source position on the reliability of binaural detection thresholds, (2) the effects of two different types of masking noise on detection of a spatial target signal, and (3) the applicability of various spondaic words for spatial audiometry.

METHOD

Subjects

Three separate groups of subjects, aged 18 to 35 years, participated in the experiments. Specifically, 10 subjects (mean age = 28.5 years) participated in experiment 1, 25 subjects (mean age = 22.3 years) participated in experiment 2, and 10 subjects (mean age = 24.7 years) participated in experiment 3. The subjects were students of a local community college. Subjects had (a) no recent history of otologic pathology, (b) air-conduction thresholds better than 15 dB HL from 0.25 to 8 kHz in octave steps (ANSI, 1996), and (c) hearing symmetry (interaural differences at each frequency were no greater than 5 dB). In addition, subjects were required to have normal tympanograms and acoustic reflex thresholds. A masking level difference (MLD) of >6 dB for a 500-Hz tone presented in narrowband noise (Olsen et al, 1976) was also required. The MLD measurement was used as a screening tool because it has been found to identify individuals with processing problems in a frequency region that is important for the detection of spondaic words in noise (Dirks and Wilson,

Table 1 Spondaic Words from the CID W-1 Word Lists Selected for Use as Target Signals

Spondaic Words
Armchair
Headlight
Horseshoe
Hotdog
Inkwell
Mushroom
Northwest
Oatmeal
Sidewalk
Toothbrush

1969). All subjects were native speakers of English and none had previous experience in hearing experiments prior to this study.

Stimuli and Apparatus

In all three experiments, the listener's task was to detect a directional target signal in the presence of a directional noise. Target signals were selected from the CID W-1 spondaic words listed in Table 1. The CID W-1 spondaic words were selected because (1) recordings of the words are available for use by any researcher or clinician, (2) the words are commonly known by adults and children, and (3) minimal time is needed to familiarize listeners with these words. The masking noise was either a broadband signal approximating the long-term average speech spectrum (SSN) (ANSI, 1992) or a multitalker noise (MTN). The MTN was 20-talker babble (8 males, 12 females) recorded by Frank and Craig (1984). Noise spectra did not differ more than ±1.8 dB when measured at ⅓-octave intervals from 0.2 to 9 kHz.

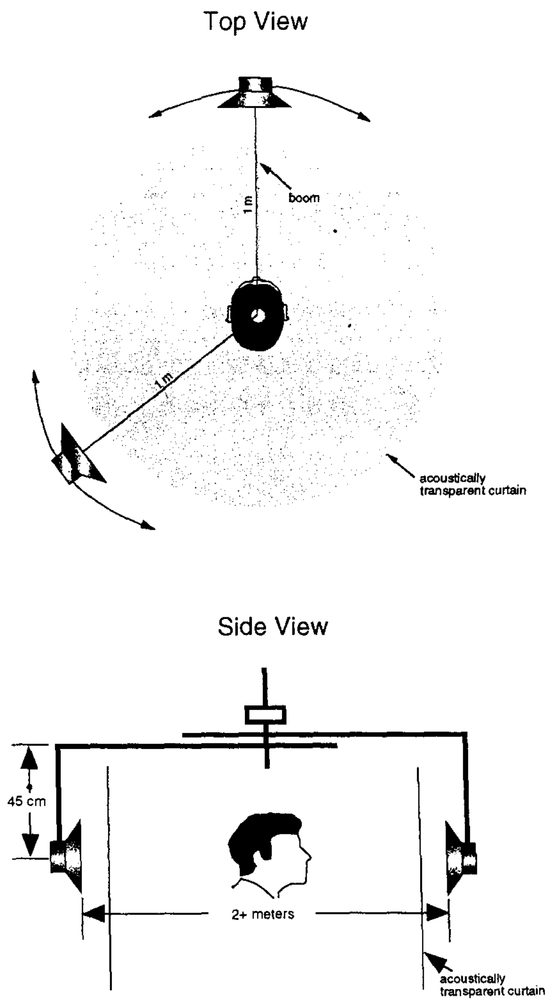

Figure 1 Experimental set-up for the measurement of binaural detection thresholds. The view from the top and the view from the side are shown in the upper and lower panels, respectively. The figure shows two independently moving loudspeakers mounted at the end of rotating booms such that the speakers were 1 meter from the subject's head at ear level.

