J Am Acad Audiol 9: 466–479 (1998)

Sound Localization in the Median Sagittal Plane by Listeners with Presbyacusis

Brad Rakerd*
Timothy J. Vander Velde*
William M. Hartmann†

Abstract

In Experiment 1, a group of listeners with substantial hearing loss due to presbyacusis and a group of listeners with normal hearing were given three localization tests: a frontal plane test in which they judged whether sounds came from the left, overhead, or the right; a sagittal plane test in which they judged whether sounds came from directly in front, overhead, or behind; and an elevation test in which they judged the vertical position of sounds coming from in front. The two groups performed similarly on the frontal plane test, which chiefly depended upon their ability to use binaural localization cues. They performed differently on the sagittal plane and elevation tests, for which the predominant localization cues were spectral. The listeners with presbyacusis were substantially less accurate than those with normal hearing in both of these instances. They had particular difficulty judging source elevation, rarely scoring much above chance. Follow-up testing of a group of subjects in the early stages of presbyacusis showed localization performance that was intermediate to the other two groups, but far more like that of the normal-hearing listeners. In Experiment 2, additional tests were run with the following conditions designed to encourage improved performance by listeners with presbyacusic hearing loss: (1) filtering of stimuli to preclude masking of more informative high-frequency components by low frequencies; (2) simplification of the elevation test and greater spatial separation of its loudspeaker sources; and (3) use of hearing aids. Conditions 1 and 2 had no appreciable effect on performance; condition 3 significantly improved presbyacusic listeners' ability to localize in the sagittal plane, particularly when sounds came from the front.

Key Words: Median sagittal plane, presbyacusis, sound localization

Abbreviations: ELV2 = two-source elevation, ELV3 = three-source elevation, FRN = frontal plane, MSP = median sagittal plane, SAG = sagittal plane

When objects sound around us, we can hear what they are and also where they are. This paper is concerned with the latter, spatial aspect of hearing. The focus is on listeners with presbyacusis and on their ability to localize sounds in the median sagittal plane (MSP).

The predominant cues to a source's location in the MSP are spectral shape cues introduced when an incoming sound is directionally filtered by the pinnae, head, and torso (Blauert, 1983; Middlebrooks and Green, 1991). An early study by Blauert (1969/70) pointed up the importance of spectral cues for MSP localization. He presented ⅓-octave noise bands from loudspeakers directly in front of a subject, directly overhead, and directly behind and observed almost no correlation between the position of the loudspeaker and a subject's localization response. Instead, responses were dictated by the frequency of the sounding noise band. When the center frequency of the band was between 500 Hz and 2 kHz, subjects predominantly responded "back;" when the frequency was between 2 kHz and 6 kHz, they responded "front;" and when it was between 6 kHz and 10 kHz, they responded "overhead."

*Department of Audiology and Speech Sciences, Michigan State University, East Lansing, Michigan; †Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan

Reprint requests: Brad Rakerd, Department of Audiology and Speech Sciences, 378 Communication Arts Building, Michigan State University, East Lansing, MI 48824-1212

Blauert also delivered broadband noises from the loudspeakers and made acoustic measurements of the spectra received in the subjects' ear canals. He found that the spectra had "boosted bands," or regions of spectral emphasis that were dependent on speaker location and that matched the regions that produced perceptions of front, overhead, and back locations.

Butler and his associates (Roffler and Butler, 1968; Butler and Belendiuk, 1977; Musicant and Butler, 1984) made a detailed study of listeners' perception of the elevation of a sound that originates in the MSP. They found that the frequencies most critical for accurate elevation perception are high, up above 4 kHz. The pinnae are chiefly responsible for the creation of these high-frequency cues (Shaw and Teranishi, 1968; Asano et al, 1990). When the pinnae are bypassed or distorted, listeners make large elevation errors (Gardner and Gardner, 1973; Blauert, 1983).

In the present study, we examined the MSP localization performance of listeners who had substantial levels of hearing loss due to presbyacusis. Our first purpose was to develop a better picture of the spatial hearing abilities—and limitations—of this large and growing patient group. Our second purpose was to determine to what extent their localization performance could be explained in terms of prevailing theories of MSP sound localization. Finally, we examined the relation between MSP localization and an individual's hearing thresholds. Given that MSP cues are predominantly spectral, it might be expected that whether an individual will have substantial difficulty with localization can be reasonably predicted on the basis of an audiogram. That possibility was tested here, with particular attention to a listener's sensitivity in the high frequencies, where pinnae cues are found.

EXPERIMENT 1

A group of elderly adults with presbyacusic hearing losses representative of those commonly seen in our university hearing clinic and a comparison group of young adults with normal hearing were tested in this experiment. Both groups were given a sagittal plane localization test using the geometry employed by Blauert (1969/70; loudspeakers front, overhead, and back) and an elevation localization test similar to that of Butler (loudspeakers in front of the listener and arrayed vertically). The stimulus presented was a broadband noise, which is optimal for MSP localization (Blauert, 1983; Kuhn, 1990). This noise was presented at several different sound levels, covering a range of commonly occurring intensities.

In addition to localizing sounds in the MSP, subjects performed two tasks that provided a context for interpretation of the MSP results. The first was a localization task that did not depend upon spectral cues. Specifically, the subjects were asked to localize sounds in the frontal plane (left-overhead-right locations). Binaural localization cues predominate in this geometry. Butler (1970) tested subjects with varying degrees of hearing loss and found that as long as the loss was bilateral, they were able to make reasonably accurate binaural localization judgments. A binaural localization test was included in the present experiment for two reasons: first, because this provided an opportunity to look at the relative strengths of subjects' binaural and spectral localization abilities; second, because Butler's findings, and some pilot test results of our own, made it seem likely that most of our elderly subjects would be able to localize sounds in the frontal plane reasonably well. (All of them had bilaterally symmetric hearing losses.) The frontal plane geometry could therefore provide an unambiguous context for familiarizing subjects with the testing protocols to be used here and for setting stimulus levels and the like.

The subjects' final task was to take a free-field hearing test. Hearing thresholds were determined for ⅓-octave noise bands covering the full spectral range of the broadband noise that was presented in the localization tests.

METHOD

Participants

Listeners with Normal Hearing

Eight young adults (mean age = 23.5 years) with normal hearing (all pure-tone thresholds at or below 20 dB HL at octave frequencies from 125 Hz to 8 kHz) were tested in this experiment as a control group. All of these subjects were undergraduate or graduate students at Michigan State University. They were paid for their participation. With one exception (author T. Vander Velde), the normal-hearing subjects had no knowledge of the hypotheses under test.

Listeners with Presbyacusis

The experiment focused on 25 older adult subjects (mean age = 72.6 years; range = 66–88 years) with presbyacusic hearing loss and with no other known audiologic pathology. Most of these subjects were present or former patients of Michigan State University's Oyer Speech-Language-Hearing Clinic and were recruited through that association. The remainder were acquaintances of the investigators. No subject in this group was aware of the hypotheses under test. Constraints on the selection of these subjects were that an individual had to be in good general health and had to have a hearing loss that was bilaterally symmetric (left and right ear thresholds within 15 dB at all pure-tone test frequencies from 125 Hz to 4 kHz and within 20 dB at 8 kHz).

