This is to certify that the

thesis entitled

EFFECTS OF AGING ON SOUND LOCALIZATION IN THE MEDIAN SAGITTAL PLANE

presented by

Timothy J. Vander Velde

has been accepted towards fulfillment of the requirements for

M.A. degree in ASC

Brad Rakerd

Major professor

Date December 18, 1996

EFFECTS OF AGING ON SOUND LOCALIZATION IN THE MEDIAN SAGITTAL PLANE

By

Timothy J. Vander Velde

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF ARTS

Department of Audiology and Speech Sciences

1996

ABSTRACT

EFFECTS OF AGING ON SOUND LOCALIZATION IN THE MEDIAN SAGITTAL PLANE

By

Timothy J. Vander Velde

Experiments were performed to examine the effects of aging on the ability to localize sounds in the median sagittal plane (MSP). Sources in the MSP are localized on the basis of spectral cues. In Experiment 1, 13 elderly subjects (mean age = 69.5) and 5 normally-hearing young- adult (mean age = 23) control subjects performed two MSP localization tests. 1) In a sagittal plane test they made judgments about whether sounds came from in front, overhead, or from the rear; 2) in an elevational test they made judgments about the elevation of sounds coming exclusively from in the front (and in full view). The elderly subjects performed the sagittal test significantly less well than did the young normally-hearing controls; they performed the elevational test significantly less well than controls and near chance. In Experiment 2, additional tests were run with the following variations designed to encourage improved performance by elderly listeners. 1) High-pass filtering of stimuli to preclude masking of more informative higher frequencies by lower ones. 2) Greater spatial separation of loudspeaker sources. 3) Use of hearing aids. None of these variations produced statistically significant improvement for the group overall. These results point up significant localization problems for listeners with age-related hearing loss when they must localize sounds on the basis of signal spectrum.

This work is dedicated to my grandparents, Edward and Priscilla Vander Velde; without their love and support this project, and other significant achievements of my graduate career, would not have been possible.

ACKNOWLEDGMENTS

I would like to express my profound appreciation to Dr. Brad S. Rakerd, for his support, encouragement, and guidance. This support has been evident not only during the period of my master's thesis, but throughout my entire graduate career. His informal personal manner and interactive style of teaching set a unique stage for learning. Additionally, I thank him for his unrelenting patience -interspersed by the timely motivational whip- and flexibility, which allowed me the freedom to explore.

I would also like to thank the other members of my thesis committee, Dr. William M. Hartmann and Dr. Jerry L. Punch, for their direction and comments.

Finally, I'd like to thank my family and friends for their continued support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

One of the most important properties of hearing is that it provides spatial information about objects in the world around us. We can tell not only what the things are that are making the sounds that we hear, but also *where* those thing are. Older adults often report some declines in their ability to localize sounds. This thesis examines aging's effects on the ability to localize sounds that originate in the median sagittal plane (MSP).

A special feature of the MSP is that all of its points are equidistant from the two ears, which means that a listener cannot discriminate among them on the basis of binaural cues. There is, for example, no binaural basis for telling the difference between a sound coming from directly in front and one coming from directly behind. Front-back decisions must be made on the basis of a signal's spectrum, as received in the ear canal. The transfer functions for front and rear sound incidence are distinct. Listeners learn the difference, and so long as an incoming signal's spectrum is sufficiently rich to allow them to recover the transfer function, they can reliably distinguish between front and back. It can be said, generally, that sound localization proceeds in the MSP by means of a search for spectral details that are uniquely associated with each angle of MSP sound incidence. These details are introduced when incoming sounds are directionally filtered by the listener's anatomy, particularly the pinna, head, and torso (Blauert, 1983; Wightman and Kistler, 1989; Shaw, 1971; Batteau, 1967; Kuhn, 1979). A number of aspects of MSP location are now fairly well understood. Notable among these are the following.

SAGITTAL PLANE (FRONT, OVERHEAD, REAR)

In a classic experiment, Blauert(1969/70; 1974) presented third-octave noise bands from each of three loudspeakers positioned directly in front, overhead, and behind a subject. The presentation level of the stimuli was varied over a 40 dB range. The noise bands were presented in a random fashion in terms of their frequency and intensity, and in terms of the location of the source of presentation. Blauert found that subjects' responses did not correspond to the source location of the speaker that sounded on each trial, nor to stimulus intensity. Instead, responses were dictated by the center frequency of the noise bands. When the frequency was between 500 Hz and 2 kHz, subjects predominantly responded "rear", no matter which speaker radiated the band. When the frequency was between 2 kHz and 5 kHz they generally responded "front", and when it was between 6 kHz and 8 kHz they responded "overhead".

Blauert subsequently made acoustical measurements in the subjects' ear canals when a (flat) broadband noise was delivered from the front, overhead, and rear loudspeakers. He found that most subjects 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 rear locations, respectively.

ELEVATION

Butler and his associates (Butler, 1970; Roffler and Butler, 1968; Musicant and Butler, 1984) have made a detailed study of listeners' perception of the elevation of a sound that originates in the MSP. Like Blauert, they have looked at the localization of narrowband signals and, in general, they find that as the frequency of the signal increases, sounds are perceived to come from higher and higher elevations. They also find that listeners have no sense of elevation, or an incorrect sense of it, when presented with broadband signals that have been low-pass filtered at 7 kHz or below. These findings agree nicely with in-the-ear measurements made by Shaw and Teranishi (1968) and others (e.g., Assano et al., 1990). Those measurements show a distinct peak in the transfer functions, and an adjacent spectral 'notch', features that are high enough in frequency to be ascribed to the response of the outer ear. These spectral features start around 7 kHz for sounds directly in front and increase in frequency as elevation increases.

AGING

The purpose of the present study was to look at how aging affects a listener's ability to localize sounds in the median sagittal plane. There are at least two reasons to think that aging's effects may be large. The first is the fact that hearing sensitivity tends to decline as an individual gets older. By age 65, the average male listener will have a 30 dB hearing loss in the speech frequencies and an even greater loss at higher frequencies. A female listener will likely have a similar hearing configuration but the extent of the hearing loss may be expected to be about 10 dB less at all frequencies (Lebo and Raddell, 1972).

The second problem facing older adults is that they often display broadened spectral tuning curves, rendering them more vulnerable to masking of one region of the spectrum when energy is simultaneously present in another region. Most especially, they are vulnerable to the masking of higher frequencies by lower ones (Dirks et al.,1977). Owing to this, an elderly listener may fail to discriminate spectral features present at levels that exceed absolute threshold. The situation is quite analogous to that of speech listening where issues of spectrum audibility and frequency selectivity jointly determine perceptual success.

EXPERIMENT 1

Experiment 1 was conducted to provide a better sense of whether, when, and to what extent older adults are likely to experience difficulties when they localize sounds in the MSP. A representative group of older adults and a comparison group of normally-hearing young adults performed a sagittal plane localization task (Blauert, 1969/70; 1983), and an elevation localization task (Butler, 1968). The stimulus presented was a broadband (white) noise, which is optimal for MSP localization (Kuhn, 1979; Blauert, 1969/70). The 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 context for the interpretation of the MSP results. The first of these 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 sensorineural hearing losses and found that so long as the condition was bilateral subjects were able to make reasonably accurate binaural localization judgments. This was true even for individuals who had lost the ability to localize accurately on the basis of spectrum.

A binaural localization test was included in the present experiment for two reasons. Reason one was that this provided an opportunity to look, as Butler had, at the relative strengths of binaural and spectral localization abilities among hearing-impaired listeners, here specifically among individuals with presbyacusis. Reason two was that Butler's findings, and some pilot testing results, made it seem likely that most presbyacusic subjects to be tested here would be able to localize sounds in the frontal plane fairly well. (All of the presbyacusic subjects to be tested had bilaterally symmetrical hearing losses). The frontal plane geometry thus could provide a relatively unambiguous context for familiarizing subjects with the testing protocols to be used here, and for setting stimulus levels, and the like. Testing in the MSP could then be undertaken with reasonable confidence that a subject understood the localization task demands and the testing methods.

The final task that all subjects performed was to take an *in situ* hearing test. A free-field audiogram was collected for each subject after localization testing had been completed. Hearing thresholds were determined for third-octave noise bands covering the full spectral range of the white noise that was presented in the localization tests. This audiogram, then, provided a picture of the spectrum audibility of the noise stimulus for each individual and, on average, for the hearing groups under comparison.

Hearing Thresholds and MSP Localization

Previous studies have shown varying degrees of relationship between a hearing-impaired person's audiometric configuration and performance on MSP tasks. In the study by Butler (1970), for example, the relationship was fairly strong. He found that as a group, subjects with substantial high-frequency hearing losses (defined as an 8 kHz threshold that was at least 25 dB greater than the pure-tone-average threshold [PTA] at 0.5, 1.0, and 2.0 kHz) performed an elevation task at levels that were not significantly greater than chance. What is more, the individuals within this group who had the most substantial high-frequency losses (8 kHz threshold at least 40 dB above PTA) tended to perform more poorly than those with less severe losses.

Noble, Byrne, and Lepage (1994) made a detailed study of the correlations between hearing-impaired subjects' pure-tone thresholds and their ability to localize sounds in what they called the median vertical plane (MVP) and the lateral horizontal plane (LHP). The MVP is a portion of the MSP; it extends 180 degrees from directly beneath a subject up and around to the front and on to overhead. The LHP extends 180 degrees around from the back, to the side, to the front. Subjects were free to move their heads in the experiment, but to the extent that they looked straight ahead, positions in the MVP are symmetrical with respect to the two ears and must be discriminated on the basis of spectrum. In the LHP a subject has the potential to make front-back errors; i.e., of confusing, say, a location in front and 45 degrees off midline to the left with one in back and 45 degrees to the left. Front-back localization depends greatly upon spectral cues (Weinrich, 1982; Asano, et. al., 1990).

For sensorineural hearing-impaired subjects, Noble et al. did find significant correlations of moderate size (r's in the 0.4 - 0.6 range) between the audiogram and localization performance in the both the MVP and the LHP. Specifically, they found that MVP performance correlated with subjects' high frequency hearing thresholds (6 kHz and 8 kHz) and LHP correlated with thresholds in two regimes (0.25-0.5 kHz and 4-6 kHz).

Finally, Hausler, Colburn, and Marr (1983) measured the minimum-audible-angle (MAA [Mills, 1958]), or difference threshold, for a change in the vertical position of a sound coming from directly in front of a subject. They found that they *could not* account for the size of a sensorineural hearing-impaired subject's vertical MAA on the basis of the audiogram. Nor could they account for the size of the horizontal MAA for sounds coming from directly off to the left or right. The horizontal MAA calls for a form of front-back discrimination. What did prove a good audiometric predictor of a subject's performance was the speech discrimination score. Vertical and lateral horizontal MAA's were large for subjects with poor speech discrimination abilities and generally smaller for those with good speech discrimination. Hausler et al. took this to imply that both speech discrimination and the localization tasks turned on a subject's ability (or inability) to resolve details in a spectrum that was broadly audible. As noted above, issues of frequency resolution may be particularly important in the present study where all of the target subjects are older listeners.

METHODS

Subjects

YOUNG ADULTS WITH NORMAL HEARING

Five young adults (mean age = 23 years) with bilaterally 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 the exception of the investigator, the normally-hearing (NH) subjects had no knowledge of the hypotheses under test.