In each experiment, the target signal (s) and directional masking noise (n) were delivered individually to two single-source, boom-mounted loudspeakers (Bose, Model 1180385A) for binaural detection threshold (BDT) testing. The loudspeaker system was located in a 2.7 m × 2.7 m × 1.9 m anechoic chamber (IAC, Microdyne™ Series; anechoic for frequencies above 170 Hz). As shown in Figure 1, the two booms were suspended from the ceiling of the chamber and pivoted on the same axis, holding the loudspeakers at a uniform 1 m from the subject's head at ear level. Each of the loudspeakers could be independently rotated to any of eight test positions (0, 45, 90, 135, 180, 225, 270, or 315° azimuth) using computer-controlled stepper motors (Arrick Robotics™). A dark, acoustically transparent curtain and a proper lighting system blocked the loudspeakers and boom system from the subject's view.

The output signals from the loudspeakers were adjusted to be equal (within 2 dB) at ⅓-octave band intervals from 0.2 to 9 kHz, using a 75 dBA pink noise as a signal input. When the loudspeakers were positioned at each of the eight test positions, sound levels measured in the center of the room (B&K 4134 microphone positioned at the subject's head location with the subject absent) varied less than

1 dB in any of the 11 ⅓-octave bands. Additionally, KEMAR (Knowles Electronic Manikin for Acoustic Research) was used to evaluate the influence of the human head on sounds at the subject's test position (Burkhard, 1978). Each loudspeaker was rotated sequentially through the eight test positions. At each position, a computer-generated chirp signal (SYSid software, Ariel Corp.) was presented through the loudspeaker and responses were measured at KEMAR's ears using B&K 4134 microphones located at the level of the left and right eardrums of KEMAR. Left and right ear sound pressure levels did not differ by more than ±1 dB for a loudspeaker at 0° azimuth. Microphone responses for other azimuth locations were in agreement with data reported by Shaw (1974).

General Procedure

The task of the subject in all experiments was to track BDTs for target signals presented in directional noise, using a standard Bekesy Tracking Procedure (Bekesy, 1947). Abouchacra et al (1996) compared the Bekesy procedure with two other adaptive threshold procedures (Ascending Up-and-Down Maximum-Likelihood) for measuring directional masking of speech. The results of the study indicate that although all three adaptive procedures yield accurate results and render similar mean thresholds, subject satisfaction reports and differences in administration time suggest the Bekesy Tracking Procedure as the method of choice for spatial detection tasks.

Subjects used a hand-held response button to track their thresholds. The target signal was initially presented at a level approximately 20 dB below the subject's estimated masked threshold and the intensity of the target signal was increased and decreased at a rate of 5 dB/sec in 0.5-dB steps. Tracking of the target signal continued over the 60 seconds after the first reversal on the tracing. The BDT was defined as the mean midpoint of all of the excursions over the 60-second period (Abouchacra et al, 1996). The first reversal was excluded from the calculation of threshold because it increases the overall error of the threshold estimate (Zwislocki et al, 1958; Lezak et al, 1964).

No restraints were used to keep the subject's head from moving during testing. Instead, two plumb-bobs were dropped from the roof of the cylindrical curtain, 50 cm apart, directly in front of the subject. Subjects were instructed to visually align the two plumb-bobs. Head orientation was monitored by a head tracking electromagnetic device (Polhemus, 3-SPACE ISOTRAK) that was mounted to the back of the subject's head using a Velcro™ strap. Any target signal presentations that occurred during excessive head movement (≥3° azimuth) were discarded and repeated. Test sessions lasted 40 to 90 minutes, depending on the experiment, with rest periods given about every 20 minutes.

EXPERIMENT 1

Purpose and Procedure

The purpose of experiment 1 was to determine whether changes in BDTs occurred as a function of varying the angular separation between the signal and noise source. The target signal was the spondaic word *northwest*. It was selected because the two syllables of the word were judged to be homogeneous with respect to audibility in eight investigations evaluating words on the CID W-1 word lists (Olsen and Matkin, 1991). The noise was SSN presented continuously at a level of 65 dBA.

