A Test of Virtual Auditory Localization

Joan M. Besing and Janet Koehnke

Objective: **The purpose of this study was to evaluate a test of virtual auditory localization including assessment of its ease of administration and its sensitivity to differences in binaural performance in children and adults. This test eliminates many potential problems inherent in any free-field localization test such as calibration problems, problems replicating source and listener locations, and issues associated with head movements.**

Design: **Binaural performance was measured using the virtual localization test and a simple binaural detection task, the masking-level difference (MLD), for three groups of subjects: adults, children with a negative history of otitis media, and children with a positive history of otitis media. There were five subjects in each group. The adults were all student volunteers; the children were recruited first and subsequently placed into groups based on their medical histories obtained from their physicians and parental reports.**

Results: **Results indicate that this test of virtual auditory localization is useful for measuring binaural performance in children and adults and is sensitive to differences in binaural processing. Performance of the adults and children with a negative history of otitis media was comparable on both of the binaural tests, and on the binaural detection task, was similar to that reported in the literature for normal-hearing listeners; but the children with a positive history of otitis media performed more poorly on both tests.**

Conclusions: **The results of this study indicate that the virtual localization test described here is easy to administer to children and adults. The signal processing techniques used in this virtual auditory localization test lend themselves to straightforward comparisons across different laboratories and clinics and make this test a potentially useful clinical tool. The development of such a clinical test is currently under study.**

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This paper describes a new procedure for measuring localization in a virtual auditory environment and presents some initial results obtained using this procedure. Specifically, this study was designed to 1) evaluate a new test of virtual auditory localization, 2) compare performance on this complex binaural localization task with performance on a basic binaural detection test measuring masking-level differences (MLDs), and 3) assess the sensitivity of this test to differences in binaural performance in individuals with a history of conductive pathology.

Department of Communication Sciences and Disorders, Louisiana State University, Baton Rouge, Louisiana

The ability to localize sound sources is essential for both safety (e.g., crossing the street) and communication (e.g., locating the speaker in a group) and is a task that is done repeatedly on a daily basis. Localization relies primarily on binaural abilities, in particular sensitivity to interaural differences in level and time of arrival. Studies of localization by adults with and without conductive hearing losses due to otosclerosis, chronic otitis media, or atresia (Abel, Birt, & McLean, 1978; Jongkees & Veer, 1957; Nordlund, 1964; Wilmington, Gray, & Jahrsdoerfer, 1994), and children with and without conductive hearing losses due to atresia (Wilmington et al., 1994), indicate poorer than normal localization for subjects with conductive pathologies. In all of these studies performance was measured in a free-field environment, and results show a very wide range of performance even for listeners with the same etiology (Abel et al., 1978; Jongkees & Veer, 1957; Nordlund, 1964; Wilmington et al., 1994). Whereas some of this variability might be due to individual differences, it is likely that differences in the experimental setup and procedures used in the various studies and especially the free-field environment accounts for at least some of the differences, because it introduces a number of potential problems. First, it is almost impossible to be certain of the characteristics of the signals actually reaching the listener's ears. Second, it is difficult to calibrate the signals in this environment. Third, it is quite cumbersome, although not impossible, to ensure that the sound sources and the listeners are in exactly the same locations for each test session. Finally, it is difficult to control other subject variables such as head movements.

There have been a number of studies investigating the ability of children with normal hearing and a history of chronic, recurrent otitis media to use the advantages provided by their binaural system (Hall & Grose, 1993; Moore, Hutchings, & Meyer, 1991; Pillsbury, Grose, & Hall, 1991; Roush & Tait, 1984). However, these studies have been confined to simple

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binaural detection (masking-level difference[1]) tasks and have not included tests of complex binaural processing such as localization. Therefore, it seems logical to evaluate the sensitivity of this virtual localization test to differences in binaural processing in children with and without a history of chronic, recurrent otitis media.

The results of many of the investigations of binaural detection indicate that children with a history of otitis media have smaller MLDs than children with no history of otitis media (Hall & Grose, 1993; Moore et al., 1991; Pillsbury et al., 1991). These differences are due primarily to poorer N0Sπ thresholds in the otitis media subjects; the N0S0 thresholds of the children with and without a history of otitis media are similar. But the overall differences between the MLDs of the two groups are typically small, ranging from less than 1 dB to 4 or 5 dB. The ranges of the thresholds and MLDs for the two groups also show a lot of overlap (Hall & Grose, 1993; Moore et al., 1991; Pillsbury et al., 1991).