ELDERLY ADULTS WITH PRESBYACUSIS

The focal group of the study were 13 elderly subjects (mean age = 69.5 years, range = 53 to 82 years) with presbyacusic hearing loss and no other known audiologic pathology. The only audiometric constraint on their participation was that the hearing loss had to be bilaterally symmetrical (left and right ear thresholds within 20 dB at all test frequencies from 125 Hz to 8 kHz). Figure 1, panels A and B, show the better-ear pure-tone audiogram for each hearing-impaired subject, as measured within 12 months prior to the experiment. The hearing configurations are reasonably representative of the range seen

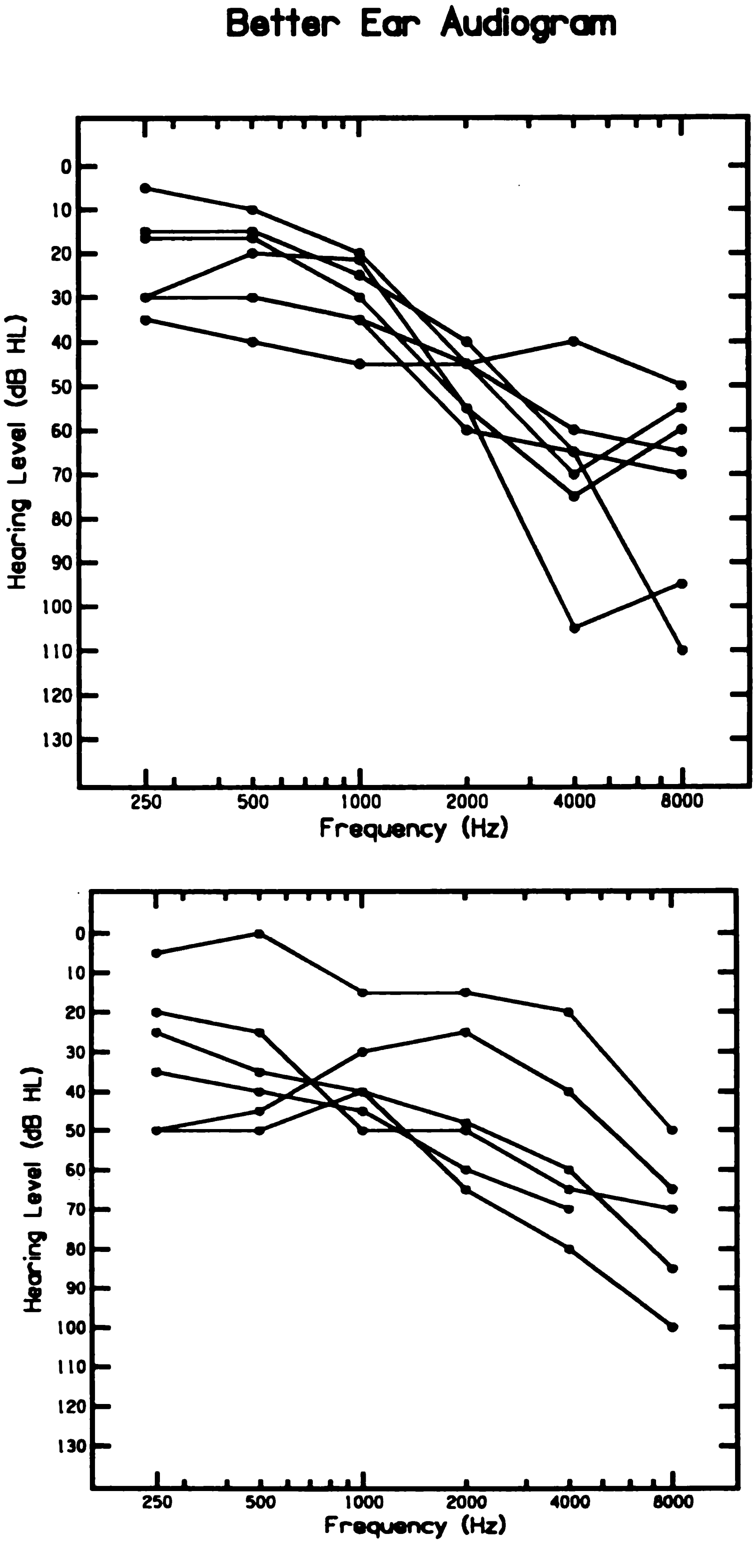


Figure 1: Pure-tone audiometric thresholds for the hearing-impaired subjects of Experiment 1.

with presbyacusic hearing loss. Three of the subjects had steeply sloping hearing losses, eight had more moderately sloping losses, and two subjects had essentially flat losses. Three-frequency pure-tone averages for these subjects ranged from 10 dB to 48.3 dB (mean = 35.1).

All of the HI subjects reported that they were in good general health. Seven of them were binaural hearing aid wearers; five wore monaural aids, and one wore no hearing aid at all. In the experiment, all tests were performed without a hearing aid. Most of the HI subjects were recruited through the university speech and hearing clinic and paid for their participation. A few were (unpaid) relatives of the investigator or one of his advisors. None of these subjects was aware of the hypotheses under test.

The Localization tests

ANECHOIC ROOM

Each subject went through a battery of three localization tests. All of those tests were conducted in an anechoic room (IAC#107480). The interior dimensions of this room were 10' wide, 14' long, and 8' high. Subjects were tested individually, while seated on a chair placed near the center of the room (details below).

STIMULUS

The stimulus was the same for each localization test in the battery. It was a white noise, pulsed on for a duration of one second with a 60 msec linear rise-fall envelope. The spectrum of this noise was flat (+/- 2 dB) from 175 Hz to 14,000 Hz. This frequency range spanned 18 ISO third-octave bands, the lowest centered on 200 Hz, and the highest centered on 12,500 Hz.

To cover a range of intensities that an individual is likely to encounter in everyday listening, the stimulus was presented at different levels in different test runs. In *low-intensity* runs the average level was 48 dB SPL; in *mid-intensity* runs it was 66 dB SPL; and in *high-intensity* runs it was 84 dB SPL. Within each run, intensity varied plus/minus 6 dB from 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. In this manner a range of intensities from 42 dB to 90 dB was presented to the listener in 6 dB increments.

Figure 2 shows the power spectrum of the white noise, as presented in its low-, mid-, and high-intensity ranges. Noise power increased with frequency at the rate of 3 dB per octave. The dotted line in the figure shows the minimum-audible-field (MAF) curve for normally-hearing young adults (Sivian and White, 1933). It is clear that normally-hearing listeners would have full-spectrum audibility for the noise stimulus, and that listeners with even a mild hearing loss would not be able to hear some portions of the noise spectrum at the lowest presentation levels.

TEST 1: FRONTAL PLANE TEST

All subjects went through the localization test battery in a fixed order. The first test was a frontal plane (FRN) test. In the FRN test, the noise stimulus was presented to a subject from any one of three loudspeaker sources, arrayed as shown in Figure 3(A). The loudspeakers were 4' away, and placed directly to the right, directly to the left, and directly above the subject's head. The subject sat facing straight ahead throughout the test, with head held still. The back of the subject chair was fitted with an L-shaped rod that could

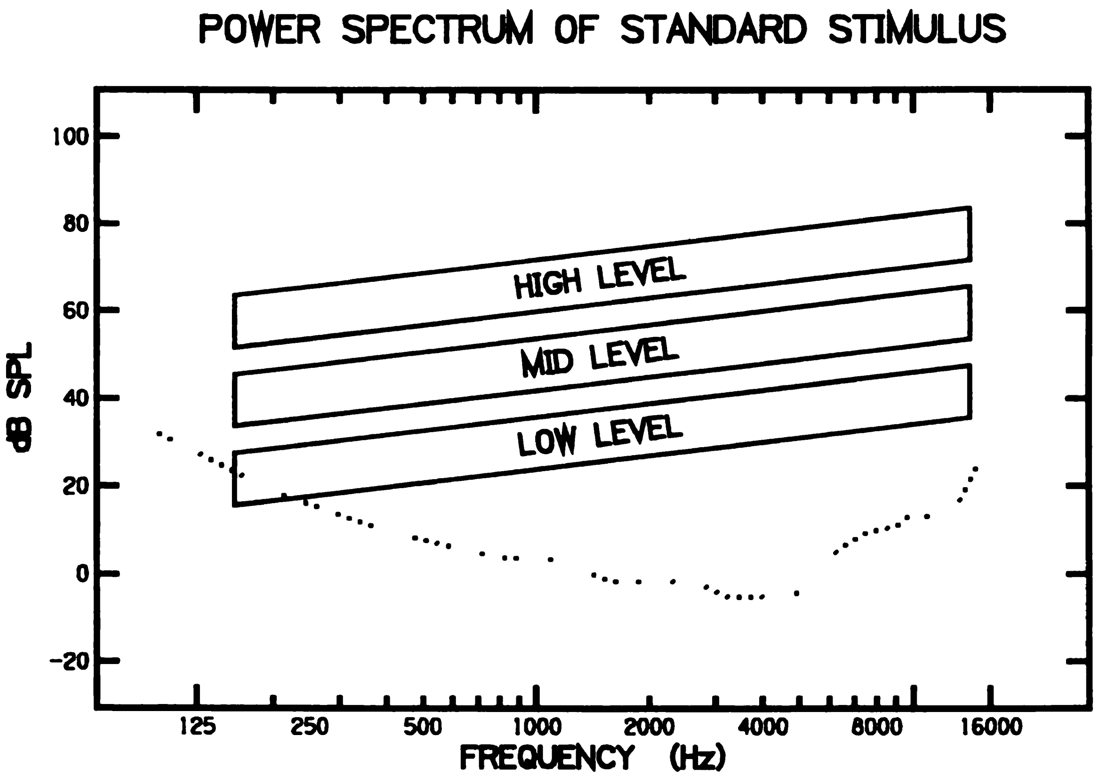


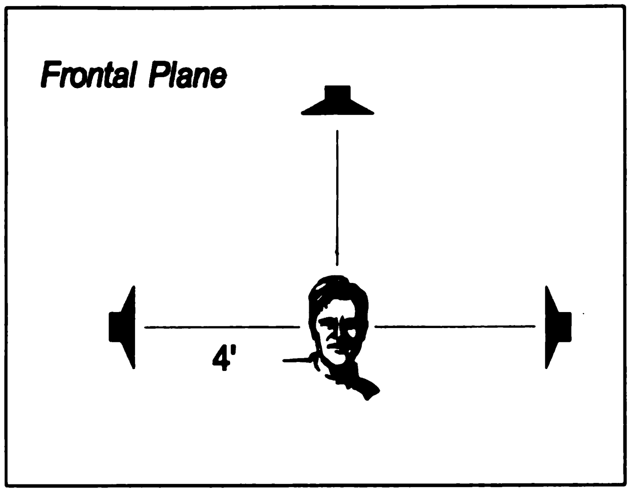
Figure 2: Power spectrum of the localization stimulus as presented at its low, mid, and high levels. The dotted line shows the MAF curve for normally-hearing young adults (Sivian and White, 1933).

be adjusted to touch the crown of the subject's head. This contact provided a physical reminder not to move the heard during a trial.

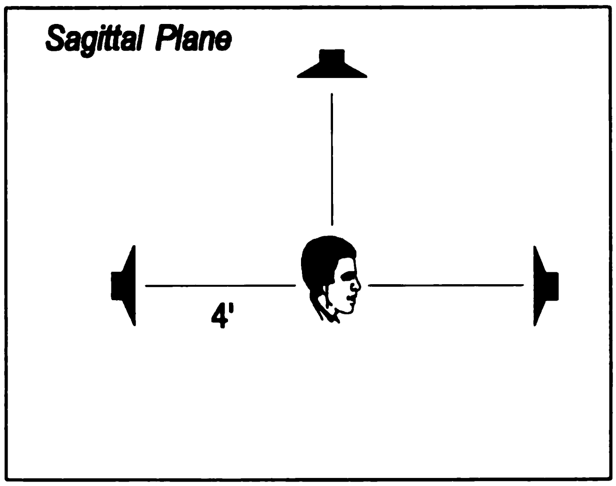
On each trial of the test the stimulus was presented from one of the three sources, selected at random. Following each trial a light came on in front of the subject, calling for a response. The subject's task was to decide which of the three loudspeakers had sounded and to report the choice to the experimental computer by means of a button press on a response box. Stimulus presentation level varied +/- 6dB from trial to trial, as detailed above. 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 NH subject ever gave a "did not hear" response. Several HI subjects intermittently responded "did not hear" at the 42 dB and/or 48 dB presentation levels, but seldom reported it at any of the higher levels. For a few elderly HI subjects (n=4) the stimulus was altogether inaudible at the low-intensity presentation level (presentations < or = 54 dB).