All of the subjects in the presbyacusic group had sloping hearing losses. Their three-frequency (500 Hz, 1000 Hz, 2000 Hz) pure-tone threshold averages ranged from 5 dB HL to 47 dB HL, with a mean of 32 dB HL. Thirteen of these subjects wore binaural hearing aids, six wore monaural aids, and six wore no hearing aid. Given the importance of high-frequency cues for spectral localization (Roffler and Butler, 1968; Asano et al, 1990), the elderly subjects were rank ordered according to their average threshold at the three highest frequencies that we could reliably test in the experiment (3150 Hz, 5000 Hz, 8000 Hz; see below). Table 1 shows the ranking, along with a subject's age, gender, and hearing aid type (if any). The alphabetic subject codes listed in Table 1 are used to refer to these subjects throughout this paper.

Table 1 Background Information Regarding the Presbyacusic Subjects*

Subject	*H3FA (dB SPL)*	*Age (yr)*	*Gender*	*HA Type*
A	26.3	67	F	Monaural
B	30.4	80	F	None
C	33.2	67	M	None
D	42.8	69	M	None
E	46.5	82	M	None
F	46.8	82	M	Binaural
G	52.1	67	M	Monaural
H	54.7	77	M	Binaural
I	56.1	66	M	None
J	57.9	73	F	Binaural
K	59.5	77	M	Binaural
L	59.4	72	F	Binaural
M	60.0	69	F	Monaural
N	60.9	66	M	Monaural
O	62.2	66	M	Monaural
P	62.7	67	M	Binaural
Q	63.0	81	F	Binaural
R	65.6	85	F	Binaural
S	66.6	77	F	Binaural
T	68.1	68	M	Binaural
U	69.2	88	F	Binaural
V	69.7	66	F	Monaural
W	73.9	66	M	None
X	74.9	68	F	Binaural
Y	81.5	70	F	Binaural

*The subjects are rank ordered according to statistic H3FA, which is an average threshold (in dB SPL) for three high-frequency noise bands (3150 Hz, 5000 Hz, 8000 Hz).

Localization Tests

Each subject was given a battery of three localization tests. Hearing aids were not worn during these tests. These tests were conducted in a 3 m wide × 4.3 m long × 2.4 m high anechoic room (IAC #107480). The stimulus was a white noise, pulsed on for a duration of 1 second with a 60-msec linear rise–fall time. The spectrum of this noise was flat (± 2 dB) from 175 Hz to 14,000 Hz. This frequency range spanned 18 ISO ⅓-octave bands, the lowest centered on 200 Hz, the highest on 12,500 Hz.

The stimulus was presented at different levels in different test runs. In low-level runs, the average level was 48 dB SPL; in mid-level runs, it was 66 dB SPL; and in high-level runs, it was 84 dB SPL. Within each run, intensity varied ± 6 dB around the average level. In the low-intensity runs, for example, stimulus presentations of 42 dB SPL, 48 dB SPL, and 54 dB SPL were randomly interspersed.

Frontal Plane

All subjects went through the localization test battery in the same order. The first test was a frontal plane (FRN) test. In this test, the noise stimulus was presented to a subject from any one of three loudspeaker sources, arrayed as shown in Figure 1(A). The loudspeakers were 1.2 m away and placed directly left, directly above, and directly right of the subject's head. The subject sat facing straight ahead throughout the test, with head held still. The back of the subject's chair was fitted with an L-shaped rod that could be adjusted to touch the crown of the subject's head. This contact provided a physical reminder not to move the head during a trial.

On each trial, the stimulus was presented from one of the three sources, selected at random. A light then came on in front of the subject, calling for a response. The subject's task was to decide which of the three loudspeakers had sounded and to report the choice by pressing a button on a response box. Stimulus presentation level varied randomly (±6 dB) from trial to

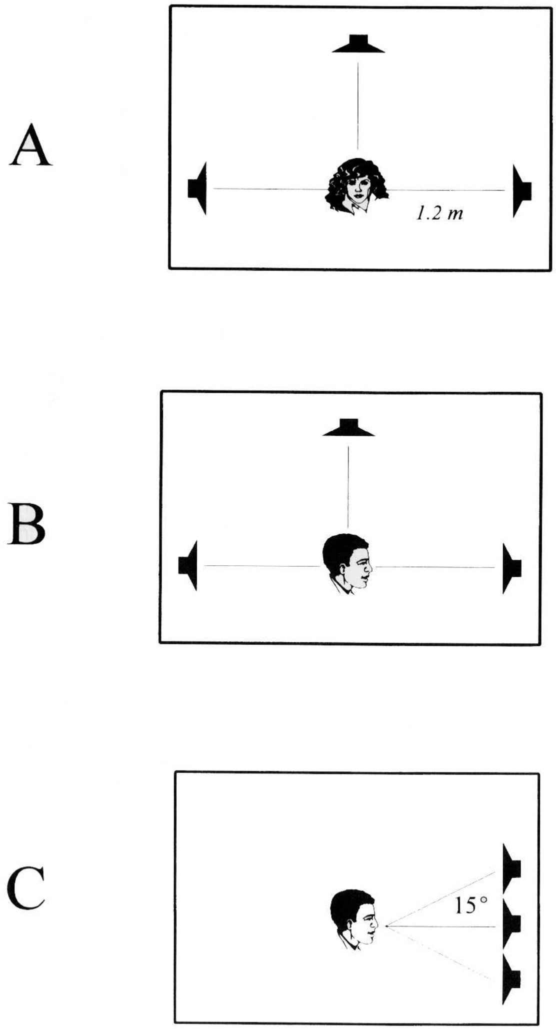

Figure 1 Source layouts employed in the frontal plane (A), sagittal plane (B), and elevation (C) tests of Experiment 1.

trial. A complete FRN run comprised 63 trials, 21 randomized presentations from each of the three loudspeakers. The run was self-paced. A new trial began only after a subject reported the response for the previous trial. Runs were typically completed in about 3 minutes.

If the stimulus presented on a particular trial was completely inaudible, the subject reported "did not hear" to the controlling computer and the program advanced to the next trial. No normal-hearing subject ever gave a "did not hear" response. Seven presbyacusic subjects reported that they could not hear the noise all or most of the time on the low-level FRN run (42–54 dB SPL). Low-level runs were excluded from the remainder of the tests in their battery.

Sagittal Plane

The second localization test was a sagittal plane (SAG) test. Methods for the SAG test were identical to those for the FRN. The only difference was the source layout. The SAG layout is shown in Figure 1(B). One loudspeaker was positioned directly in front of the subject, the others were directly above and behind. All were 1.2 m away.

Elevation

The third localization test was a three-source elevation (ELV3) test. Again, the special feature of the test was its source layout. As shown in Figure 1(C), one loudspeaker was situated directly in front of the subject and 1.2 m away at ear height. A second loudspeaker was 15 degrees up from this point, and a third was 15 degrees down.