One difficulty with measuring binaural detection thresholds to obtain MLDs is that the task is difficult for children under the age of 7 or 8 yr. Even for the older children, it is not a task that maintains their interest for long periods of time. Therefore, it is important to find another procedure for measuring binaural performance in children and for investigating the effects of otitis media on binaural performance in children. Localization was chosen because it is a relatively straightforward task and can be measured quite easily, even in infants (e.g., Ashmead, Clifton, & Perris, 1987).

While there have been many studies of binaural performance of individuals with conductive hearing loss on a single binaural task, only Wilmington et al. (1994) have measured performance on both binaural detection and localization for the same group of individuals with conductive pathology. When they compared binaural performance pre- and post-surgery for their subjects with congenital, unilateral, conductive hearing loss, they found improved binaural performance on all tasks, with greater improvement on basic binaural tasks such as discrimination and detection than on more complex tasks of localization and speech intelligibility. About 60% of their subjects had post-surgical performance comparable to normal on the binaural detection task, but only 20% had performance comparable to normal on the localization task (Wilmington et al., 1994). Wilmington et al. also found that the individuals whose binaural processing for detection was affected by the conductive pathology had poor localization.

Theoretical evidence (Levitt & Rabiner, 1967; Zurek, 1993) indicates that a relationship between binaural detection ability and performance on complex binaural tasks may also be observed for individuals with other auditory pathologies. According to these models, speech intelligibility in noise can be predicted by measures of binaural detection. Specifically, Zurek (1993) predicts the ability to understand speech in noise is based on the advantages obtained from detecting differences in the signals reaching the two ears. This information is obtained through binaural interaction (as measured by the MLD) and the head-shadow effect. Because localization is thought to rely on the same binaural information as speech intelligibility, it is likely that localization ability can also be predicted based on binaural detection.

In light of this theoretical and experimental evidence, a test of localization was developed to measure binaural performance. To avoid the difficulties often encountered in measuring localization in the free-field, state-of-the-art signal processing techniques were used to process the auditory signals so that they could be presented through headphones in a virtual auditory environment. To 1) evaluate the sensitivity of this test to differences in binaural processing in children with and without a history of otitis media, 2) compare performance of children and adults on this test, and 3) compare basic binaural detection and localization, performance was measured for three groups of subjects on this test of virtual auditory localization and on a test of masking-level differences.

METHODS

A three step testing protocol was used to evaluate the subjects in this study. The first step included audiological measures to assess hearing sensitivity and middle ear function. The second and third steps included two measures of binaural performance: localization and masking-level differences (MLDs) [N0S0 and N0Sπ thresholds]. These binaural tests were conducted in random order across subjects.

All testing was conducted in a sound-treated room. Subjects listened to signals presented over TDH-50 earphones in MX41/AR cushions. Test sessions varied in length from 1 to 2 hr (depending upon the attention span of the subject) and included frequent breaks. The subjects received training to familiarize them with both binaural tasks. For most individuals this involved about 30 minutes for the MLD task and 5 to 10 minutes for the localization task.

[1] Masking-level differences (MLDs) are typically obtained by measuring detection thresholds for a diotic signal in diotic noise (N0S0) and an interaurally phase reversed signal in diotic noise (N0Sπ). The difference between these thresholds (N0S0 − N0Sπ) is the MLD.

TABLE 1. Subjects with a positive history (P Hx) of otitis media.

Subject	Age at 1st episode (years,months)	Age at last episode (years,months)	Age at testing (years,months)	No. of episodes	No. of p.e. tubes
P Hx 1	0,5	9,3	11,5 to 11,9	27	1
P Hx 2	0,5	8,3	8,1 to 8,5	27	0
P Hx 3	1,2	10,9	10,10 to 11,1	31	2
P Hx 4	0,1	10,6	11,1 to 11,4	30	5
P Hx 5*	~1,0	~9,8	10,3	Many**	0

** indicates no medical records could be obtained; ** parent could not recall the exact number.*

Subjects

Three groups of normal-hearing subjects participated in this study: five adults, five children with a negative history of otitis media, and five children with a positive history of otitis media.[2] Normal hearing was defined as pure tone thresholds of 25 dB HL or better at octave frequencies from 250 Hz through 4000 Hz.[3] The subjects in the adult group were all college students 18 to 29 yr old (mean 23.6 yr). The children in the negative otitis media history group were 7 to 12 yr old (mean 10.4 yr); and the children in the positive otitis media history group were 8 to 11 yr old (mean 10 yr).

Subjects were obtained through the Speech and Hearing Clinics at the University of Connecticut and Louisiana State University and by word of mouth from employees at these Universities. The children were first recruited as subjects; then their parents were questioned regarding their history of otitis media, and medical records were obtained from the children's pediatricians and otolaryngologists.