A complete FRN test run in the frontal plane comprised 63 trials, 21 randomized presentations from each of the three loudspeakers. A run was typically completed in about 3 minutes. The computer program was initially set to present the stimulus for a new trial 1 sec after the response for the previous trial. In some cases, subjects found this one second delay uncomfortably short. In these instances the delay was increased as necessary up to as long as 2.0 sec, to keep the subject operating within a comfortable regime. A two-way intercom was set up between the subject and the examiner. If at any time the subjects became confused or believed there was some sort of difficulty this could be reported immediately. This arrangement proved quite helpful for quick questions and clarification

(A)



(B)



(C)

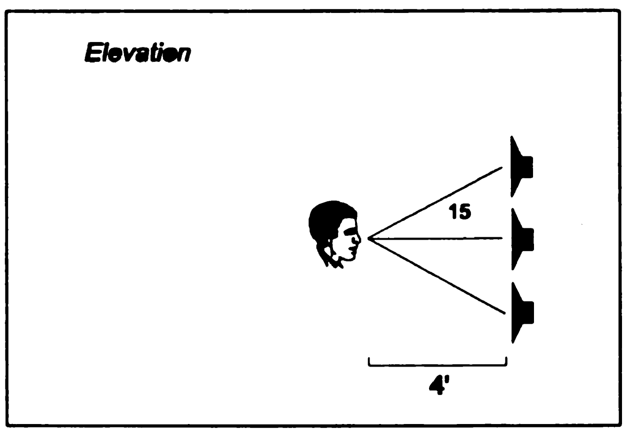


Figure 3: Source layout for the three localization tests of Experiment 1.

of the task at hand.

TEST 2: SAGITTAL PLANE

The second test in the localization battery was a sagittal plane (SAG) test. Methods for the SAG test were identical to those for the FRN test, except for the source layout. The SAG layout is shown in Figure 3(B). One loudspeaker was positioned directly in front of the subject (and 4' away); the others were directly above and behind.

TEST 3: ELEVATION

Localization test three was a three-source elevation (ELV3) test. Again the special feature of the test was its source layout, which is shown is Figure 3(C). The mid loudspeaker source was situated directly in front of the subject, at ear height. A second loudspeaker was 15 degrees up from this point, and a third was 15 degrees down. The subject localized sounds presented from the sources according to the same procedure as previously outlined.

In Situ Hearing Test

After the localization tests were completed, subjects were given an *in situ* free field hearing test. Free-field measures of the listener's hearing thresholds were obtained for third-octave noise bands covering the same frequency range as 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 Bekesy-like tracking procedure was used to determine thresholds, first for the 200 Hz band, and then for octave bands of increasing frequency up through 12,500 Hz. In the interest of time, thresholds were obtained for every other one-third-octave band throughout the relevant spectral range (200 Hz, 315 Hz, 500 Hz, 800 Hz, 1250 Hz, 2000 Hz, 3150 Hz, 5000 Hz, 8000 Hz, and 12,500 Hz). The test began with an intensity level chosen by the examiner to be comfortable for the subject. The subject's instructions were as follows:

1. If the stimulus is audible, hold down a button on the response box.
2. As you hold down the button the stimulus will become more and more quiet.
3. Once the stimulus is so quiet that you can no longer hear it, release the button; this will allow the stimulus to rise in level.
4. As soon as you can hear the stimulus, once again, hold down the button until the stimulus is just quiet enough that you can no longer hear it. Once you can no longer hear it release the button and repeat the process.
5. We are looking for the most quiet sound that you can hear, so it is important that if you can hear the stimulus at all, regardless of how quiet it is, that you hold the button down.
6. Once you have "tagged" the stimulus several times, it will change in pitch. Just repeat the process as we step up in pitch from low to

high.

A testing light was placed in front of the subject to show when the test was in progress. Subjects were cautioned that sometimes when the stimulus stepped up in pitch it might take them a few moments to hear it, but as long as the light was on, and their finger was not on the button, the sound would eventually become loud enough for them to hear.

Prior to obtaining thresholds for the one-third octave bands listed above, listeners were acclimated to the task by doing a demonstration run which presented frequencies of 500 Hz and 1000 Hz only. The examiner was present in the anechoic room with the subject for the demonstration run. This allowed the examiner to immediately answer any question the subject might have, and to further instruct the subject as necessary. The demonstration run was repeated as necessary, for both the subject and examiner to be comfortable with the procedure and results.

The stimulus was one half second in duration, with an additional one half second delay prior to the next presentation. Intensity varied at a rate of one dB per second, up or down depending on the position of the button on the subject's response box. A ceiling intensity of 85 dB SPL was used for all noise bands. This ceiling was selected to minimize the possibility of discomforting the subjects and to avoid distortion in the loudspeakers which grew at very high presentation levels. Six "turns" were recorded for each noise band. The first two turns were dropped. The remaining four were averaged to estimate the subject's free-field threshold for a band.

The Complete Testing Session

As noted above, each subject went through the localization test series in the same order. It can be said, more generally, that all aspects of the (approximately 2 hour) test session were held constant, so much as possible. Upon arriving at the testing facility, subjects were given a general introduction to the testing environment and an explanation of what their involvement in the study would require. A general audiological case history was taken and research consent form was signed by the subject. Next the subjects were given a through orientation to the anechoic room, including response box operation, significance of the response light, and their responsibilities regarding communication of perceived location of the source of the test stimuli. Once these issues had been covered and it was believed the subject had a firm grasp of the task at hand, they completed their first runs in the FRN plane. In addition to ensuring the listener's ability to make reasonable use of binaural cues when available, this array also provided the subjects with a chance to become familiar with the three-alternative forced-choice paradigm being employed, while interacting with relatively unambiguous source location cues. Subjects were fully familiarized with the stimulus and its range of presented intensity levels in this plane. Subjects were screened to ensure each had access to at least the medium and high presentation levels, and ideally some access at the low level.[1] At this time it was also ensured that none of the high levels of presentation were uncomfortably loud for the subject.

Subjects proceeded through the range of stimulus intensities as follows. First the mid-level (66dB,+/-6dB), then the low-level (48dB,+/-6dB) if audible, and finally the high-level(84dB,+/-6dB).

---

[1]In cases where the low-level stimuli were inaudible the low-level run was simply omitted. Some of the subjects, particularly those with greater degrees on hearing impairment, experienced difficulty becoming familiarized with the stimulus at the mid-level. When this situation arose, intensity levels were raised to the high-level, and then subsequently reduced. Testing continued in this fashion, as the subject then proceeded through the remainder of the localization tests, in the SAG and ELV3 arrays.

RESULTS

In Situ Hearing Test

The results of the *in situ* hearing test are shown in Figure 4. Plotted are the mean thresholds for each subject group, at each frequency. Error bars show +/- 1 standard deviation across subjects (n=5 NH subjects, n=13 HI subjects). Recall that thresholds reported here are for detection of 1/3-octave noises presented in free field. The thresholds for the normally hearing subjects are in good agreement with the minimum-audible-field (MAF) curve (Sivian and White, 1933) which is shown in the figure

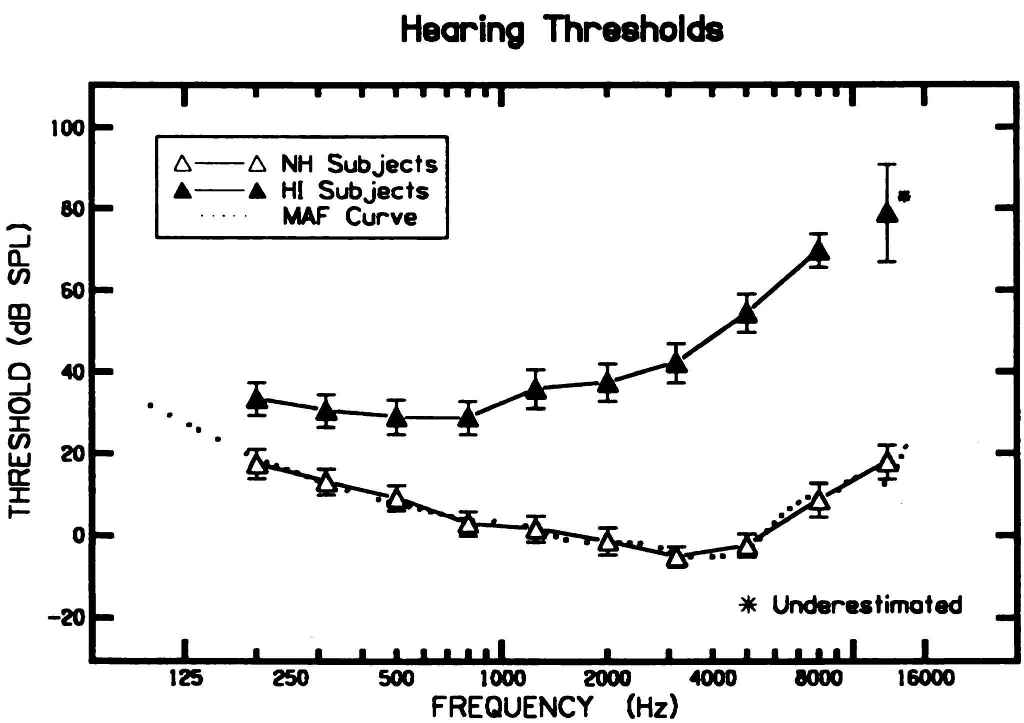


Figure 4: Mean (+/- 1 std. dev.) in situ threshold measures for the hearing-impaired (n=13) and normally-hearing (n=5) listeners of Experiment 1. Thresholds reported are for detection of 1/3-octave noises presented in free field.

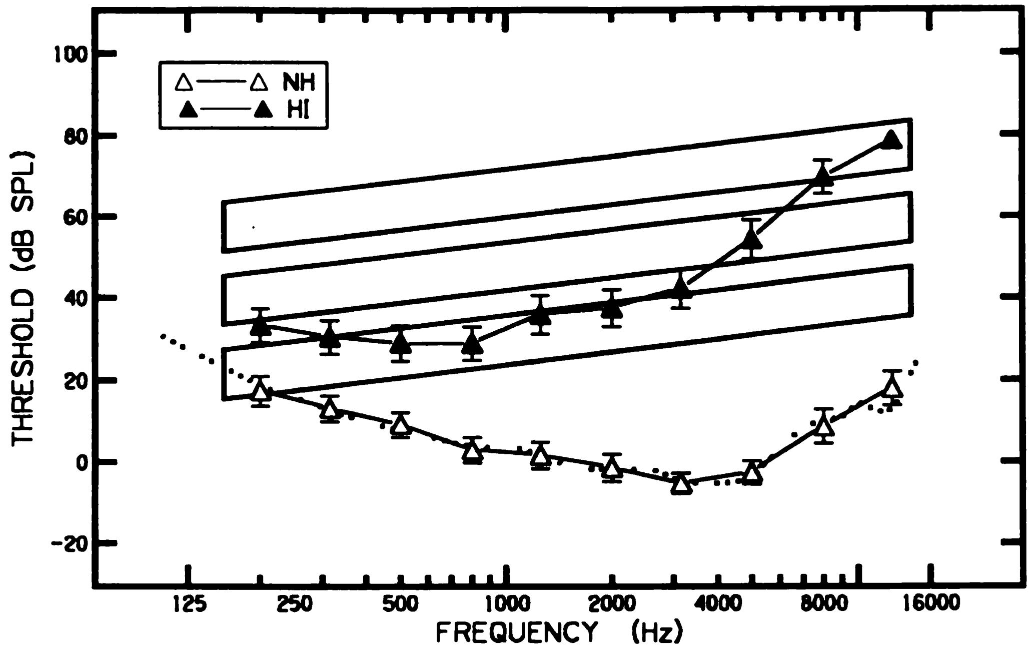


Figure 5: Comparison of hearing-impaired and normally-hearing group mean (+/- 1std. dev.) hearing thresholds with the power spectrum of the white noise stimulus (see Figures 2 and 4 for details).

as a dotted line. Thresholds of the HI subject group were higher than normal at all frequencies, and the difference progressively increased with frequency, as is commonly the case with older adults.