Sixteen loudspeaker configurations were used in the study, constituting eight "mirror" loudspeaker pairs (Table 2). A "mirror" configuration for the condition s45n90, for example, is a target presented at 315° azimuth and a noise at 270° azimuth. Thresholds measured in mirror conditions were tested to determine whether the sound field in the anechoic chamber was symmetric in the horizontal plane. If BDTs measured at mirror conditions are comparable, only half of the configurations need to be tested in further experiments, that is, the BDT at one loudspeaker configuration can be estimated from a BDT measured at its mirror condition. The ability to assume such symmetry is important for audiologic evaluations because it permits a considerable reduction in the time needed for testing. In theory, if the room is acoustically symmetric at the mirror conditions, loudspeaker pairs should produce similar BDTs for listeners with symmetric hearing sensitivity. For individuals with asymmetric hearing sensitivity, however, conditions on both sides of the midline would have to be tested.

BDTs for the target signal *northwest* presented in SSN were measured in the 16 loudspeaker configurations. Three of the 16 test configurations (s180n90, s0n270, s180n270) were tested twice to determine threshold stability. During the 40-minute session, subjects

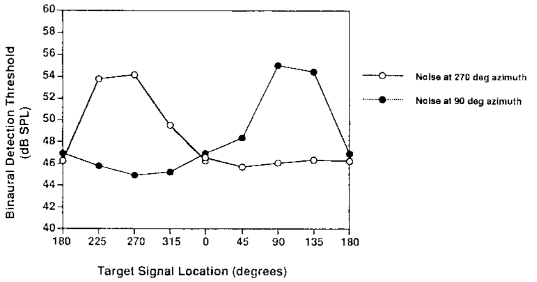

Figure 2 Mean binaural detection thresholds (BDTs) measured for mirror signal and masker pairs, with northwest as the target signal and SSN as the masker. Open circles represent BDTs with SSN located at 270° azimuth. Solid circles represent BDTs with SSN located at 90° azimuth.

were given a 5-minute break after the first 20 minutes of testing.

Results

Detection thresholds were analyzed using a two-way analysis of variance (ANOVA) with repeated measures on loudspeaker configuration (eight arrangements) and loudspeaker orientation (original vs mirror configuration) using Greenhouse-Geisser corrections (Vasey and Thayer, 1987). As expected, there was a significant effect of loudspeaker configuration on BDTs (F [15, 323] = 46.1, $p < .001$). No statistically significant differences were found between BDTs measured in an original loudspeaker configuration and its mirror arrangement ($p > .05$). Paired t-tests were performed on the three test and retest BDTs and revealed no statistically significant differences between test and retest thresholds ($p > .5$).

Figure 2 shows mean BDTs measured in experiment 1. The results suggest that masked BDTs improve as the separation between the target and noise source increased. When the target word and noise shared the same spatial position (e.g., s90n90 or s270n270), subjects had the most difficulty detecting the target signal. BDTs improved approximately 10 dB when both of the loudspeakers were off the median plane and separated by at least 180° azimuth (e.g., s90n270 or s270n90).

EXPERIMENT 2

Purpose and Procedure

The purpose of experiment 2 was to determine whether BDTs similar to those measured with SSN would be obtained using a MTN

Table 2 **Loudspeaker Configurations for Experiments 1, 2, and 3**

Experiment 1		*Experiment 2*				*Experiment 3*	
Condition Number	*S-location/ N-location/*	*Condition Number*	*S-location/ N-location*	*Condition Number*	*S-location/ N-location/*	*Condition Number*	*N-location/ S-location*
1	s0n90	1	s0n0	18	s45n315	1	s0n0
2	s45n90	2	s0n45	19	s90n0	2	s180n0
3	s90n90	3	s0n90	20	s90n45	3*	s180n0
4	s135n90	4	s0n135	21	s90n90	4	s0n180
5	s180n90	5	s0n180	22	s90n135	5	s180n270
6*	s180n90	6	s180n0	23	s90n180	6	s270n0
7	s225n90	7	s180n45	24	s90n225	7	s270n180
8	s270n90	8	s180n90	25	s90n270	8	s270n90
9	s315n90	9	s180n135	26	s90n315		
10	s0n270	10	s180n180	27	s135n0		
11*	s0n270	11	s45n0	28	s135n45		
12	s315n270	12	s45n45	29	s135n90		
13	s270n270	13	s45n90	30	s135n135		
14	s225n270	14	s45n135	31	s135n180		
15	s180n270	15	s45n180	32	s135n225		
16*	s180n270	16	s45n225	33	s135n270		
17	s135n270	17	s45n270	34	s135n315		
18	s90n270						
19	s45n180						