Clearly, retrospective studies such as this have certain disadvantages. However, since the focus of this study was on the evaluation of the virtual localization test rather than the effects of otitis media, we considered the two sources of retrospective information sufficient for a general comparison. Unfortunately, medical records could not be obtained for one of the children in the positive history group and one of the children in the negative history group, and so in these cases information is only from the parental report.

All of the children in the negative history group had at most three episodes of otitis media according to medical records and parental report; all of the children in the positive history group had multiple, recurrent episodes of otitis media according to medical records and parental report. Tables 1 and 2 summarize the information about all of the subjects in the positive and negative otitis media history groups, respectively. The tables include the child's age at the first episode, age at last episode, age at time of testing, approximate number of otitis media episodes, and for the positive otitis media group only, the number of pressure equalization (p.e.) tube insertions. Of the positive history children, three had been treated one or more times with p.e. tubes. One of these had p.e. tubes in place at the time of testing. To try and rule out the presence of abnormal middle ear function at the time the experiments were conducted, a test procedure was completed at the beginning of every test session and is described below.

Testing Protocol

Step 1: Pure Tone Testing and Acoustic Immittance Screening • All subjects in this study were required to have normal hearing and normal middle ear function at the time the binaural tests were conducted. Therefore, before beginning the binaural experiments, pure tone thresholds were measured at octave frequencies from 250 through 8000 Hz for each subject. Unfortunately, according to parental reports and medical records, audiograms had not

TABLE 2. Subjects with a negative history (N Hx) of otitis media.

Subject	Age at 1st episode (years,months)	Age at last episode (years,months)	Age at testing (years,months)	No. of episodes
N Hx 1	8,1	9,2	11,3 to 11,8	3
N Hx 2	1,0	6,6	6,11 to 7,2	3
N Hx 3	NA**	NA	11,10 to 12,0	0
N Hx 4	NA	NA	11,10 to 12,0	0
N Hx 5*	4,0	5,2	12,0	2

** indicates no medical records could be obtained; ** NA = not applicable*

[2] The fact that there are five subjects in each of the positive history and negative history groups is purely coincidental. Originally, 13 subjects were recruited. According to parental report, seven of them were identified as belonging to the positive history group and six of them were identified as belonging to the negative history group. However, one subject did not complete the testing and two other subjects produced very inconsistent results, apparently due to their short attention spans. Therefore, these subjects' data are not included here.

[3] One of the children in the positive history group had a threshold of 30 dB HL at 4000 Hz. However, because the virtual localization and MLD tests were conducted using wideband stimuli at suprathreshold levels (a wideband masker for the MLD test), it is unlikely that this 4000 Hz pure-tone threshold affected the binaural performance of this subject.

been routinely obtained from the subjects before and after episodes of otitis media. Therefore, the audiometric history of the subjects in this study cannot be documented. Acoustic immittance screening was also done before binaural testing. The same acoustic immittance screening was completed on each day of testing for all of the children in both the positive and negative otitis media history groups. Any child failing the screening (middle ear pressure less than −150 mm H_2O) did not continue with binaural testing on that day. For the one child with p.e. tubes in place at the time of the study, immittance testing was done to insure that the tubes were patent.

Step 2: Localization of Speech • Virtual localization was measured in quiet in both anechoic and reverberant, simulated, sound-field environments using phrases spoken by two males with a general American dialect. By simulating the listening environments and source locations from which the stimuli were presented, and then delivering them via headphones, extraneous confounding factors such as sound-field calibration and head movements are eliminated. It should be noted that, in the reverberant condition, the stimuli are clearly externalized. Both anechoic and reverberant listening conditions were included because natural reverberation occurring in everyday listening situations tends to diminish the binaural cues used in localizing sound sources. Therefore, it seemed possible that localization performance would be poorer when measured in the simulated, reverberant, environment than the simulated, anechoic environment.

Four different three-word phrases were used as stimuli including: 1) "mark the spot," 2) "fly by night," 3) "crack the walnut," and 4) "come here later," chosen to include commonly encountered phonemes and common English words. Preliminary measurements indicated that there were no discernible differences between talkers or phrases affecting performance on the virtual localization task.