Presentation level was "capped" at 85 dB SPL in the hearing test. Eight HI subjects reached this cap when listening to the 12,500 Hz noise band, which meant that their thresholds for that band could not be reliably estimated. The value reported in the figure reflects the mean plus/minus one standard deviation for those subjects(n= 5) whose thresholds could be reliably estimated. Obviously the true group mean threshold would be higher.

Figure 5 shows the group thresholds overlaid on a representation of the power spectrum of the noise stimulus, as presented at low, medium, and high levels. It shows that portions of the noise spectrum were inaudible or only barely audible to most hearing-impaired subjects, particularly at the low and mid presentation levels. In contrast, the normal hearing group had full spectrum audibility over the entire range of levels.

Given the importance of high frequency cues for spectral localization (Asano et. al., 1990; Roffler and Butler, 1968; Noble, Byrne, and Bernadette, 1994), the HI subjects were rank-ordered according to their performance at the three highest frequencies that we could reliably test *in situ* (3150 Hz, 5000 Hz, 8000 Hz). Table 1 shows the ranking based on average threshold for these three high frequencies (H3FA). Also shown are the subjects' ages, and patterns of HA use.

TABLE 1: Profile of Experiment 1 subjects; including age, High three frequency average thresholds (H3FA, see text), and current hearing aid use.

Subject	Age	H3FA	HA Use
A	67	26.3	monaural
B	80	30.4	none
C	82	46.5	monaural
D	82	46.8	binaural
E	66	56.1	binaural
F	66	57.8	monaural
G	69	60.0	monaural
H	77	61.7	binaural
I	66	62.2	monaural
J	67	62.7	binaural
K	81	63.0	binaural
L	53	74.1	monaural
M	68	74.9	binaural

Localization Tests

NH SUBJECTS

The NH subjects' performance on the three localization tests is summarized in Figure 6. Results for the FRN, SAG, and EVL3 tests are given in the left, center, and right panels, respectively. Within each panel, mean percent correct scores are plotted as a function of stimulus presentation level. The shaded area running across the figure shows a 5% confidence interval around the level of chance performance for these tasks, 33% correct. All scores above that area can be said to confidently exceed chance ($p<0.05$).

NH listeners were perfect or near perfect in the frontal and sagittal planes at all presentation levels. They performed less well, though far above chance, on the elevational test (ELV3), with scores ranging from 75-90% correct. Notable is the fact that normally hearing listeners displayed evidence of a *negative level effect* on ELV3, such that their average level of performance declined by about 20% when the stimulus presentation level increased, from 66 dB to 84 dB (mid-level: 90.5% correct; high-level 72.7 % correct). It is rare to see a negative level effect of this kind. Yet four of five NH subjects exhibited at least some decrease in performance at the highest level of presentation, relative to their performance at either the low or mid levels of presentation. The effect seen here is reminiscent of one recently reported for normally-hearing listeners localizing click stimuli in the sagittal plane (Hartmann and Rakerd,

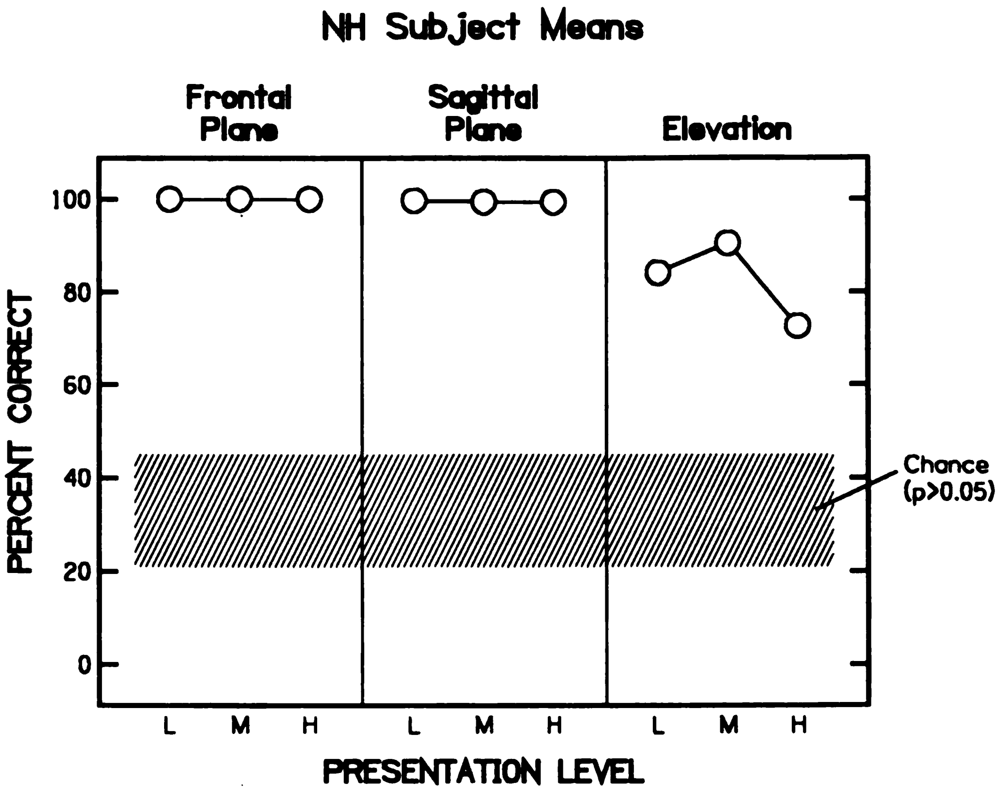


Figure 6: Mean localization performance of the young adult listeners (n=5) in the frontal, sagittal, and elevational source tests. The hashed area represents a 5% confidence interval about chance performance (33% correct).

1993). This observation will be addressed further and in greater detail below (General Discussion).

HI SUBJECTS

Figure 7 displays the group mean performance for the hearing impaired subjects. Middle and high level means for the HI group reflect the performance of all 13 subjects. At the lowest level some subjects were unable to hear the stimulus in one or more experiments.

The low-level means are based on scores from 9 subjects in the FRN test, and 8 subjects in the SAG and ELV3 tests.

In the FRN test, where the relevant localization cues were binaural, all of the HI listeners were able to make reasonably accurate localization judgments most of the time. This pattern is consistent with Butler's (1970) report of good localization accuracy in a binaurally cued task for subjects with hearing losses similar to those of the present subjects. Some of the present subjects performed

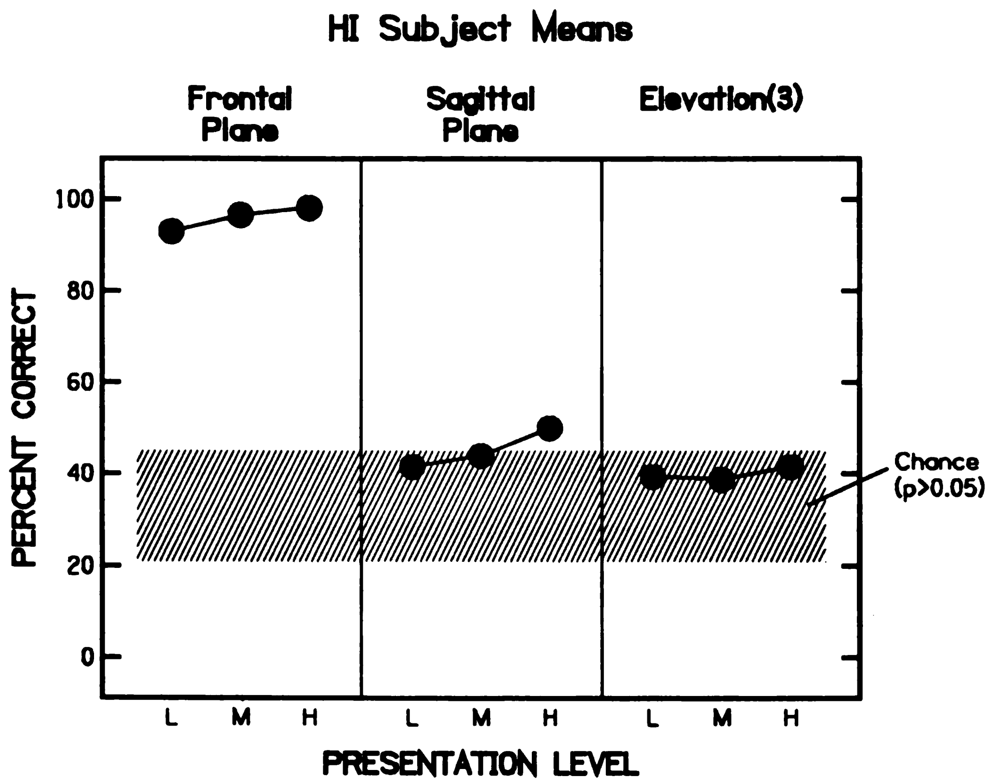


Figure 7: Mean localization performance of the presbyacusic listeners (n=13) in the frontal, sagittal, and elevational source tests. The hashed area represents a 5% confidence interval about chance performance (33% correct). The low-level means are based on 9,8, and 8 subjects in the frontal, sagittal, and elevational tests, respectively (see text).

well at all levels and all subjects performed the test with greater than 90% accuracy at at least one test level. The mean percent correct scores for low, middle, and high-level runs, respectively, were 98.2%, 96.6%, and 98.0% correct.

Hearing-impaired subjects were much less successful in localizing sound sources when they made judgments on the basis of spectrum, both in the SAG test and in the ELV3 test. As a group they performed the SAG test somewhat above 33% correct (chance) at all presentation levels (Low: 41.49% correct; Mid: 43.88% correct; High: 49.95% correct), but their performance statistically exceeded chance ($p<0.05$) at the highest level only. In the ELV3 test, the subjects never performed statistically better than chance at any level (Low: 39.33%; Mid: 38.66%; High: 41.49%).

INDIVIDUAL DIFFERENCES

Sagittal Plane: Figure 8 shows how the HI subjects performed individually in the SAG test. Percent-correct scores for each subject are reported 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 two subjects performed above chance at at least one stimulus level. On the other hand it is clear that even when performing at the most advantageous intensity level, no hearing-impaired subject approached the near perfect sagittal plane performance of the normally-hearing group. Evidently, the declines in

SAG plane localization performance due to aging are widespread.

Recall that the subjects were rank ordered according to their H3FA thresholds as measured on the free field hearing test. A scan of Figure 8 from left to right and top to bottom, then, provides information about the importance of sensitivity in the H3FA region (3150 Hz-8000 Hz) for subjects' sagittal plane performance. There is some limited evidence that these thresholds mattered. The five subjects with the poorest high frequency thresholds (subjects I,J,K,L,M) performed noticeably less well than did the eight with better high frequency hearing.

Another point to note is that individual performance tended to exhibit a positive level effect, with subject performance generally improving with increasing stimulus presentation level. This however, was not always the case. Three subjects performed best at one of the lower levels. This result is most likely a statistical accident for one subject (M) who never performed better than chance at any level. It seems more likely a real effect for the other two subjects (C and G), who both performed well above chance at the mid-level, and distinctly less well at the highest presentation level.

Table 2 shows a confusion matrix for responses made by the 13 HI subjects combined. Data for each individual came from the subject's "best level" run, i.e., the run in which the subject had the highest percent-correct score.

TABLE 2: Distribution of responses in the sagittal plane test by the elderly listeners (N=13) of Experiment 1.