The numbers following the letter s represent azimuth location of the target signal. The numbers following the letter n represent azimuth location of the directional noise source. Whenever the signal and noise were located at the same spatial position (e.g., s180n180), both stimuli were presented through a single loudspeaker. An asterisk indicates a repeated condition.

Table 3 Comparison of BDTs Measured in Directional SSN and MTN

Loudspeaker Configuration	*Difference (dB) (MTN-SSN)*
s0n0	0.2
s0n45	–2.0
s0n90	–2.1
s0n135	3.1
s0n180	–0.1
s180n0	0.8
s180n45	2.8
s180n90	2.5
s180n135	3.2
s180n180	0.2
s45n0	3.2
s45n45	–0.4
s45n90	–0.5
s45n135	–0.3
s45n180	2.0
s45n225	0.2
s45n270	–0.1
s45n315	2.0
s90n0	3.0
s90n45	–0.2
s90n90	–0.5
s90n135	3.3
s90n180	1.7
s90n225	–0.2
s90n270	1.8
s90n315	2.2
s135n0	1.1
s135n45	–0.4
s135n90	1.6
s135n135	0.2
s135n180	–0.1
s135n225	0.3
s135n270	0.3
s135n315	0.1

masker. Some clinicians and researchers prefer to use MTN as the masker in speech detection and discrimination measures because it is more realistic. A MTN also has more variability in amplitude (intensity) across frequency over time, because of natural variations in speech. It would be more desirable, however, to use SSN for clinical measurement of BDTs because it is easier to generate, calibrate, and standardize. Therefore, experiment 2 was designed to compare BDTs obtained using SSN and MTN. If similar thresholds are obtained with both maskers, then SSN can be adopted for clinical use; if thresholds obtained with the two maskers differ, the decision of which masker to use would depend on whether temporal uniformity or realism is more important for a particular application.

As in experiment 1, the target signal was the spondaic word *northwest*. The noise was SSN or MTN presented at a level of 65 dBA. BDTs for the target signal, *northwest*, were measured for the 34 loudspeaker configurations listed in Table 2 for experiment 2. In contrast to experiment 1, sound source configurations in experiment 2 included locations in the front and back of the subjects for both the target and noise. During the 90-minute test session (separated by 5-minute breaks about every 20 minutes), BDTs were measured in the 34 loudspeaker configurations for each of the 25 subjects.

Results

Mean differences in BDTs averaged across subjects between SSN and MTN are listed in Table 3. The differences in BDTs varied from –2.1 dB to +3.3 dB, depending on the loudspeaker configuration. Positive threshold differences indicate that the MTN masked the target signal more than the SSN. Negative differences indicate that the target signal was more difficult to detect in SSN than in MTN. Using multiple t-tests with Bonferroni correction for multiple comparisons, the differences between BDTs obtained with SSN and MTN maskers for a given loudspeaker configuration were evaluated. All differences between BDTs were nonsignificant at the 0.05 level. To be certain that the lack of a significant difference between BDTs with SSN and MTN was not due to variability in the data, correlations were calculated between the BDTs for these two maskers. A correlation of 0.925 ($p < .001$) indicates that the scores obtained are consistent with the lack of statistical significance between BDTs obtained with SSN and MTN.