The phrases were presented from nine simulated locations in the horizontal plane from +90° (near the right ear) to −90° (near the left ear) in 22.5° steps. As indicated above, signals were all presented via headphones. The sound-field conditions were simulated using source-to-eardrum transfer functions measured in actual sound-fields for each source location in both the anechoic and reverberant environment using the KEMAR manikin (Burkhard & Sachs, 1975). The reverberation time was approximately 0.25 sec below 800 Hz and 0.4 sec above that frequency. To compensate for KEMAR's ear-canal resonance, an equalization filter was used (Killion, 1979). The signals for all the experimental conditions were processed on a DEC micro-VAX computer

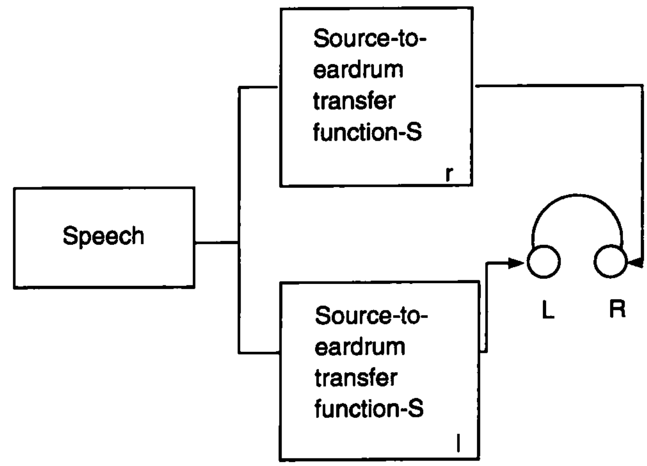

Figure 1. Block diagram showing the signal processing scheme for the virtual localization experiment. The signals for the right and left ears are processed according to the source-to-eardrum transfer functions, and then presented to the subjects via headphones.

and then transferred to a 386 microcomputer for presentation to the subjects.

As shown in Figure 1, the source-to-eardrum transfer functions were convolved with each digitized speech stimulus. This resulted in a single speech output for each ear: S_r for the right ear and S_l for the left ear. These digital stimuli were transferred to a digital-to-analog converter, attenuated to the desired level and presented to the subjects via headphones. When presented binaurally, these stimuli create the virtual locations in the anechoic and reverberant environments.

The speech signals were presented at 70 dB SPL when the source was at 0°. In the other source locations, the actual level at each ear varied depending upon the location of the source relative to each of KEMAR's ears due to the head-shadow effect. Each of the four phrases was presented in each of the two listening environments for a total of eight experimental conditions. Experimental runs for the eight conditions included 45 trials, five from each of the nine locations for one of the four phrases in one of the two virtual listening environments. Each condition was repeated once.

A single-interval, nine-alternative, forced-choice identification procedure with feedback was used to measure localization ability. The subject indicated the virtual location of the talker by pressing a key from 1 to 9 on a computer keyboard. A drawing was mounted on the wall directly in front of the subject indicating the location of the listener's head and the nine possible locations of the talker relative to the head.

Nine by nine confusion matrices were constructed for each run. The root-mean-square (RMS) localization error in degrees and the percent correct was calculated from the confusion matrices for each experimental run. These values were then averaged across repetitions, talkers, and phrases for each environment, resulting in a single RMS error and percent correct score for each of the two listening environments. Confusion matrices were also analyzed for bias and response variability to characterize the subject's errors.

Step 3: Binaural Detection Tests (MLDs) • N0S0 and N0Sπ thresholds were measured for each subject at four test frequencies: 250, 500, 2000, and 4000 Hz. The targets were pure tones and the masker was a 4500 Hz low-pass noise. The masker was presented at an overall level of 75 dB SPL (38 dB spectrum level) and the level of the target was varied to determine the threshold signal-to-noise ratio in dB.

All the signals for the binaural detection experiment were digitally generated on a DEC microVax computer using a 20-kHz sampling rate. The duration of the stimuli was 300 msec with a 15 msec linear rise/fall time and a 300 msec interstimulus interval. To eliminate aliasing, the stimuli were low-pass filtered at 4500 Hz at the output of the digital-to-analog converter. This filter had a slope of more than 100 dB/octave. The signal and masker were gated on and off simultaneously.

Thresholds were measured using a 2-down/1-up, adaptive, two-interval, two-alternative, forced-choice procedure with feedback (Levitt, 1971). Each experimental run included 14 reversals; the last 10 were averaged to calculate threshold. The initial step size was 4 dB; after the first four reversals this was reduced to 2 dB. To ensure that performance in any particular run was consistent, an interquartile rule was employed. According to this rule, if the interquartile range of the levels for all trials during the last 10 reversals was greater than the difference between the levels one step above and below the threshold, the data were not included and the experimental run was repeated.

In most cases two adaptive runs (meeting criteria) were completed for each data point. However, if the difference between the thresholds for the two adaptive runs was greater than 4 dB (2 steps), then one or two more adaptive runs were completed so that two thresholds within 4 dB were obtained. The thresholds reported here are the average of all the estimates meeting criteria for a particular condition.[4]

[4] There were a few instances when one threshold was dramatically different (more than 10 dB) from the others. These were considered anomalous and not included in the average.