	RESPONSE PERCENTAGE			
Source	**Front**	**Over**	**Rear**	**"Not Audible"**
Front	*38.8*	25.9	24.2	1.1
Over	13.6	*54.2*	32.2	0
Rear	4.4	29.3	*65.9*	0.4

As a group the subjects failed to localize the front source significantly better than chance, even at their best level (38.8% correct). They were more successful in correctly identifying the overhead (54.2% correct) and rear (65.9% correct) sources. Five of the 13 subjects were rather better than the rest of the group at identifying the front source. (Each of the five had a percent-correct-front score of 66% or greater.) To see whether some aspect of hearing sensitivity might account for this performance, the free field thresholds of the "good" front localizers were compared to the average thresholds of the remaining subjects. Figure 9 displays those threshold comparisons.

One of the five "good" subjects had thresholds that were not notably different from those of the "poor" localizers. The other four "good" subjects all had thresholds that were better than those of the "poor" group in at least some portion of the mid frequency region (2-5 kHz). Blauert (1974) reports there to be a "boosted band" for front sound incidence in precisely this region. Also, Nobel et al. (1993) report that sensitivity in the region 4-6 kHz is important for front-

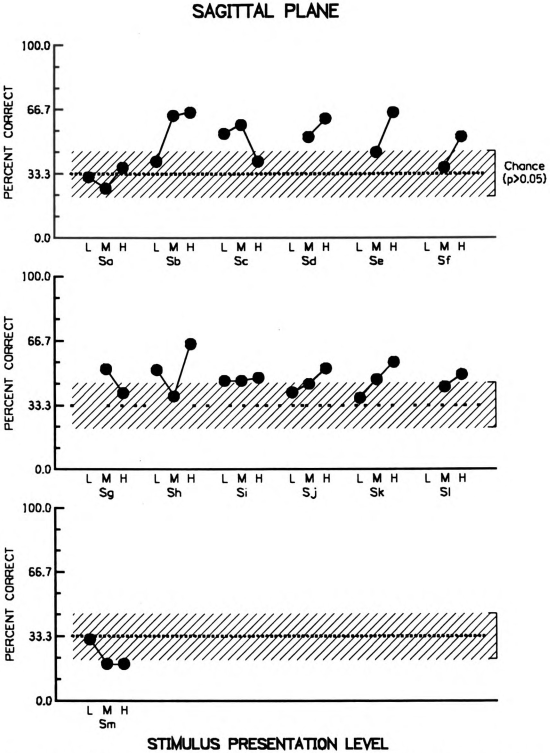


Figure 8: Individual results for presbyacusic subjects localizing sounds in the sagittal plane.

rear discriminations. It would appear that mid-to-high frequency threshold sensitivity plays a significant role in predicting one's ability to correctly identify frontal locations in the median sagittal plane, though clearly this does not represent the entire picture. It is possible that some other functional variable, such as speech discrimination or central processing abilities, may also play a role in determining ones ability to accurately localize sound sources originating in front of the listener.

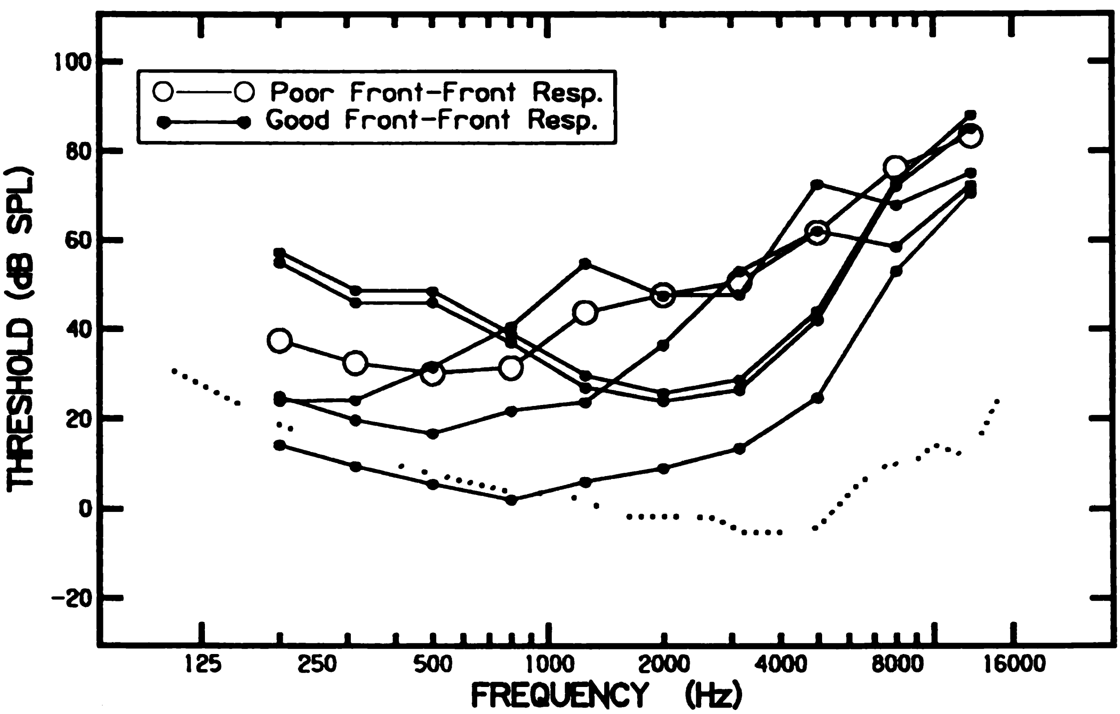


Figure 9: Threshold comparisons of good and poor localizers of the front source. The dotted line shows the MAF curve for normally-hearing young adults (Sivian and White, 1933).

<u>Elevation:</u> Individual results for the ELV3 test are shown in Figure 10. They make it clear that difficulties with elevation localization were quite general among the HI subjects. Only three of the 13 subjects (B,C, and F) were able to perform the task with even a reasonable level of success. Consistant with Butler's (1970) findings, they were among the subjects with the best high frequency hearing. But H3FA's were good as well for subjects A, D, and E, who localized elevation poorly. Overall, these findings support the conclusion that reasonably good high frequency hearing is required for successful elevational localization. They also make it clear that other factors are involved as well. Perhaps there were some lower frequency cues to elevation of which the listeners were able to take advantage. The length of known hearing impairment for the majority of the 13 subjects seen here was eight years or greater. Perhaps listeners who have had adequate time to adjust to their hearing impairment become more alert to the lower frequency cues associated with head, shoulder, and body reflections.

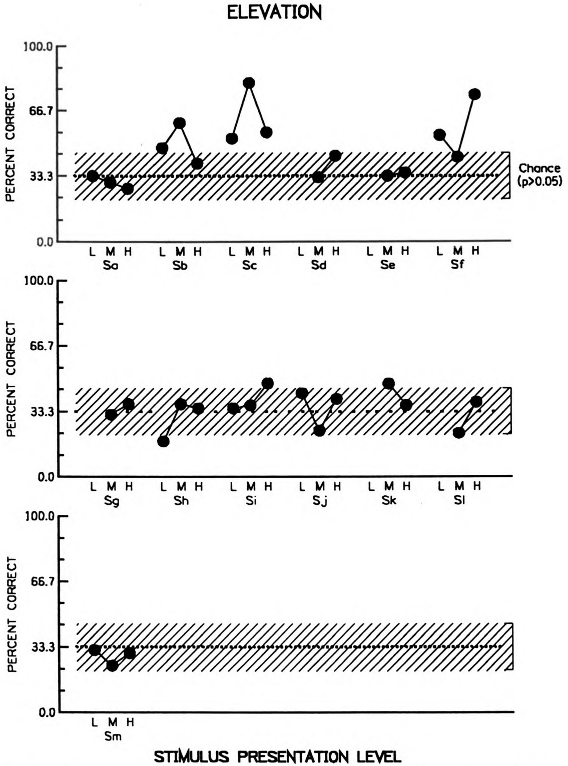


Figure 10: Individual localization results for presbyacusic subjects localizing sounds in the elevation test.

DISCUSSION

All 13 of the elderly HI subjects tested here were mediocre to poor at making elevational judgments. There appears to be significant and widespread decline in this aspect of human sound localization performance as a consequence of aging. With high probability, elderly subjects may be expected to perform substantially less well than younger adults when required to judge the elevation of a sound source.

The situation is somewhat less bleak for sagittal plane (front-overhead-rear) performance, though perhaps not so much so as previous studies would suggest. A number of investigators have reported that cues for front and rear locations are predominantly in the low to mid frequencies (Asano et. al., 1990; Blauert 1969/70; 1974), where older listeners generally retain reasonable spectral sensitivity. Nevertheless, the subjects of this experiment performed distinctly less well than younger NH adults on the SAG test, even at the highest stimulus presentation levels. Apparently they had difficulty resolving details of a spectrum even when clearly above threshold, perhaps due to masking of one part of the spectrum by another.

Error Distibution

It is widely agreed that the dominant cue to overhead location is found in a high frequency region, around 8Khz (Blauert, 1974). A reasonable prediction, therefore, is that the listeners with presbyacusic hearing losses would generally experience their greatest degree of difficulty in the sagittal plane with the overhead source.

In other words, the predominant SAG error would be expected to be a failure to recognize sounds as coming from overhead. This did not prove to be the case in Experiment 1. Figure 11 shows how each HI subject's errors were distributed over the front, overhead, and rear locations. It can be seen that overhead source errors were the predominant error for just three of the thirteen subjects (subjects D,F,J). More commonly, a subject lacked either a clear sense of front, or a clear sense of rear, or both. Apparently, the absence of audible high frequency cues, brought about by sensorineural hearing loss, creates difficulties for median plane listening that are quite general, and in particular, difficulties in reliably distinguishing the front from rear hemispheres.

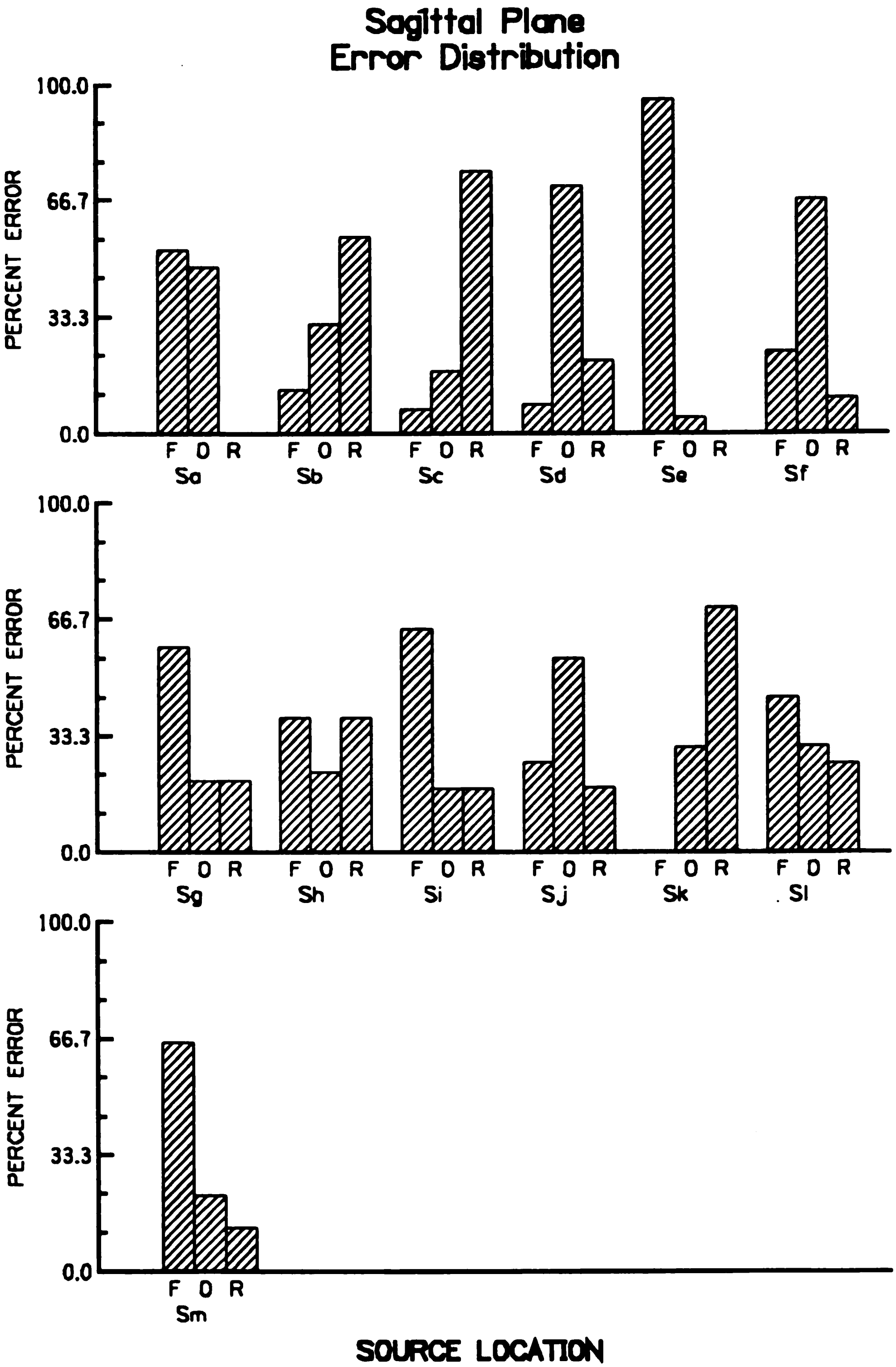


Figure 11: Percentage of a subjects total localization errors associated with the front, overhead, and rear sources.