EXPERIMENT 3

Purpose and Procedure

The purpose of experiment 3 was to determine the effect of loudspeaker configuration on spondaic word detectability in noise for a number of different spondaic words. Specifically, the goal was to assess the integrity of the 10 spondaic words listed in Table 1. These words have been recommended for use in audiologic tests conducted in noise (Wilson et al, 1982a, b). Wilson et al have found these words to (a) be equally audible in noise under headphones and (b) provide large MLDs in detection and recognition

Table 4 Mean BDTs and Standard Deviations (in Parenthesis) for the Target Spondaic Words as a Function of Loudspeaker Configuration

Configuration	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	s0n0	*s180n0*	*s180n0**	*s0n180*	*s180n270*	*s270n0*	*s270n180*	*s270n90*
Armchair	59.8 (1.8)	48.8 (2.3)	48.4 (1.8)	46.5 (3.6)	42.0 (2.5)	42.9 (4.1)	45.0 (1.7)	40.9 (2.3)
Headlight	61.6 (1.6)	51.1 (2.1)	51.7 (2.2)	48.3 (2.2)	42.7 (3.1)	44.4 (4.0)	47.0 (1.8)	44.2 (2.4)
Hotdog	61.6 (1.7)	49.9 (2.0)	51.4 (1.8)	49.1 (1.9)	43.2 (2.5)	45.1 (2.9)	47.4 (2.0)	44.3 (1.9)
Inkwell	61.2 (1.5)	52.6 (3.4)	51.3 (4.4)	47.6 (3.6)	41.2 (3.7)	43.8 (3.0)	48.5 (1.6)	43.1 (2.4)
Toothbrush	61.5 (2.4)	51.9 (4.1)	52.9 (2.1)	48.7 (2.6)	40.8 (4.1)	42.8 (2.9)	46.7 (1.4)	42.3 (2.8)
Mushroom	57.1 (2.3)	52.0 (3.0)	53.5 (4.1)	50.8 (1.9)	49.5 (2.5)	43.6 (3.1)	49.0 (2.1)	48.7 (2.9)
Northwest	57.3 (2.5)	51.7 (2.9)	52.5 (2.5)	50.6 (2.9)	46.3 (3.8)	43.8 (3.3)	47.1 (2.4)	45.7 (2.2)
Oatmeal	57.0 (2.8)	52.3 (4.7)	52.8 (3.5)	51.8 (2.7)	45.6 (3.9)	43.4 (3.7)	51.1 (2.7)	48.0 (2.9)
Sidewalk	56.1 (1.6)	52.0 (3.2)	51.1 (2.3)	51.8 (3.0)	46.6 (3.4)	42.1 (3.7)	47.9 (2.7)	44.6 (1.9)
Horseshoe	53.6 (2.8)	46.6 (3.4)	48.0 (2.6)	38.4 (4.3)	33.8 (3.1)	36.6 (3.8)	40.0 (3.3)	30.9 (1.3)

An asterisk refers to a repeated condition.

tasks. In the present experiment, the masker was SSN presented at constant level of 65 dBA. During a 90-minute test session, BDTs were measured for the 10 spondaic words in each of the eight loudspeaker configurations listed in Table 2. A total of 80 BDTs were measured for each of the 10 subjects.

Results

BDTs were analyzed using a two-way ANOVA with repeated measures on word (10 spondaic words) and loudspeaker configuration (eight configurations). Results of the analysis showed that the main effects of word (F [9, 81] = 68.3) and loudspeaker configuration (F [7,63] = 125.9), as well as the interaction between word and loudspeaker configuration (F [63, 342] = 4.7), were significant at the 0.001 level. As listed in Table 4, mean BDTs averaged across subjects for each loudspeaker configuration and each word in the 65 dBA noise ranged from 30.9 to 61.6 dB (a 30.7-dB difference), depending on the spondaic word and loudspeaker configuration. However, variability of BDTs across subjects for a given word was quite small, with standard deviations for individual words ranging from 1.4 to 4.7 dB.