Hearing Test

After the localization tests were completed, subjects were given an in situ hearing test. Free-field hearing thresholds were obtained for a series of ⅓-octave noise bands covering the spectral range of the test stimulus. For these measurements, as for the localization test, the subject sat with head still, facing straight ahead. Test signals were presented from the front loudspeaker. A tracking procedure was used to determine thresholds, first for the 200-Hz band and then for bands of increasing frequency up through 12,500 Hz. In all, thresholds were obtained for 10 bands: 200 Hz, 315 Hz, 500 Hz, 800 Hz, 1250 Hz, 2000 Hz, 3150 Hz, 5000 Hz, 8000 Hz, and 12,500 Hz.

RESULTS AND DISCUSSION

Hearing Test

The results of the hearing test are shown in Figure 2. Plotted are the mean thresholds for each subject group, at each frequency. Error bars show ±1 standard deviation across subjects. Results for the normal-hearing listeners are given by the open symbols. At every test frequency, their thresholds were in good agreement with the minimum audible field curve (Sivian and White, 1933), which is shown in the figure as a dotted line. Thresholds of the presbyacusic listeners (filled symbols) were higher

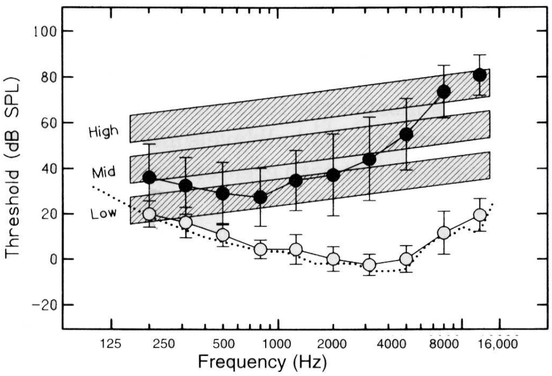

Figure 2 Group thresholds for detection of ⅓-octave noise bands, as measured in a free-field hearing test. Open circles: normal-hearing listeners. Filled circles: listeners with presbyacusis. Values reported are the mean ±1 standard deviation over subjects. Bars running across the figure indicate the spectral range of the broadband noise stimulus, as presented on low-, mid-, and high-level runs in the localization tests. The dotted line shows the minimum audible field curve from Sivian and White (1933).

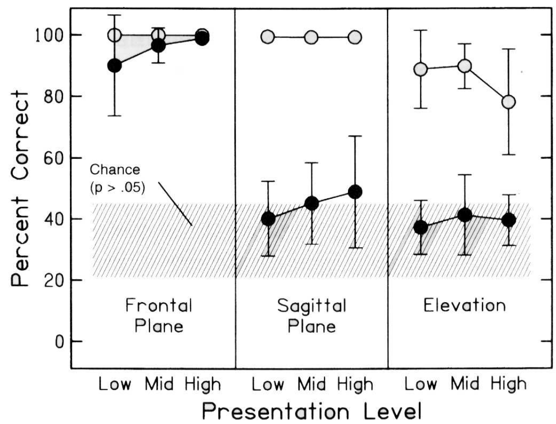

Figure 3 Mean percent-correct scores for the frontal plane, sagittal plane, and elevation localization tests. Results are plotted as a function of the presentation level of the noise stimulus. Error bars represent ±1 standard deviation over subjects. The hatched area running across the figure represents a 5% confidence interval around chance performance (33% correct). Open circles: normal-hearing listeners. Filled circles: listeners with presbyacusis.

than normal at all frequencies, and the difference progressively increased with frequency, as is commonly the case (Lebo and Reddell, 1972).

Presentation level was "capped" at 85 dB SPL in the hearing test. Fifteen presbyacusic subjects had thresholds for the 12,500-Hz noise band that could not be measured because they were higher than this level.[1] The 12,500-Hz value reported in the figure reflects the mean ±1 standard deviation for those (n = 10) subjects whose thresholds could be estimated.

The bars extending across Figure 2 show the spectral range of the noise stimulus, as presented on low-, mid-, and high-level localization test runs. It is clear that portions of the noise spectrum were inaudible or only barely audible to most presbyacusic subjects, particularly at the low and mid presentation levels. In contrast, the listeners with normal hearing had full spectrum audibility over the entire range of levels in the localization experiments.

Localization Tests—Listeners with Normal Hearing

The localization test results are shown in Figure 3. Results for the FRN, SAG, and ELV3 tests are given in the left, center, and right panels, respectively. Within each panel, scores are plotted as a function of the stimulus presentation level. The shaded area running across the figure shows a 5-percent confidence interval around chance performance for these tasks (33% correct). Only scores above that area can be said to statistically exceed chance ($p < .05$).[2]

Mean percent-correct scores for the normal-hearing group are plotted with open symbols. Error bars (large enough to be visible only for

[1]A six-turn staircase was used to determine the threshold in each noise band. As noted in the text, a threshold estimate could not be obtained for 15 elderly subjects for the 12,500-Hz band. For these subjects, the staircase failed to "turn" even once prior to reaching the 85 dB SPL "ceiling" level that was set for the hearing test. For six of these subjects, there was a related but less severe problem with the threshold estimate at 8000 Hz. The staircase made several "turns" below 85 dB (always at least 3) but not a complete set of six. In this instance, the threshold estimate was made on the basis of the reduced turn set.

[2]Chance performance is given by the binomial distribution, which, for large N, is approximately normally distributed with a mean of Np and a variance of √ Npq, where N is the number of trials in a run, p is the probability that a listener will respond correctly when guessing, and q is the probability that the listener will make an error (Guilford and Fruchter, 1973). The mean ±1.96 standard deviation units bracket a 5% confidence interval for responses due to chance. For the runs shown in Figure 3, N = 63, p = .33, and q = .67, and the 5% confidence interval is 13.7–28.3 correct trials per run (out of 63 possible), or 22%–45% correct.

the elevation test) show ±1 standard deviation over the subjects in this group. The normal-hearing subjects were perfect or near perfect in the frontal and sagittal planes at all presentation levels. They performed less well, although far above chance, at all levels on the elevation test.

The normal-hearing subjects were less accurate in judging source elevation on high-level runs (mean score = 78.2% correct) than they were on mid- (93.4%) and low-level (88.9%) runs. This pattern is reminiscent of a result previously reported for normal-hearing listeners localizing click stimuli in the sagittal plane. Hartmann and Rakerd (1993) presented clicks at intensities ranging from 68 to 94 dB SPL and found that listeners generally localized them more accurately at the lower levels. They speculated that this negative level effect arose due to the inability of the peripheral auditory system to resolve spectral details of the clicks, as filtered by the listener's anatomy, for front, overhead, and back sound incidence. This failure of the peripheral auditory system is likely due to saturation at high levels of stimulation.

Hartmann and Rakerd found no effect of level on localization of noise in a front-overhead-back test, equivalent to the SAG test of the present study, nor was an effect seen here in the sagittal plane. The negative level effect for noise showed up uniquely in the elevation test. Very likely, this is because the elevation task, with its 15-degree speaker separation, required finer spectral discrimination than the sagittal task, where neighboring sources were 90 degrees apart.