EXPERIMENT 2

The results of Experiment 1 paint a rather discouraging picture of sound localization prospects for elderly persons when they must localize sounds in situations where the available cues are predominantly spectral in nature. The present experiment looked at the replicability of the basic findings of Experiment 1, and going beyond them, at whether HI subjects' performance could be improved significantly by any of several manipulations.

The first of these manipulations was motivated by the fact that the three-speaker elevation task of Experiment 1 proved rather difficult. Even the normally-hearing listeners performed the ELV3 test substantially less well (84.1% correct overall) than the FRN (100% correct) or SAG (99.6% correct) plane tests. To ease the difficulty of the elevation task in this experiment, the middle speaker was removed, leaving only the upper and lower speakers separated by 30 degrees. This new array was then used in a two-alternative forced-choice elevation test (ELV2).

The second manipulation was designed to provide relief from possible problems caused by masking. One expects the effects of the masking to be particularly detrimental to those in the hearing-impaired subject group due to the broadened neural tuning curves often associated with sensorineural hearing loss (Scharf and Florentine; 1982). Two new stimuli were introduced in Experiment 2, to reduce the upward spread of masking effects. Both stimuli were created by high-pass filtering the standard localization stimulus, in one case at 1 kHz, in the other at 5 kHz. These cutoff frequencies were chosen to reduce the amount of low frequency energy in the stimulus without interfering with frequencies believed to be of greatest significance to the specific localization tasks at hand. This topic is discussed in greater detail in the stimulus section below.

The third manipulation designed to improve subject performance was to allow hearing-impaired subjects to wear their hearing aids during testing. Both monaural and binaural amplification wearers participated.

A final feature of Experiment 2 was that it included a new subject group. In addition to young (NH) and elderly (HI) groups comparable to those tested in Experiment 1 there was a *middle-aged* group, which was intermediate to the other groups both in age and in hearing sensitivity.

METHODS

With the exception of those items noted below, experimental methods for Experiment 2 remained as previously described for Experiment #1.

Subjects

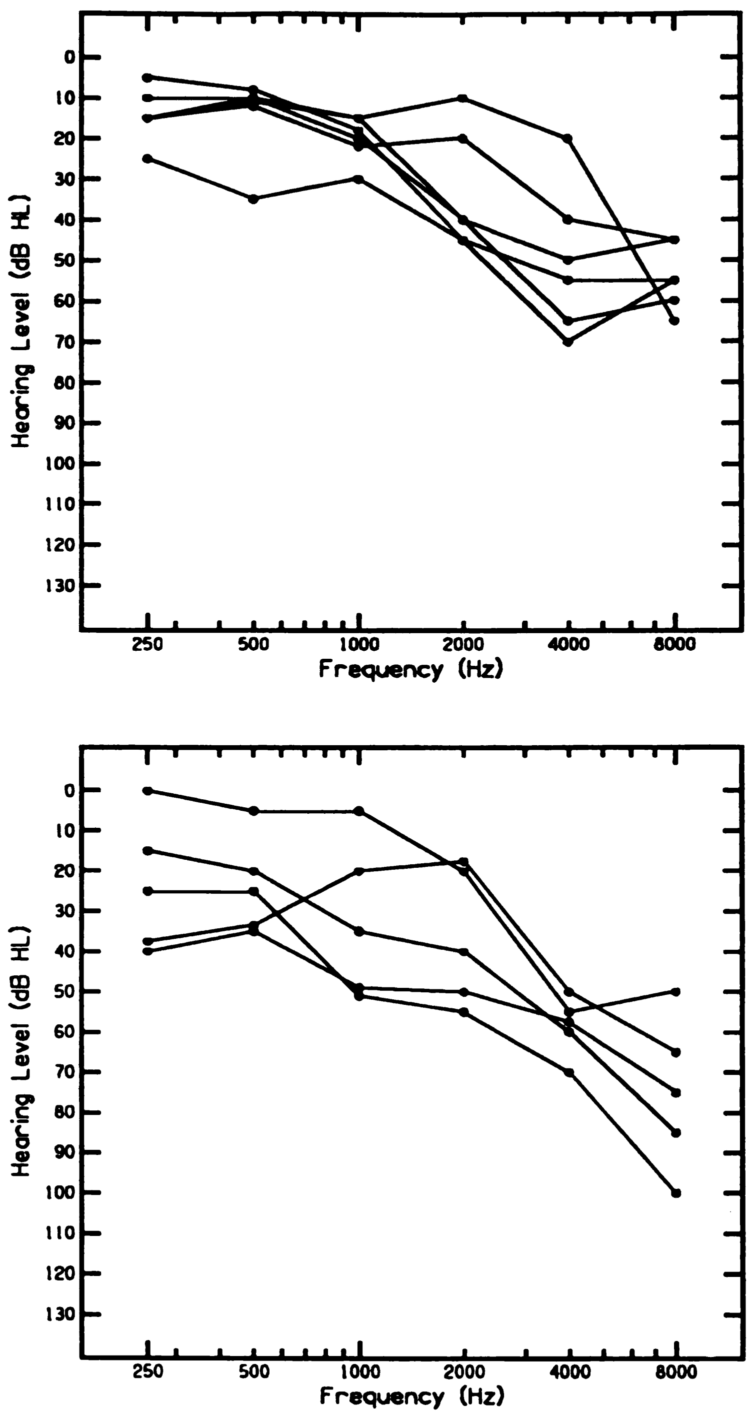
Four new young NH subjects and fourteen new elderly adults with presbyacusic hearing loss were recruited for this experiment. In addition one NH subject (the investigator) and 2 HI subjects who participated in Experiment 1 were retested in this experiment. Finally, a group of 5 middle-aged subjects were recruited. All of these middle aged subjects had hearing thresholds intermediate between those of the NH and HI groups, but overall their thresholds were nearer to the NH group. They will, therefore, be referred to here as the near-normally-hearing (NNH) group. The average ages of the NH, NNH, and HI subjects were 23.6 years, 52.4 years, and 71.6 years, respectively.

None of the NNH subjects wore a hearing aid. Twelve of the HI subjects made regular use of amplification. Four of them wore a monaural aid, eight wore binaural aids. Figure 12 shows the presbyacusic HI subjects better-ear audiograms. Figure 13 displays the better-ear audiograms for the NNH subjects.

Localization Tests

The battery of localization tests for this experiment included the three from Experiment 1 and one new test. A two-source elevation 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 deg. Stimulus presentation and data collection for ELV2 were again controlled by computer. Testing was done in runs of 42 trials, with 21 randomized presentations from each of the two sources.

Expt. 2 Better Ear Audiograms



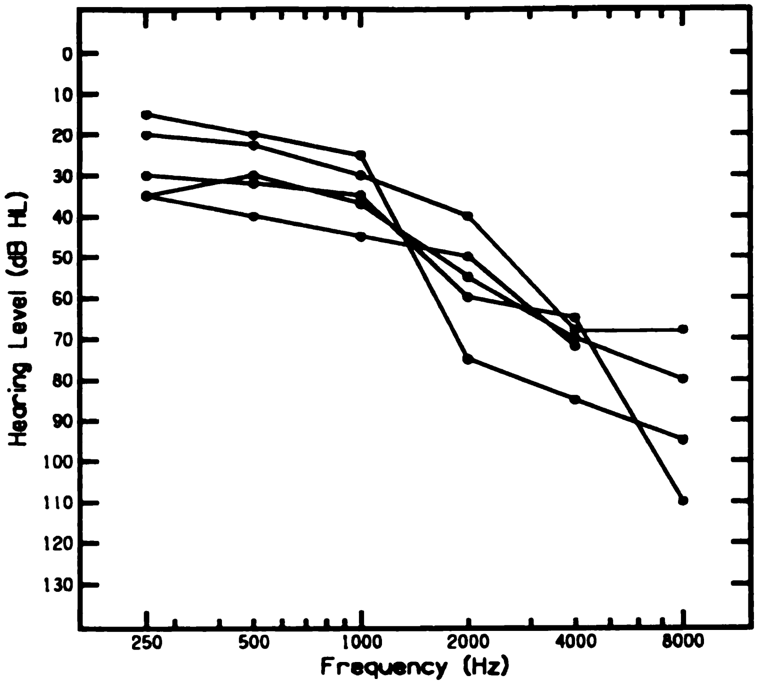


Figure 12: Pure-tone audiometric thresholds for the hearing-impaired subjects of Experiment 2.

Stimuli

Three stimuli were used for the localization tests in Experiment 2, the standard broadband noise stimulus (See Methods section for Experiment 1), and two high-pass-filtered versions of this noise (filter roll-off = -96 dB/octave). A 1-kHz high-pass noise was created for use in the SAG experiment where many of the relevant localization cues are found in the mid and mid-to-high frequencies (Blauert, 1983). A 5-kHz high pass noise was created for the ELV2 and ELV3 tests, based on findings that the critical elevation cues are predominantly high-frequency cues (Roffler and Butler, 1968; Blauert, 1983).

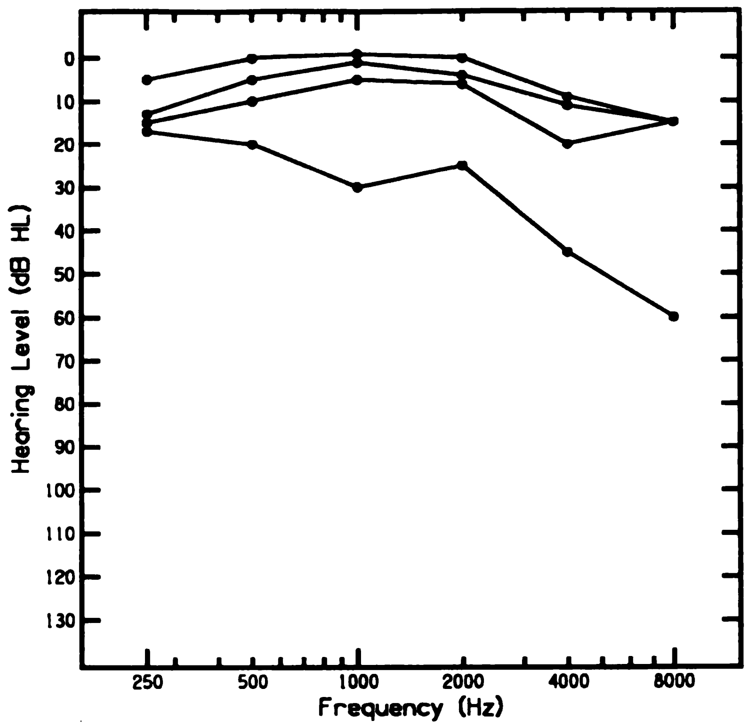


Figure 13: Pure-tone audiometric thresholds for four of five near-normally-hearing subjects of Experiment 2.