TABLE 3. Mean audiometric thresholds in dB HL and interaural asymmetries in dB for all three subject groups.

	Frequency (Hz)				
	250	500	1000	2000	4000
Positive history					
Mean threshold	11	9.5	8.5	5.5	8
Thresh range	0–15	0–20	0–15	0–10	0–30
Mean asymmetry	2	9	3	1	4
Asymmetrical range	0–5	0–20	5–15	0–10	0–30
Negative history					
Mean threshold	4.5	6.5	5.5	4	4.5
Thresh range	0–15	0–15	0–15	0–10	0–10
Mean asymmetry	1	1	1	2	1
Asymmetrical range	0–5	0–10	0–10	0–10	0–5
Adult					
Mean threshold	4	2	1.5	0.5	1
Thresh range	0–15	0–5	0–5	0–5	0–5
Mean asymmetry	2	0	3	1	2
Asymmetrical range	0–10	0–5	0–5	0–5	0–5

RESULTS

Following a description of the subjects' hearing sensitivity, the results are presented first for the virtual localization test and then for the MLD test. Relative performance across the two binaural tasks is considered in the discussion. The data for all of the subjects in each of the three subject groups have been averaged and the standard errors are shown to illustrate the variability among subjects in the same group.

To illustrate the similarity among the three subject groups in terms of hearing sensitivity, Table 3 provides the average pure-tone air conduction thresholds at each frequency and the range of thresholds for the subjects in each group as measured in step 1 of the test protocol. The table also indicates the average threshold asymmetry at each octave frequency, and the range of asymmetries. These thresholds indicate that, in terms of audibility, there are no large or consistent differences among the subjects in each group. Although the adults have slightly better sensitivity than both the negative otitis media history children and the positive otitis media history children, all three groups have sensitivity well within the normal range. Thus, it is unlikely that any differences observed in their binaural performance are due to the audibility of the signals.

Virtual Localization

The test of virtual localization proved to be easy to administer to all three subject groups. In comparison to the MLD test, subjects found this task interesting; none of the children appeared to become distracted or bored as they sometimes did with the

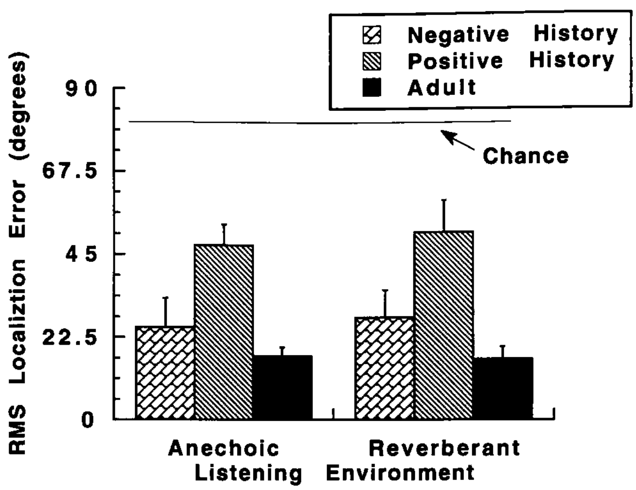

Figure 2. Sound source localization for three subject groups. The RMS localization error in degrees is indicated by the height of the bar versus the type of listening environment. Data for the anechoic environment are on the left and data for the reverberant environment are on the right. Chance performance is indicated by the solid line at 82°. The filled bars represent the data of the adults, the diagonal lined bars the positive history children, and the hatched bars the negative history children. Standard errors are indicated for each condition.

MLD test. None of the children reported any difficulty with the task, even though as the results described below clearly illustrate, some of the children performed much more poorly on the task than other children.

The results of the virtual localization experiment are shown in Figure 2 and Table 4. The bar graph in Figure 2 indicates the RMS localization error in degrees for each subject group in both the anechoic and reverberant listening environment. Since the source locations were separated by 22.5°, the ordinate is incremented in 22.5° steps.

Table 4 indicates the overall percent correct, the mean localization errors in degrees, and the RMS localization errors in degrees for each of the subject groups in both listening environments on the virtual localization test. The mean errors indicate whether there is any directional bias on the average in the responses of the subjects for judgments of location to the right or left of the actual sound source. A mean error of zero indicates no directional bias.

The RMS localization error is calculated by averaging the squared deviations of the errors at each location. It provides information to evaluate the magnitude of the average localization errors in addition to the overall percent correct. If subjects were completely unable to localize the source, and simply guessed, randomly selecting one of the nine possible responses, the RMS error would be 82°, as indicated by the solid line in Figure 2.