Localization Tests—Listeners with Presbyacusis

Filled symbols in Figure 3 show group means for the subjects with presbyacusis. Means for mid- and high-level runs reflect the performance of all 25 subjects. At the low level, several subjects were unable to hear the stimulus (see Method section). Low-level means are therefore based on scores from n = 18 subjects for the FRN test, and n = 17 for the SAG and ELV3 tests.[3]

On the FRN test, where the relevant localization cues were binaural, the presbyacusic listeners were able to make accurate localization judgments most of the time. Several of the subjects performed well at all levels and all subjects performed the test with greater than 90-percent accuracy at at least one test level. The mean percent correct scores for low-, mid-, and high-level runs were 90.1 percent, 96.7 percent, and 99.0 percent correct.

Subjects in the presbyacusic group were much less successful in localizing sound sources when they had to make their judgments on the basis of spectral cues. As a group, they performed the SAG test somewhat better than the pure guessing rate of 33 percent correct at all presentation levels (low: 40.2% correct, mid: 45.3% correct, high: 49.0% correct), but their performance statistically exceeded chance ($p < .05$) at the highest level only. On the ELV3 test, the presbyacusic subjects' mean percent-correct scores were 36.2 percent at the low level, 41.2 percent at the mid level, and 39.4 percent at the high level; none of these values was statistically above chance.

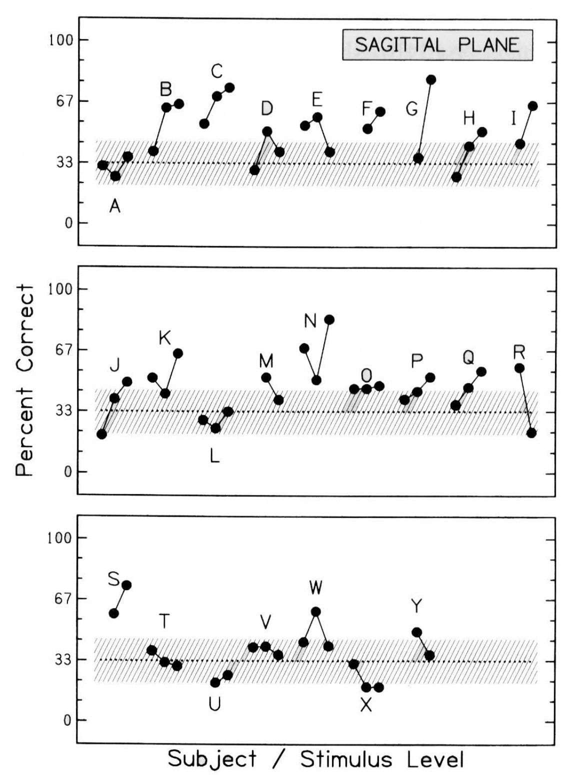

Figure 4 Individual sagittal plane results for the presbyacusic subjects. Percent-correct scores are plotted as a function of the stimulus level: low (42–54 dB SPL); mid (60–72 dB); high (78–90 dB). Alphabetic labels correspond to the subject codes given in Table 1.

[3]One elderly subject who reported that he could hear the low-level noise on the FRN test nevertheless said that he could not hear it most of the time on the SAG test. He was excused from SAG test. The same situation arose with another subject on the ELV3 test.

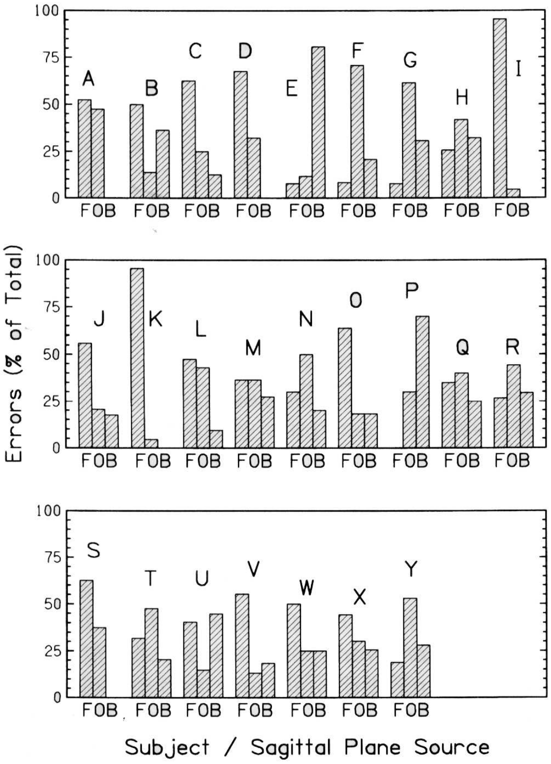

Figure 5 Distribution of a subject's total errors over the three source locations tested in the sagittal plane: F = front, O = overhead, B = back. Error scores come from the subject's "best" level (i.e., the level at which the subject localized most accurately). Alphabetic labels correspond to the subject codes given in Table 1.

Individual Differences—Sagittal Plane

Figure 4 shows how the presbyacusic subjects performed individually on the SAG test. Percent-correct scores are plotted for each subject as a function of signal level. It can be seen that a number of individuals outperformed the group average by a good margin, and that all but six subjects (A, L, T, U, V, X) performed above chance on at least one stimulus level. At the same time, it is clear that even when performing at the most advantageous level, no presbyacusic subject approached the near perfect sagittal plane performance of the normal-hearing subjects.

Figure 4 orders subjects according to their high-frequency hearing thresholds, as measured on the free-field hearing test (see statistic H3FA in Table 1). A scan of Figure 4 from left to right and top to bottom, then, provides information about the importance of high-frequency hearing thresholds for subjects' sagittal plane performance. There is some evidence that these thresholds mattered. When listening at their "best" level (i.e., the level at which they had the highest localization score), subjects in the top panel had an average percent-correct score of 60.4 percent, those in the middle panel had an average of 56.1 percent, and those in the bottom panel had an average of 47.3 percent. Four of the six subjects who failed to score above chance at any level were among the last group, with the poorest thresholds.

On the other hand, the figure also shows a number of instances in which neighboring subjects, with similar levels of high-frequency hearing loss, performed the SAG test in dissimilar ways (compare, for example, subjects A and B, and K and L). Results of this kind clearly point up the fact that while high-frequency hearing was important, other factors were at work here as well.

Figure 5 shows how each subject's errors were distributed over the front, overhead, and back locations when listening at the best level. Overhead source errors were the most frequently occurring error for eight of the subjects (F, G, H, N, Q, R, T, Y). This is an expected outcome because potent cues to overhead location are found up above 6 kHz (Blauert, 1969/70), where all of these listeners had relatively poor hearing. More surprising was the finding that a number of the subjects had their greatest difficulty with either the front (subjects A, B, C, D, I, J, K, L, O, S, V, W, X) or the back source (E, P, U). In most instances, these subjects completely lacked a sense of front or a sense of back, even when listening at the best level. A model of MSP localization that speaks to front and back localization difficulties is considered below.