Hearing Aided Listening

Eleven HI subjects, all frequent hearing aid wearers, participated in a special added battery of test runs while wearing their hearing aid(s). All of these runs were done after the standard test battery had been completed. Prior to the start of hearing aided localization testing, these subjects were asked to insert their aid(s) and to adjust them to a normal and comfortable volume setting. Seated in the anechoic room, they were then asked to readjust their volume level, if necessary, to obtain a "most comfortable listening level" (MCL) while listening to the standard stimulus. The stimulus was delivered at a level of 66 dB SPL, from the front speaker of the localization array. Once MCL was acquired with the 66 dB signal, the stimulus level was then varied by plus/minus 6 dB to ensure that those more intense signals of 72 dB SPL were not uncomfortably loud, or that those at 60 dB SPL were not inaudible. If either of these complications arose, the subject was once again asked to adjust the hearing aid(s) to achieve a comfortable balance. Once this balance had been reached, the subject was asked not to change the volume setting until the end of the testing session. With MCL achieved, the subject then completed five additional localization runs and an *in situ* hearing test with the use of the hearing aid(s). Four of the hearing-aided localization runs were conducted with the standard stimulus, one run in each of the four localization test loudspeaker arrays (FRN, SAG, ELV3, ELV2). An additional SAG test run was done with the 1000 Hz high-pass stimulus. Data collection was carried out as noted for the unaided runs described above. Finally, hearing-aided threshold measures were obtained in a special run of the *in situ* hearing test.

RESULTS AND DISCUSSION

Hearing Tests

Figure 14 shows the results of the *in situ* hearing test for the subjects of Experiment 2. Thresholds for the NH and HI groups of Experiment 2 were very similar to those seen for the comparable groups of Experiment 1 (Figure 4). Thresholds for the NNH group were

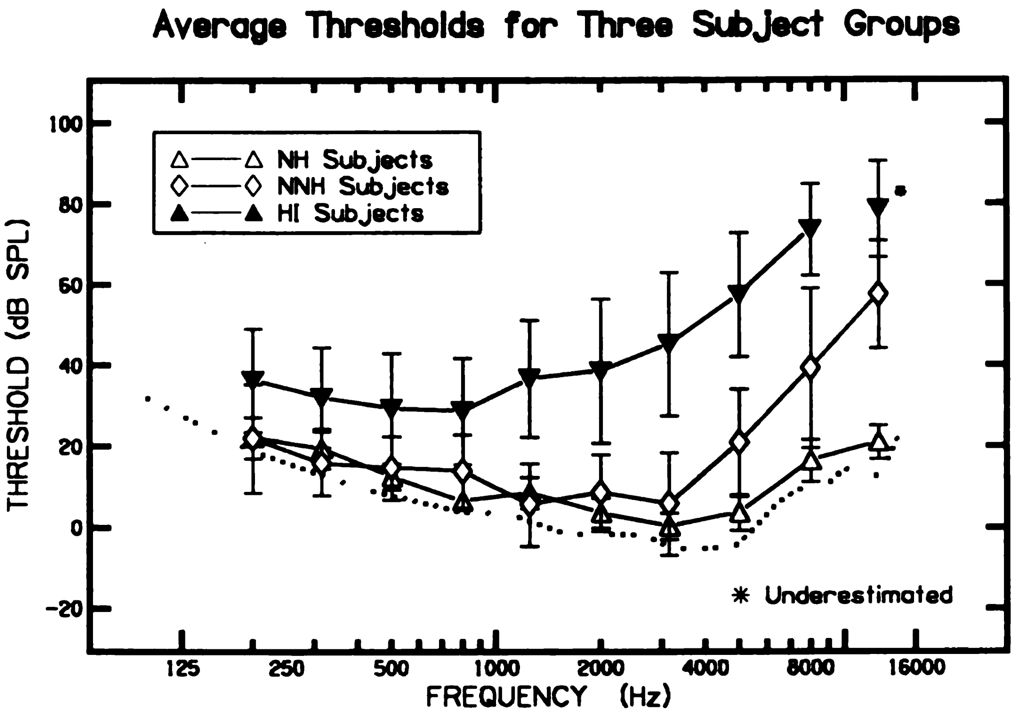


Figure 14: Mean (+/- 1 std. dev.) *in situ* threshold measures for the young adult (NH), near-normally-hearing (NNH), and presbyacusic (HI) listeners of Experiment 2.

indistinguishable from those on the NH group at frequencies at or below 1 kHz. At higher frequencies the NNH group exhibited progressive hearing loss.

Localization Tests

STANDARD STIMULUS CONDITIONS

Results for the standard stimulus conditions of the FRN, SAG, and ELV3 tests are given in the left, center and right panels of Figure 15, respectively. Separate functions are shown for each subject group (NH: open circles; NNH: filled pentagons; HI: filled circles).

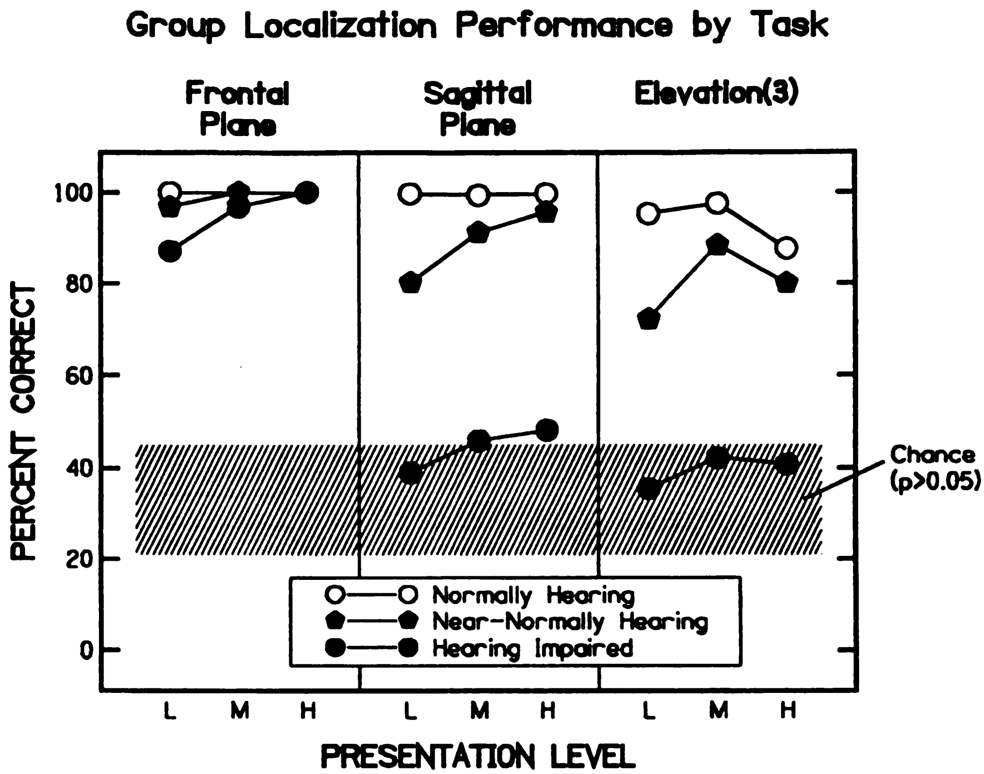


Figure 15: Mean localization performance of the normally-hearing (n=5), near-normally-hearing (n=5), and hearing-impaired listeners (n=16) in the frontal, sagittal, and elevational source tests. The hashed area represents a 5% confidence interval about chance performance (33% correct). The hearing-impaired low-level means are based on 9 subjects.

<u>NH and HI Subjects:</u> A comparison of Figure 15 with Figures 6 and 7 shows that both the NH and HI groups tested here performed very much as did their counterparts in Experiment 1. Hence the present experiment confirms the earlier pattern of results and adds to the number of subjects on which those patterns are based. Combining

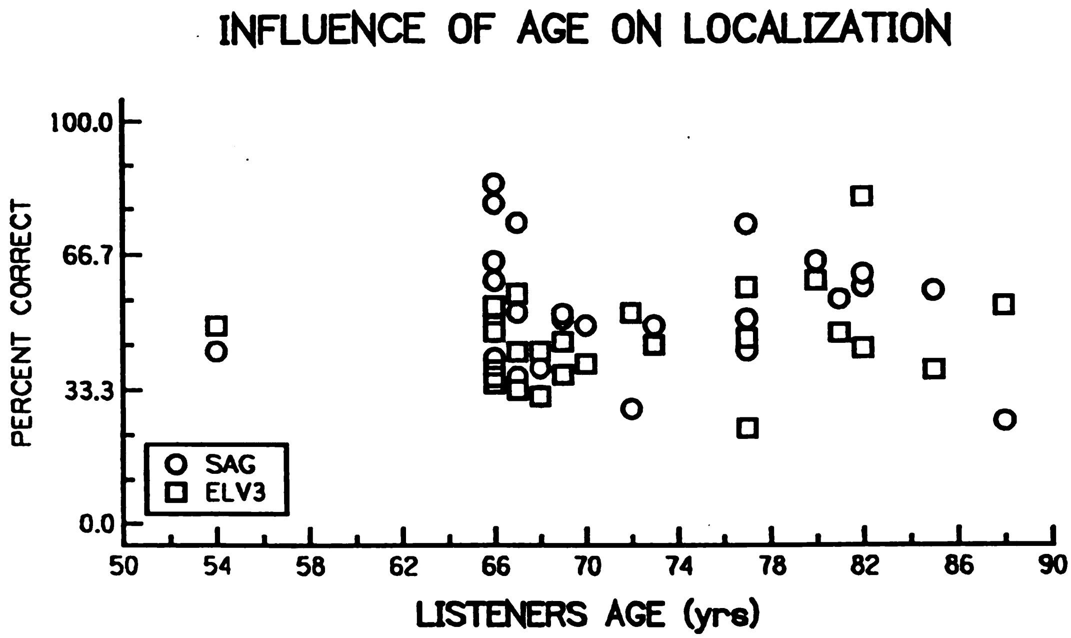


Figure 16: Relationship between localization performance and age for elderly listeners. Data are plotted for best level performance for the SAG and ELV3 tests for elderly listeners from Experiments 1 and 2 (n=29).

Experiments 1 and 2 (and allowing for the fact that one NH and two HI subjects participated in both) the total number of young adult NH subjects who have participated in these tests is 10, the total number of elderly HI subjects is 29.

The hearing-impaired subjects ranged in age from 54 to 88 years. Figure 16 shows their best level SAG and ELV3 scores, plotted as a function of age. It can be seen that the subjects were fairly poor at both tasks, as noted above. There are only 3 best level scores of any kind better than 75% correct. There is no visible evidence that the subjects in their 80's were especially different from those in their 70's or 60's.

NNH Subjects

Figure 15 shows that the NNH group performed at levels that were intermediate to those of the other two groups in nearly every instance tested. This suggests that age-related declines in localization ability are likely to be gradual and cumulative.

Negative-Level Effect Revisited

A noteworthy replication is the negative level effect of the NH subjects in the ELV3 test. The NH subjects of Experiment 1 showed clear evidence of a negative level effect in the ELV3 test. The same result appears here, with 4 of the 5 subjects showing the effect to a greater or lesser degree. In fact, on average no group showed improved performance when tested at the highest level.