The results in Figure 2 show a large and significant difference in the localization ability among the three groups in the anechoic ($F_{2,\ 12} = 7.2, p \leq 0.01$) and reverberant environments ($F_{2,\ 12} = 6.5, p \leq 0.01$). Post-hoc Fisher's protected least significant difference (PLSD) tests indicate that the differences between the positive history and negative history and the positive history and the adult groups are significant at the 0.05 level of confidence. Whereas the adults and negative history children have localization errors on the average of less than one location, the errors of the positive history children are slightly greater than two locations in both the anechoic and reverberant environments. That is, on the average, the children with a history of otitis media identified the location of the sound source as being more than two positions away from the actual source location.

This difference in localization ability can also be seen in the overall percent correct scores indicated in Table 4. The positive otitis media history group only achieves 26% correct identification of source location, whereas the adult group and the negative otitis media history group are more than twice as accurate with scores ranging from 51% correct to 67% correct.

A paired t-test indicated no significant effect ($t = -1.28, p = 0.22$, df = 14) of listening environment on localization ability. As shown in Figure 2 and Table 4, the RMS errors are very similar in the anechoic and reverberant conditions. The mean errors in Table 4 are close to zero and indicate that there is very little, if any, response bias for any of the subject groups in either listening environment. The percent

TABLE 4. Mean percent correct, RMS error, and mean error in anechoic and reverberant environments.

	Anechoic % Correct	Error		Reverb % Correct	Error	
		Mean[a,b]	RMS[a]		Mean[a,b]	RMS[a]
Positive history	25.03	6.92	47.73	26.32	8.94	52.88
Negative history	45.75	3.91	30.53	50.61	3.03	31.54
Adult	59.66	3.37	18.22	65.62	1.89	18.56

[a] Errors in degrees, calculated by multiplying the absolute error by 22.5°, the distance between adjacent speakers.
[b] Positive mean errors indicate a directional bias to the right.

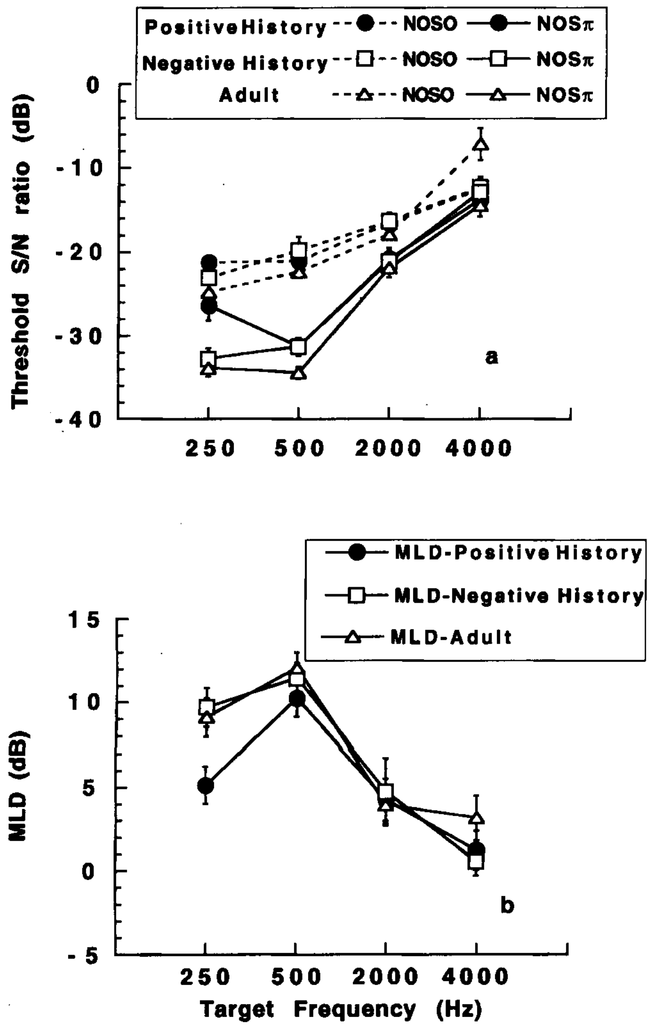

Figure 3. Binaural detection data for all three subject groups. Adults are indicated by the open triangles, negative history children are indicated by the open squares, and positive history children are indicated by the filled circles. In the top panel N0S0 and N0Sπ threshold signal-to-noise ratios in dB are plotted as a function of the target frequency. Standard errors are also shown. N0S0 thresholds are connected by dashed lines and N0Sπ thresholds are connected by solid lines. In the bottom panel the MLDs in dB for the three groups of subjects are plotted as a function of the target frequency.

correct scores are also comparable across listening environments although there is a slight tendency for the adults and negative history children to have slightly higher scores in the reverberant condition than in the anechoic condition.