Individual Differences—Elevation

Individual subject results for the ELV3 test are shown in Figure 6. Difficulties with elevation localization were quite general among the presbyacusic subjects. Fourteen of them (A, D, F, I, J, K, M, P, R, T, V, W, X, Y) failed to perform the task significantly better than chance at any level. Only three subjects (B, E, G) were able to perform above chance at more than one level. These were among the subjects with the best high-frequency hearing. But high-frequency hearing was comparable for subjects A, D, F, H, and I, who localized elevation poorly. Overall, these findings indicate that good high-frequency hearing is necessary but not sufficient for successful elevation localization.

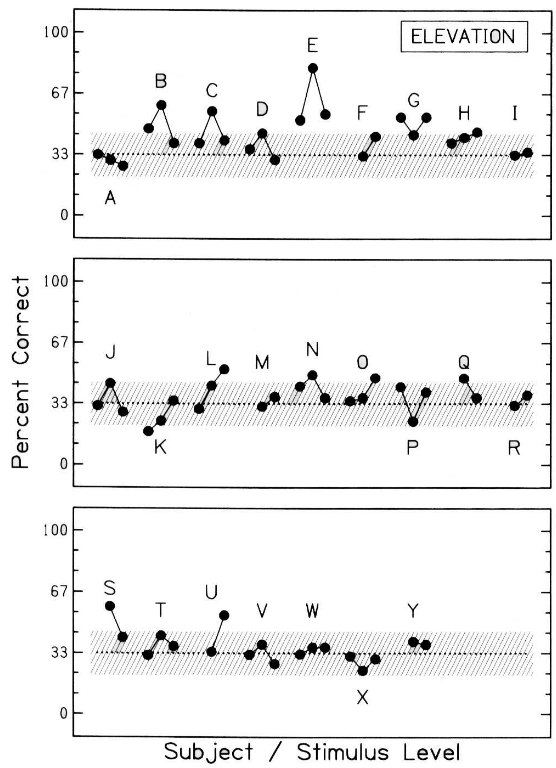

Figure 6 Same as Figure 4, except the results are for the elevation test.

Listeners in the Early Stages of Presbyacusis

All of the hearing-impaired subjects tested in Experiment 1 were elderly listeners, with substantial levels of presbyacusic hearing loss. As a group, and individually, they proved to be mediocre to poor at making localization judgments in the MSP. In a follow-up study, we asked whether middle-aged listeners, in the early stages of presbyacusis, would show any signs of decline in their MSP localization performance. Five subjects (two of them authors) with a mean age of 52.4 years participated. They were given the full battery of tests.

Hearing Test

On average, hearing thresholds for the middle-aged listeners were indistinguishable from those of the normal-hearing young adults for test frequencies below 2 kHz. At higher frequencies, the middle-aged listeners exhibited progressive hearing loss. One subject in the group had a high-frequency hearing loss (as measured by statistic H3FA) that was approximately 25 dB worse than that of any of the other subjects.

Table 2 Localization Test Results for Five Middle-aged Subjects in the Early Stages of Presbyacusis

	Frontal Plane			*Sagittal Plane*			*Elevation*		
Subject	*Low*	*Mid*	*High*	*Low*	*Mid*	*High*	*Low*	*Mid*	*High*
M1	100	100	100	89	98	98	76	89	67
M2	100	100	100	87	100	100	76	97	84
M3	100	100	100	95	100	100	89	86	95
M4	100	100	100	94	100	98	94	86	98
M5	84	100	100	42	57	79	25	56	56

Low, mid, and high refer to stimulus presentation levels, as indicated in the text.

Localization Tests

Table 2 shows how the middle-aged subjects performed on the battery of localization tests. All five were perfect at localizing in the frontal plane at the mid and high presentation levels. Four were perfect at the low level as well. The subject with the most substantial high-frequency hearing loss (subject M5) made some errors at the low level.

On the SAG test, subjects M1, M2, M3, and M4 were essentially perfect at the mid and high levels, which matched the performance of the normal-hearing listeners. At the low presentation level, subjects M1–M4 made some errors (mean score = 91% correct), in contrast to the normal-hearing subjects, who did not make errors at the low level. Subject M5 made a number of sagittal plane errors at all levels, but particularly at the low level.

The ELV3 test scores show the same pattern as the SAG scores, that is, near normal-hearing accuracy at mid and high levels and below normal-hearing accuracy at the low level for subjects M1–M4. Subject M5 had an especially difficult time with the elevation task, never scoring above 56 percent correct.

Overall, these results indicate that listeners in the early stages of presbyacusis can be expected to have limited difficulties with MSP localization, especially in instances where they must attend to relatively faint sounds.

EXPERIMENT 2

The results of Experiment 1 paint a rather discouraging picture of MSP sound localization prospects for persons with substantial presbyacusic hearing loss. Experiment 2 was conducted to see whether these listeners' performance could be improved significantly by any of several manipulations. Also tested, for comparison, were a group of listeners with normal hearing and a group with modest presbyacusic hearing loss.

The first manipulation was designed to minimize any listening difficulties that may have been due to masking. The broadband noise was high-pass filtered to eliminate its low-frequency components while maintaining spectral density. The low frequencies convey relatively little localization information. They were removed to ensure that they could not mask more informative high-frequency components. This topic is discussed in greater detail in the Method section below.

The second manipulation was motivated by the fact that the three-speaker elevation task of Experiment 1 proved rather difficult. Even the normal-hearing listeners performed the ELV3 test substantially less well (86.8% correct overall) than they did the FRN (100%) and SAG tests (99.6%). To ease the difficulty of the task in this experiment, we designed a two-source elevation test (ELV2).

The final manipulation designed to improve performance in this experiment was to allow subjects to wear their hearing aids during testing. Both monaural and binaural amplification wearers participated.

METHOD

Participants

The subjects of Experiment 2 were five young adults (mean age = 23.6 years) with normal hearing, five middle-aged adults (mean age = 52.4 years) with limited presbyacusic hearing loss, and 15 elderly adults (mean age = 71.6 years) with substantial presbyacusic hearing loss. All of these subjects also participated in Experiment 1.

High-Pass Filtered Noise—Sagittal Plane

Important cues for "front" and for "back" location are found in the mid frequencies; important cues for "overhead" are found at higher frequencies (Blauert, 1969/70, 1983).

A 1-kHz high-pass filtered noise was created as the stimulus for a SAG test because it preserved most of these important cues and, at the same time, afforded potential relief from upward masking by low-frequency noise components. The high-pass noise was produced by passing the broadband noise (Experiment 1) through a "brickwall" high-pass filter (filter roll-off rate = 96 dB/octave). Because a number of presbyacusic listeners had difficulty with the low presentation level in Experiment 1, we ran the SAG test—and other localization tests with multiple-level ranges—at mid and high levels only in Experiment 2.

High-Pass Filtered Noise—Elevation

A 5-kHz high-pass noise was created for use in elevation tests, based on the finding that the most critical elevation cues are high-frequency cues introduced by the pinnae (Roffler and Butler, 1968; Blauert, 1983).