Figure 3 presents the data of experiment 3 in a format where BDTs are compared to the poorest (highest) detection threshold obtained when both the target signal and noise were located directly in front of the subject (i.e., loudspeaker configuration 1). Therefore, the BDT at that location was used as the reference for comparison of the data obtained in other configurations. The loudspeaker configurations for the target signal and noise are indicated along the abscissa. Difference threshold is represented along the ordinate, with 0 dB representing no difference from the "anchor" loudspeaker configuration (i.e., s0n0). Comparison of BDTs at the various loudspeaker configurations indicates improvements in BDTs on the order of 4 to 20 dB, depending on the configuration and spondaic word. However, the pattern of change for the individual words across loudspeaker configurations was quite similar (with the exception of the spondaic word *horseshoe*. In summary, the results of experiment 3 indicate that, for all spondaic words, BDTs improved as the amount of spatial separation between the target and masker increased. BDTs obtained at a given loudspeaker configuration were not uniform across words.

DISCUSSION

Results of the three experiments described here indicate that detection of speech signals in noise improves as the separation between the speech and noise sources increases. However, the exact amount of improvement depends on the particular spondaic word used as the target signal. Maximum improvement in BDT for a target signal occurred when both the target and noise source were off the median plane and separated by at least 90° azimuth. Holding the noise position constant at any location, the largest improvement in BDTs resulted whenever the target signal originated from a frontal position and was separated from the noise source. As expected, when the target signal and noise shared the same spatial position, regardless of

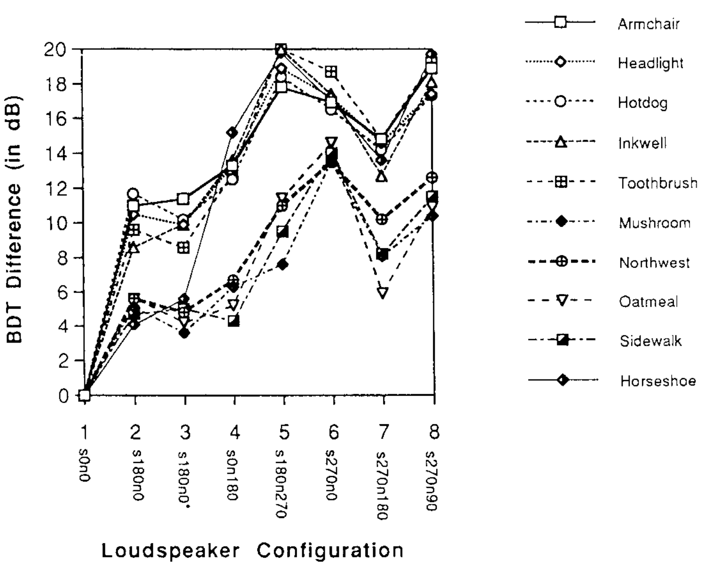

Figure 3. Mean BDTs for ten spondaic words as a function of the spatial configuration of the signal and noise. Plotted thresholds were derived by subtracting the measured threshold for a given word at a given configuration from the threshold measured at s0n0 for the same word.

azimuth, subjects had the most difficulty detecting the signal. Observed differences in BDT due to changes in horizontal separation of signal and noise sources varied from 0 to 20 dB, indicating that this test is sensitive to the spatial configuration of sound sources. These differences in BDTs measured in the anechoic conditions of the present study are similar to other reports of BDTs for speech and nonspeech stimuli (e.g., pure tones or narrow bands of noise) under similar environmental conditions (Hirsh, 1950; Kock, 1950; Norlund and Fitzell, 1967; Ebata et al, 1968; Dirks and Wilson, 1969; MacKeith and Coles, 1971; Tonning, 1971; Plomp, 1976; Plomp and Mimpen, 1981; Duquesnoy and Plomp, 1983; Calhoun et al, 1987; Gelfand et al, 1988; Bronkhorst, 1990; Festen and Plomp, 1990; Good and Gilkey, 1992; Saberi et al, 1992). As revealed in experiment 1, differences in BDTs are symmetric for listeners with normal hearing as long as basic symmetry of the listening space is preserved. The improvement in BDTs with speech and noise separated reflects the use of binaural information. Thus, if used clinically, spatial detection testing would provide the audiologist with a measure of an individual's ability to use the binaural cues of interaural time of arrival differences and interaural intensity differences to detect signals from spatially distinct locations. However, information about sensitivity to the individual cues of interaural time and interaural intensity would not be obtained with a spatial detection test because these cues occur together in typical complex listening environments. While information about sensitivity to each of these cues would be interesting, it is most important for the audiologist to measure spatial acuity in an everyday listening situation in which these cues occur simultaneously.