Binaural Detection—Masking-Level Differences

The results of the binaural detection tests are shown in Figure 3. The N0S0 and N0Sπ thresholds are in the top panel, and the MLDs (N0S0 − N0Sπ thresholds) are in the bottom panel.

It can be seen clearly in the top panel, that the N0S0 thresholds for all three groups overlap, indicating no difference in the ability of these subjects to detect diotic signals presented in diotic noise. However, the N0Sπ thresholds are not as similar. While N0Sπ detection is comparable for the adults and the negative otitis media history group, the positive otitis media history group has poorer N0Sπ thresholds, at the lowest frequency. At 250 Hz, a significant difference in threshold signal-to-noise ratio exists among the groups ($F_{2,\ 12} = 7.9$, $p \leq 0.05$). Post-hoc PLSD tests reveal a significant difference between the positive history and negative history groups as well as a significant difference between the positive history and adult groups ($p = 0.05$).

These differences in N0Sπ detection are also reflected in the MLDs in the bottom panel of Figure 3. At 250 Hz, the average MLD for the positive history group is 4 to 5 dB smaller than for the other two groups. This difference is significant ($F_{2,\ 12} = 4.8$, $p \leq 0.05$). Post-hoc PLSD tests indicate a significant difference in scores between the positive history and negative history groups and the positive history and adult groups ($p = 0.05$).

As expected, in the higher frequencies the MLDs are negligible and there are no significant differences among the three groups. This, along with the comparable N0S0 and N0Sπ thresholds obtained at 2000 and 4000 Hz for all three groups indicates that the positive history children do not have trouble with the detection task per se; their difficulty is confined to binaural processing.

DISCUSSION

This is the first reported study in which performance of children has been measured on a virtual localization task, and in which binaural detection has been measured as a function of frequency in the same group of subjects. To evaluate the feasibility of using this virtual localization measure with children, and to assess the potential use of the virtual localization test for identifying children with binaural processing problems, performance was measured for adults as well as for children with and without a history of otitis media. Overall, these initial data indicate that virtual localization is a straightforward task that is sensitive to differences in binaural processing ability. The children had no difficulty with the task and no training was necessary prior to data collection.

Although the subject groups were admittedly small, the children with a history of otitis media clearly demonstrated poorer binaural performance than the adults and the children without a history of otitis media on both the simple binaural detection task and on the virtual localization task. However, the children with a negative history of otitis media demonstrated performance comparable to that of the adult subjects.

It is unlikely that the poorer binaural performance exhibited by the children with a positive history of otitis media can be accounted for by either absolute acuity or the ability to perform binaural tasks. Table 3 indicates that the average thresholds of the children in the positive history group were from 1.5 to 7 dB poorer than those of the negative history children and the adults. However, it is unlikely that this explains the poorer binaural performance because, as Figure 2 indicates, the N0S0 thresholds of all three subject groups were virtually the same for all the test frequencies. If performance were related to audibility, we would expect to see the threshold differences reflected in the N0S0 as well as the N0Sπ thresholds. It is also interesting to note that Table 3 shows that the positive history children had a fairly large (9 dB) interaural threshold asymmetry at 500 Hz, whereas the other groups had essentially no interaural asymmetry. However, because the N0Sπ thresholds of the positive history children at 500 Hz were not significantly different from the other groups, the asymmetry clearly did not have a large or consistent effect on binaural performance. This is in agreement with results obtained on N0Sπ detection for listeners with sensorineural hearing loss (Koehnke, Colburn, & Owen, 1988).

The thresholds for all three subject groups on the N0S0 detection test and on the high frequency (2000 and 4000 Hz) N0Sπ detection test are similar. This indicates that the poorer binaural performance of the positive history children is related to their history of otitis media, and not to an inherent inability to do binaural tasks.

The results of the binaural detection test are generally in agreement with other studies of MLDs in children with a history of otitis media (Hall & Grose, 1993; Moore et al., 1991; Pillsbury et al., 1991). That is, children with a history of otitis media have smaller MLDs than adults and children without a history. In the previously reported studies, binaural detection was only measured at 500 Hz, the masker bandwidth was much narrower, and the masker level was about 15 dB more intense than in the present study. Although the MLDs are slightly, but not significantly smaller in the positive history group at 500 Hz, at 250 Hz the difference is significant and is at least as large as the difference obtained at 500 Hz in the other studies (Hall & Grose, 1993; Moore et al., 1991; Pillsbury et al., 1991). The magnitude of the MLDs obtained in the present study at 500 Hz is also slightly smaller than reported in the other studies. However, this is likely due to the differences in both the masker bandwidth and level. It is well documented that MLDs get larger as the masker bandwidth decreases (e.g., Zurek & Durlach, 1987) and as the masker level increases (Hirsh, 1957).