Two-Source Elevation Test

The battery of localization tests for this experiment included a new test, ELV2. Its source layout was identical to that for ELV3 except that the middle speaker was removed, leaving the top and bottom sources separated by 30 degrees. Because the ELV2 array had only two-thirds as many speakers as the ELV3 array, ELV2 test runs had only two-thirds as many trials (42 trials). The ELV2 test was run with the broadband noise stimulus so that it could be directly compared with the ELV3 test of Experiment 1.

Hearing-Aided Listening

After they completed their unaided listening tests, 10 presbyacusic subjects—seven of whom wore binaural hearing aids and three of whom wore monaural aids—were given a special battery of hearing-aided test runs. These runs included SAG and ELV3 with the broadband noise stimulus and a run of the in situ hearing test.

For these localization tests, the noise stimulus was always presented at the mid level of 60 to 72 dB SPL. Prior to the start of localization testing, a subject adjusted hearing aid volume control(s) to obtain a "most comfortable listening level" for this intensity range. The volume setting was maintained constant thereafter.

RESULTS AND DISCUSSION

High-Pass Filtered Noise—Sagittal Plane

Figure 7 shows the results from the SAG test with a 1-kHz high-pass noise. Mid-level results

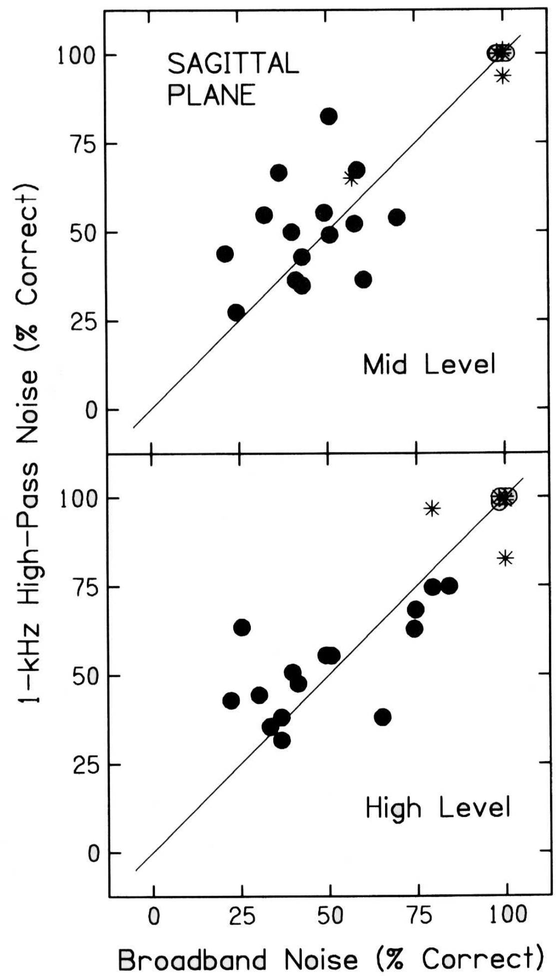

Figure 7 Scatter plots comparing individual subject performance on the sagittal plane test when localizing broadband noise (Experiment 1) and 1-kHz high-pass noise (Experiment 2). The upper panel gives results for the mid presentation level (60–72 dB SPL); the lower panel gives results for the high presentation level (78–90 dB). Open circles: young adults with normal hearing. Asterisks: middle-aged adults with modest presbyacusis. Filled circles: elderly adults with substantial presbyacusis.

are shown in the top panel of the figure, high-level results in the bottom panel. Within each panel, a subject's percent-correct score with high-pass noise is plotted against the score that the subject obtained with broadband noise (SAG test of Experiment 1). To the extent that high-pass filtering helped performance, the symbols lie above the 45-degree line.

Individual results for the normal-hearing, young-adult subjects are plotted with open circles. All of these subjects localized high-pass noise in the sagittal plane at or near perfection at both presentation levels, which matched their performance with broadband noise in Experiment 1.

High-pass filtering the noise had no appreciable effect on the middle-aged subjects with modest presbyacusis (results plotted with asterisks). In general, they were good at localizing 1-kHz high-pass noise in the sagittal plane at both levels, just as they were good at localizing broadband noise in Experiment 1. The one subject (M5) who had difficulty with the broadband noise when it was presented at the mid level in Experiment 1 (56% correct) also had difficulty with the high-pass noise (65% correct).

Individual results for the elderly subjects with substantial presbyacusis are plotted with filled circles in Figure 7. Those symbols "straddle" the 45-degree line in both panels, indicating that high-pass filtering the noise neither helped nor hurt these listeners to any substantial degree.

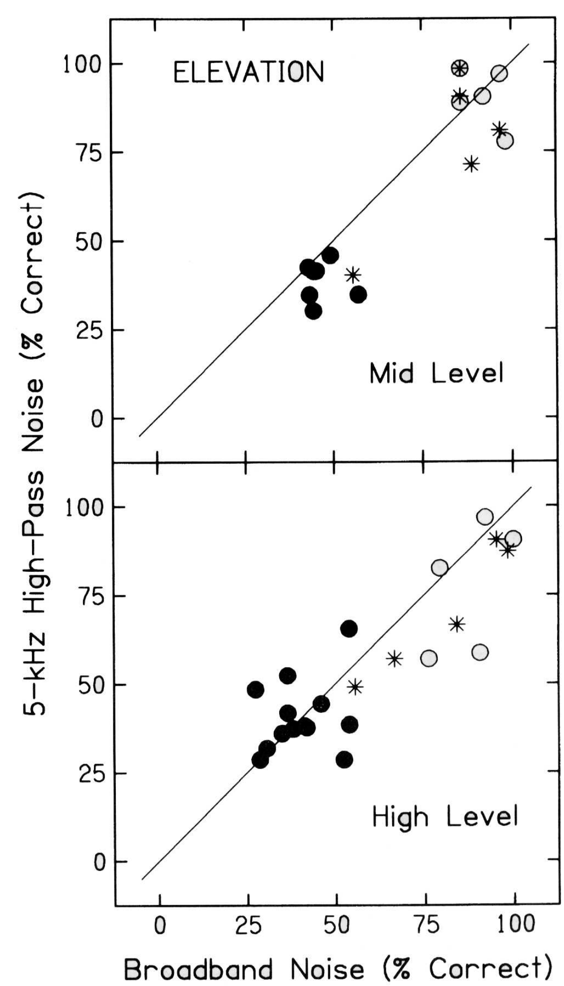

Figure 8 Same as Figure 7, except that the test was three-source elevation, and the high-pass cut-off of the noise was at 5 kHz.

High-Pass Filtered Noise—Elevation

Figure 8 shows how high-pass filtering noise at 5 kHz affected performance on the ELV3 test. It had little or no systematic effect on the young or the middle-aged adults at the mid level. It hurt all of the middle-aged subjects and several young-adult subjects at the high presentation level. (Their symbols fall below the 45-degree line, although not much below.) High-pass filtering also hurt the elderly subjects, but their deficit showed up when listening at the mid level. All of the elderly listeners who could hear the high-pass noise at the mid level localized it less well than they did broadband noise.[4] Overall, it is clear that high-pass filtering afforded no benefit to listeners in this experiment and sometimes proved harmful.