The fact that BDTs measured in the presence of SSN and MTN maskers do not differ significantly (experiment 2) suggests that the masking effectiveness of SSN and 20-voice MTN is comparable. The similarity of the BDTs in the two noise types also indicates that either noise type can be used in spatial audiometric tests. This is especially true if the noise source is located at 180° azimuth because differences in BDTs were always ≤2 dB. Clinicians concerned about creating more realistic environments may choose the MTN for measuring spatial detection thresholds. On the other hand, clinicians concerned about calibration and control issues may select SSN for clinical testing because SSN provides essentially the same BDT data as the 20-talker MTN used in this study. Thus, based on the results of this study, it is expected that the use of MTN or simulated speech noise should result in practically identical results in a diagnostic evaluation.

In order for any test to be adopted for general clinical use, it must be easy to administer and score and must be conducted in a timely manner. To simplify BDT testing, the results of the three experiments reported here suggest limiting the choice of test signal, background noise, and loudspeaker configurations. Specifically, these data indicate that a single spondaic word, such as the word *northwest*,[1] and the SSN masker would be a good choice of stimuli for clinical spatial audiometry. The use of several spondaic words for a number of different loudspeaker configurations would not be appropriate, as the results from experiment 3 indicate. Likewise, repeating the same loudspeaker configuration using several spondees would add noise to the data. A single, homogenous spondaic word presented in a noise at a select number of loudspeaker configurations should maximize the reliability and efficiency of spatial audiometric detection testing. Based on the present results, including the s0n0, s180n0, s270n0, and s270n90 would sample the range of BDTs and the range of speech and noise source configurations.

The reliability and efficiency of spatial audiometry reported in the present study that is necessary for a viable clinical test may not be attainable in standard audiometric test booths. There are numerous problems with soundfield testing that have been identified in a tutorial on soundfield calibration (ASHA, 1991), such as (a) the large variability among sound sources used for testing, (b) the effect of loudspeaker and listener position in the room on the results of audiometric tests, and (c) the more cumbersome calibration and greater complexity of testing equipment (ASHA, 1991). These and many of the other difficulties associated with soundfield testing can be eliminated or reduced by conducting spatial audiometric testing using a virtual audio display (VAD).

A VAD is a technology allowing sounds presented through earphones to be perceived as originating at various locations outside the earphones and around the head. To create this three-dimensional percept, sounds are routed through special filters that mimic the natural cues necessary for spatial hearing. This unique filtering restores the cues that are required for accurate sound localization (Wightman and Kistler, 1989a, b; Middlebrooks and Green, 1991).

In addition to eliminating many of the difficulties associated with traditional soundfield testing, VADs provide the flexibility to design acoustic environments that closely resemble everyday communication settings. Therefore, it would be advantageous to modify the spatial audiometric detection test described here to incorporate a VAD, like our spatial localization and speech intelligibility tests (Besing and Koehnke, 1995; Koehnke and Besing, 1996).

CONCLUSIONS

Overall, the results of this study have provided information regarding some of the relationships between spatial locations of sound sources and spatial hearing performance in noise, at the level of detection. Although the dependence of BDTs on spatial configuration of sound sources is not a new concept in the literature, this research suggests that spatial audiometry is a promising method for evaluating hearing performance under spatially realistic conditions. The results also provide the information necessary to select an appropriate set of stimuli and set of speech and noise source configurations for a clinical test of spatial detection. The development of a standardized spatial detection test would enable clinicians to (a) measure appropriateness of a hearing aid fitting, (b) determine higher than normal risk in missing acoustic signals coming from specific directions, and (c) evaluate communication ability in noise in typical everyday environments.

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[1] Any single spondaic word evaluated in this experiment can be used as a test signal in place of *northwest*, with the exception of the word *horseshoe*. Although BDTs for the word *horseshoe* followed the same pattern as the BDTs for the other spondaic words, the BDT increased significantly between loudspeaker configurations 3 and 4 compared to the other conditions (see Fig. 3).

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