These binaural detection results are also in agreement with studies of binaural detection in adults with otosclerosis (Hall & Derlacki, 1986, 1988; Hall, Grose, & Pillsbury, 1990; Magliulo, Gagliardi, Muscatello, & Natale, 1990). These investigators found that MLDs were much smaller than normal not only before corrective surgery when their hearing was, in many cases, abnormal, but also, for many of their subjects, even post-operatively when their hearing was within the normal range.

Although there have been no studies of localization in children with or without a history of otitis media, the results of this study are comparable, at least quantitatively, to those obtained for adults with normal hearing and with otitis media (Jongkees & Veer, 1957; Nordlund, 1964) and for children and adults with other conductive pathologies (Abel et al., 1978; Jongkees & Veer, 1957; Nordlund, 1964; Wilmington et al., 1994). These investigators found abnormal localization in many of their subjects with otosclerosis pre- and post-operatively, in their subjects with chronic otitis media, and in subjects with atresia.

In addition to demonstrating poorer localization ability overall, the children with a history of otitis media in this study showed much greater variability in their localization performance. This was noted when comparing the confusion matrices for the three groups (not shown here). The range of responses for any particular source location were spread over a wider range for the positive history group than for the negative history or adult subject groups. Abel et al. (1978) and Nordlund (1964) also found greater variability than normal in the localization responses of their subjects with otitis media and otosclerosis.

It was somewhat surprising that listening environment did not affect localization performance for any of the groups. Since reverberation reduces some of the available binaural information, it seemed likely that localization would be poorer in the reverberant condition. However, the reverberation time used in this simulation was fairly short (0.25 to 0.4 sec) and apparently did not reduce the available binaural information enough to affect performance.

Although the results of the individual binaural tests are generally comparable to other studies, only Wilmington et al. (1994) measured performance on both a simple binaural detection test and a localization test. However, they measured localization in a free field. They also found that performance on both these tests was usually poorer in individuals with atresia, even 24 wk or more after corrective surgery, than in children and adults with no history of middle ear pathology. At 24 wk or more post-surgery, localization was poorer than normal for all but three of their subjects, but MLDs for more than half their subjects were within the normal range. The initial results obtained for the children with a history of otitis media in this study were also consistently poorer for the virtual localization test than for the binaural detection test. Thus, the results of both of these studies indicate that localization is a test that is at least as sensitive to differences in binaural processing due to conductive pathology as binaural detection. To further assess the sensitivity of the virtual localization test to binaural processing problems in children with a history of otitis media, we are measuring speech intelligibility in noise with and without virtual spatial separation of the signal and noise (Besing, Koehnke, & Goulet, 1993; Besing, Koehnke, Goulet, & Allard, 1992). Together with the localization results, these data will enable us to evaluate the effects of otitis media on spatial aspects of communication.

As mentioned above, one difference between the study of Wilmington et al. (1994) and the present study is that Wilmington et al. measured localization in a free field. There is no reason to expect that there would be any difference between virtual localization and free-field localization, assuming the stimuli used in the virtual localization were processed using source-to-eardrum transfer functions for environments comparable to the actual free field. However, an experiment is underway to address this question.

These initial results indicate that, at least for the group of subjects under study, children with a history of otitis media are likely to have difficulty with both simple and complex binaural processing tasks, even though they have normal hearing sensitivity. This conclusion is based on the difficulty that the otitis media subjects demonstrated with the virtual localization task as well as with the more often used MLD measure. However, more data are needed to corroborate these results for 7- to 12-yr-old children, and the experimental procedure needs to be applied with younger children.

In summary, the results of this initial study indicate that the virtual localization test described here is easy to administer and is useful for measuring binaural performance in children and adults. It is, in fact, also presently being used to compare the effectiveness of different amplification configurations in adult listeners with impaired hearing (Koehnke & Besing, 1995; Koehnke, Besing, Goulet, Allard, & Zurek, 1992). The importance of such a virtual localization test is that it enables one to avoid many potential problems inherent in any free-field localization test. Specifically, we have eliminated calibration problems, problems replicating source and listener locations across test sessions, issues associated with head movements, and any questions about the characteristics of the signals reaching the subjects' ears. In addition, the signal processing techniques used here lend themselves to straightforward comparisons across different laboratories and clinics. Test-retest reliability also appears to be good and is presently being investigated in more detail in the process of developing a clinical test of virtual auditory localization.

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Address for correspondence: Joan M. Besing, Dept. of Communication Sciences and Disorders, Louisiana State University, 163 Music and Dramatic Arts Building, Baton Rouge, LA 70803.

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