Simplified Elevation Test (ELV2)

Figure 9 shows the effect of reducing the level of difficulty of the elevation task. A subject's score on the ELV2 test is plotted against the score on the ELV3 test. This figure has a different appearance from the two previous figures because the chance performance rate for ELV2 was 50 percent, not 33 percent, as for all of the other tests. For reference, lines have been drawn through the figure at the pure-chance performance points for three-source and two-source elevation.

Results for the young-adult listeners and for the middle-aged listeners clearly show that ELV2 was an easier task than ELV3, as intended. All of the subjects in the young-adult group, and all but one in the middle-aged group (M5), scored above 95 percent correct at the mid and high levels on the ELV2 test. Despite this eased difficulty level, elderly listeners had substantial problems making accurate elevation judgments on the ELV2 test. At the mid presentation level, plotting symbols for the elderly subjects cluster no further above chance on ELV2 than they do on ELV3. At the high level, a few subjects did show some improvement with ELV2, but the group as a whole improved little. Overall, the results of the ELV2 test reinforce our earlier conclusion that elderly listeners with substantial presbyacusis can be expected to have considerable difficulty when they must judge the elevation of a sound source.

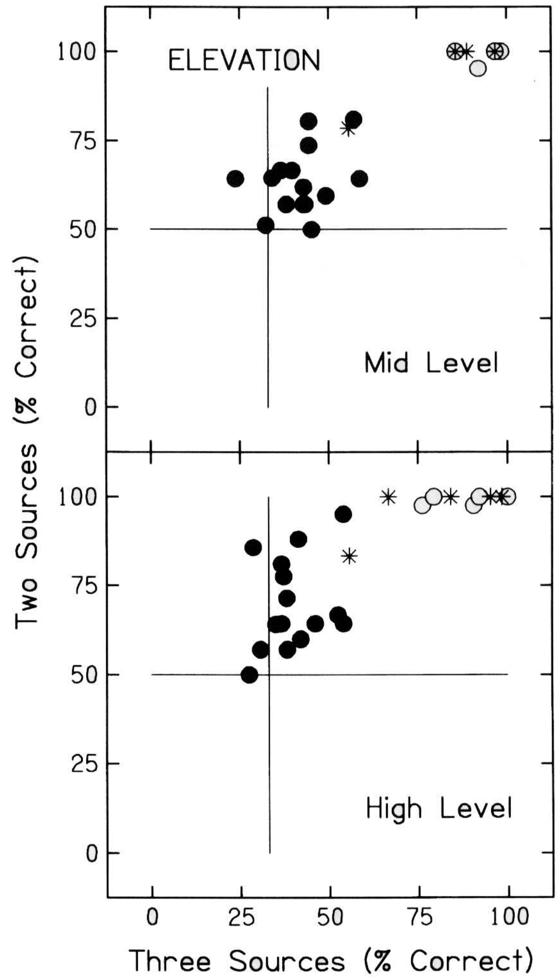

Figure 9 Scatter plot comparing individual subject performance when making judgments about the elevation of a broadband noise. The x-axis shows the case where there were three sources covering a total span of 30 degrees; the y-axis shows the case of two sources covering the same span. The vertical and horizontal lines in the figure indicate chance performance levels on the three-source (33% correct) and two-source (50% correct) tests. Plotting symbols are as in Figure 7.

Hearing-Aided Testing—Functional Gain

To obtain a measure of the functional gain produced by a listener's hearing aid(s), we compared ⅓-octave band thresholds for hearing test runs done with and without aids. All but two of the subjects received 10 dB or more of gain at

[4]The 5-kHz high-pass noise proved to be inaudible for eight of the elderly subjects when presented at the mid level. These eight included the seven subjects with the poorest H3FA thresholds, as measured in Experiment 1, and one with a slightly better H3FA score. The high-pass noise was inaudible at the high presentation level for one subject only, the subject with the poorest H3FA score. One other subject was excused from the high-level test for incidental reasons. The final elderly subjects' counts for Figure 8, then, were n = 7 at the mid level and n = 13 at the high level.

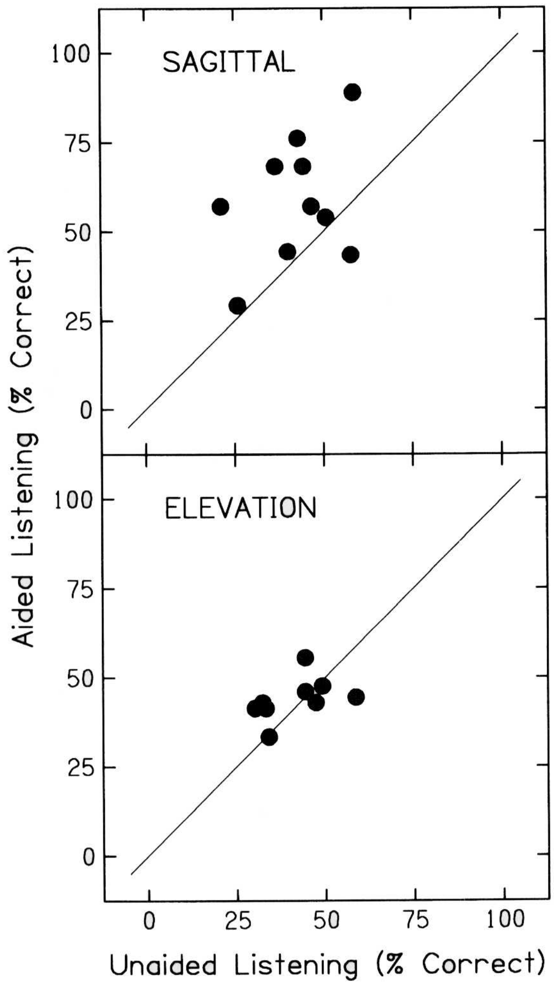

Figure 10 Scatter plots comparing individual performance when localizing broadband noise without wearing a hearing aid and while wearing an aid (or aids). Results in the upper panel are for the sagittal plane localization test; those in the bottom panel are for the three-source elevation test.

1250 Hz, 2000 Hz, 3150 Hz, and 5000 Hz. The mean gain for these four bands for all subjects was 14 dB.

Hearing-Aided Testing—Localization

The noise stimulus was presented at the mid level on all hearing-aided localization tests. The localization benefit afforded by a hearing aid was therefore assessed by comparing a subject's aided listening score with the score obtained when listening to noise at the mid level unaided. The top and bottom panels of Figure 10 show this comparison for the SAG and ELV3 tests.

Listening with a hearing aid clearly improved localization scores on the SAG test (upper panel). Plotting symbols for all but one of the subjects lie above the 45-degree line, some by a good margin. Four subjects, including one who used a monaural aid and three who used binaural aids, showed improvements of 30 percent or more in the aided condition. On average, the subjects improved their sagittal plane accuracy by 16 percent when listening with a hearing aid. This change was statistically significant ($t[9] = 3.01$; $p < .05$). Much of the overall improvement for the sagittal plane was accounted for by a large increase in accuracy for the front source (59% correct aided vs 22% unaided).

Listening with a hearing aid had no appreciable effect on elevation localization scores (bottom panel). This result is, perhaps, not surprising, given that the most important elevation cues are at frequencies above the response range of most commercial hearing aids.

MODEL

Taken together, Experiments 1 and 2 point up a significant deficit for listeners with presbyacusic hearing loss when they must localize sounds on the basis of spectrum. We note a correspondence between the results of the experiments—particularly the results of the SAG test—and a recent model of MSP sound localization put forth by Asano et al (1990). They conducted a number of experiments with digitally modified spectra. Based on the results of those experiments, and on prior studies with band-limited stimuli, Asano et al proposed that judgments about source elevation, and judgments about front-back position, represent separate components of MSP localization. According to the model, cues to elevation reside almost exclusively in the high frequencies, above 5 kHz. When those cues are omitted from the stimulus—or, it appears, when the listener cannot detect available cues due to high-frequency hearing loss—judgments about elevation deteriorate dramatically.

The front-back situation is more complicated. A first condition for accurate front-back localization is that a listener must have access to fine spectral details below 2 kHz. The presbyacusic subjects of the present study generally had access to those details, based on their audiograms. But for satisfactory front-back localization, there must also be some supporting information from what Asano et al call "macroscopic spectral features" that are present at much higher frequencies. When they deleted those features from their spectra, normal-hearing listeners made numerous front-back errors.

Our presbyacusic listeners were clearly compromised in their ability to detect any high-frequency features present in their inputs. This would seem to explain why they had such difficulty with front and/or back source locations in the sagittal plane.

An as yet unresolved exception to the model is elderly subjects' performance with the overhead source in the present study. Overhead represents the most extreme case of elevation. The model stresses the high-frequency nature of elevation cues and, that being the case, elderly listeners should have particular difficulty localizing the overhead source. But, in fact, they did not. On the average, the overhead source was perceived more accurately than the front source and nearly as accurately as the back source. One explanation for this may be that listeners were able to identify overhead by default in a three-alternative SAG test after ruling out the other two possibilities. Alternatively, it may be that some spectral cues to the overhead location are present at lower frequencies, where elderly listeners retain substantial sensitivity. Interviews with subjects tend to favor the latter explanation.

SUMMARY AND CONCLUSIONS

In two experiments, we found that listeners with clinically relevant levels of presbyacusis, while generally able to make use of binaural sound localization cues, were greatly compromised in their ability to make spectrally cued localization decisions. They rarely performed much above chance when asked to judge the elevation of a sound source, regardless of the presentation level of the stimulus. This was found to be the case in a relatively difficult ELV3 test employing broadband noise as the stimulus, and in subsequent tests where the difficulty level of the test was eased in two ways: first, by high-pass filtering the noise stimulus to minimize masking and second, by using fewer loudspeaker sources spaced further apart. The poor performance of these listeners on elevation localization tasks was attributed, at least in part, to the fact that they have substantial high-frequency hearing loss that makes it difficult or impossible for them to detect informative high-frequency cues.

These listeners performed somewhat better in a SAG test that required that they localize sounds coming from in front, overhead, and behind. Nevertheless, no subject in the presbyacusic group ever performed the task as well as young adult listeners with normal hearing, either when listening to broadband noise or to high-pass filtered noise that minimized masking. In this paradigm, it was observed that a number of presbyacusic listeners lacked either a clear sense of front location or a clear sense of rear location. A group of listeners who took the sagittal plane test while wearing their hearing aids improved overall, particularly regarding their ability to localize sounds coming from in front.

Tests on a group of middle-aged listeners in the early stages of presbyacusis showed localization performance that was intermediate between that of the young adults with normal hearing and elderly adults with more advanced presbyacusis, although, overall, far more like that of the young adults. The middle-aged subjects diverged most from the normal-hearing subjects when they had to make judgments about sounds that were presented at relatively faint levels.

Overall, the findings of this study point up the fact that in everyday listening situations, elderly persons with commonly occurring levels of presbyacusic hearing loss are likely to experience difficulties when they localize sound sources in the median sagittal plane. It is not, as yet, possible to fully explain the origin of their difficulties. A relationship to diminished hearing sensitivity, particularly diminished high-frequency sensitivity, was pointed up in the present study. But there was also evidence that other factors were at work as well. These latter may include central auditory processing and/or other, nonsensory changes due to aging (Maurer and Rupp, 1979; Willott, 1991). A definitive answer to the question of causal factors will require further study. For now, we would highlight the high likelihood of this hearing difficulty for listeners with presbyacusis and the fact that it is, in some respects, ameliorated through the use of hearing aids.

Acknowledgment. This study was supported by NIH (NIDCD) grant #DC00181. The experiments formed the basis of a master's thesis by the second author. We thank the staff of the Oyer Speech-Language-Hearing Clinic for their help in recruiting subjects for this study. We thank the reviewers for their helpful comments on a previous version of this paper.

REFERENCES

Asano F, Suzuki Y, Sone T. (1990). Role of spectral cues in median plane localization. *J Acoust Soc Am* 88:159–168.

Blauert J. (1969/70). Sound localization in the median plane. *Acustica* 22:205–213.

Blauert J. (1983). *Spatial Hearing: The Psychophysics of Human Sound Localization*. Cambridge, MA: MIT Press.

Butler RA. (1970). The effect of hearing impairment on locating sound in the vertical plane. *Intl Audiol* 9:117–126.

Butler RA, Belendiuk K. (1977). Spectral cues utilized in the localization of sound in the median sagital plane. *J Acoust Soc Am* 61:1264–1269.

Gardner MB, Gardner RS. (1973). Problem of sound localization in the median plane: effect of pinnae cavity occlusion. *J Acoust Soc Am* 53:400–408.

Guilford JP, Fruchter B. (1973). *Fundamental Statistics in Psychology and Education*. New York: McGraw-Hill.

Hartmann WM, Rakerd B. (1993). Auditory spectral discrimination and localization of clicks in the sagittal plane. *J Acoust Soc Am* 94:2083–2092.

Kuhn GF. (1990). Physical acoustics and measurements pertaining to directional hearing. In: Yost WA, Gourevitch G, eds. *Directional Hearing*. New York: Springer, 3–25.

Lebo CP, Reddell RC. (1972). The presbycusis component in occupational hearing tests. *Laryngoscope* 82:1399–1409.

Maurer JF, Rupp RR. (1979). *Hearing and Aging*. New York: Grune & Stratton.

Middlebrooks JC, Green DM. (1991). Sound localization by human listeners. *Ann Rev Psychol* 42:135–159.

Musicant AD, Butler RA. (1984). The influence of pinnae-based spectral cues on sound localization. *J Acoust Soc Am* 75:1195–1200.

Roffler SK, Butler RA. (1968). Factors that influence the localization of sound in the vertical plane. *J Acoust Soc Am* 43:1255–1259.

Sivian LD, White SD. (1933). On minimum audible fields. *J Acoust Soc Am* 4:288–321.

Shaw EAG, Teranishi R. (1968). Sound pressure generated in an external-ear replica and real human ears by a nearby point source. *J Acoust Soc Am* 44:240–249.

Willott JF. (1991). *Aging and the Auditory System*. San Diego: Singular Publishing.