HI: Individual Differences

SAGITTAL PLANE TEST

HI subjects' individual performance is shown for the SAG test in Figure 17. As in Experiment 1, listeners are presented with regard to their high frequency threshold sensitivity as quantified by H3FA thresholds measured with the *in situ* threshold tracking procedure. Those with the lowest, or most sensitive, H3FA's are presented first. Subject S01, then, had the most sensitive H3FA of the group, and subject S16 had the least sensitive, or highest H3FA. The figure shows that subjects with the poorest H3FA's (11-16) performed the SAG test less well than those with better H3FA's. Again this points to a role for mid-to-high frequency hearing sensitivity in sagittal plane localization.

ELV3

Individual performance for the ELV3 test is shown in Figure 18. HI subjects' difficulties with the three-source elevation test were again substantial and quite general. Only 7 of the 16 HI subjects demonstrated an ability to perform significantly above chance at even a single presentation level, and no HI subject proved able to perform significantly above chance at more than one level. Hence, Experiment 2 confirms the generality of elderly listeners' difficulties with elevational judgments.

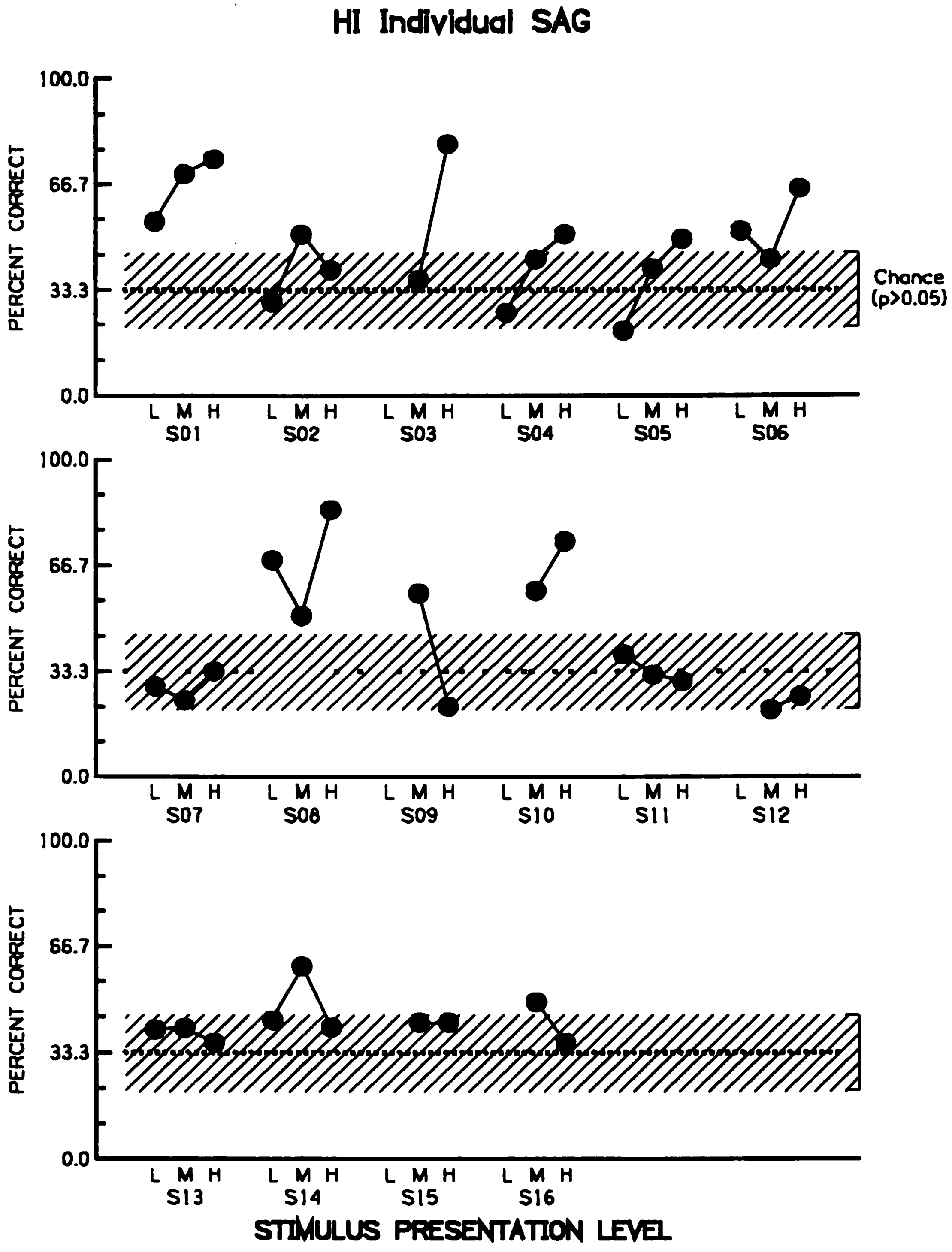


Figure 17: Individual localization results for presbyacusic subjects localizing sounds in the sagittal plane.

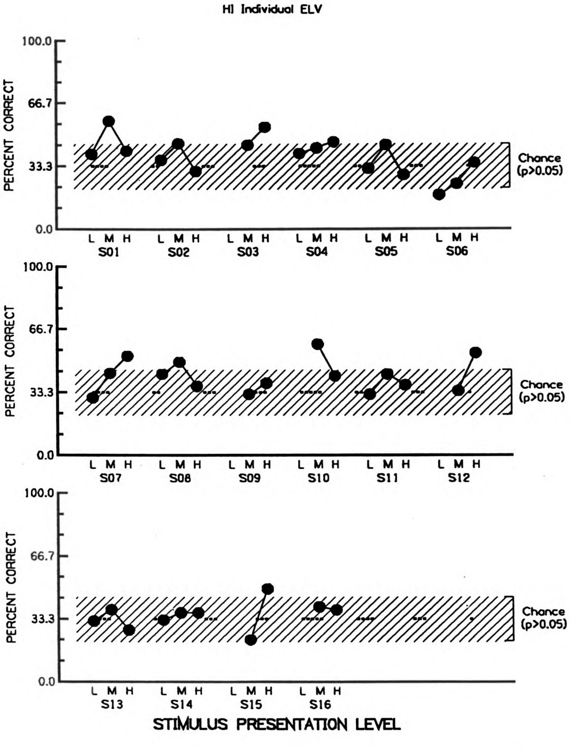


Figure 18: Individual localization results for presbyacusic subjects localizing sounds in the elevation test.

Attempts to Improve Performance

HIGH PASS NOISE TESTS

Figure 19 shows the results of the tests done with high pass (HP) noise. Recall that a 1 kHz HP noise was used for SAG tests (left panel of the figure), and a 5 kHz HP noise for the ELV3 tests (right Panel).

Sagittal Plane Test: NH subjects performed the SAG 1 kHz HP test at or near perfection, regardless of stimulus presentation level. The NNH subjects performed less well than the NH subjects, but only slightly so. The NNH group did show some evidence of having been helped by the high-pass filtering at the lowest presentation level, (compare figures 19 and 15). Their performance improved significantly ($t=3.73$, $p<.02$) with a 1 kHz high pass noise (86.7% correct), compared to the full broadband noise (80.2% correct). This improvement in NNH subjects performance at low levels suggests that in cases where the spectral characteristics of the stimulus may be at or near the listener's threshold, the reduction of low frequency energy provided by the 1 kHP filter can provide some useful relief from the upward spread of masking.

There was no evidence that subjects in the HI group were helped by HP filtering at either presentation level in the SAG test. HI group performance did not differ significantly ($p>.05$) between the standard stimulus and 1kHP condition at any level of stimulus presentation.

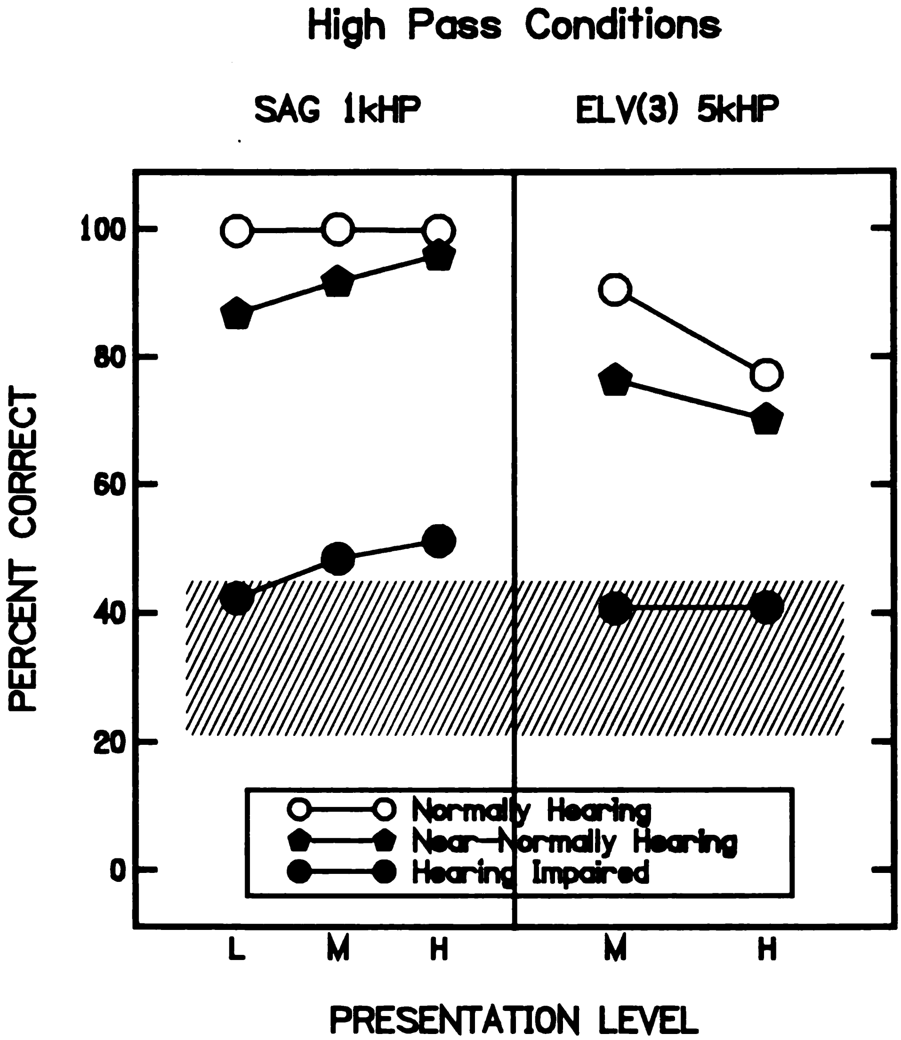


Figure 19: Results of listeners localization performance in the front-overhead-rear geometry (SAG) and three source elevational (ELV3) tests, with the 1 kHz and 5 kHz high pass stimuli, respectively.

Individual HI listeners' localization performance with the 1 kHP stimulus in the SAG array, is seen overlaid on standard stimulus performance in Figure 20. A few listeners (subjects 8,11, and 12) displayed improved performance with the 1kHP stimulus over the standard stimulus. This, though, was not the case for most subjects. Again, overall, the HI listeners did not demonstrate a significant advantage in localization performance from the 1kHP condition, over the standard stimulus in the SAG test($p>.05$).

Three Source Elevation: The 5-kHz high pass noise (5kHP) stimulus was used in elevation tests. Results for the ELV3 5kHP condition are shown for each of the three subject groups in the right panel of Figure 19. Overall, NH subjects performed slightly less well, though not significantly differently, with the 5kHP stimulus than with the standard stimulus. Their mean performance by level ranged from 77.12 to 90.47 percent correct.

Group means for the NNH subjects again revealed that they performed less well, though not significantly differently ($p>.05$), from NH listeners when listening with the 5 kHP stimulus. On the average, NNH listeners' localization accuracy decreased under the 5 kHP condition, as compared to their performance with the standard stimulus.

HI subject mean performance in the ELV3 test with the 5kHP stimulus was never significantly better than chance, with group mean scores ranging from 38.78 to 40.71 percent correct. Clearly, HP filtering afforded the HI group no help and may, in fact, have done some harm.

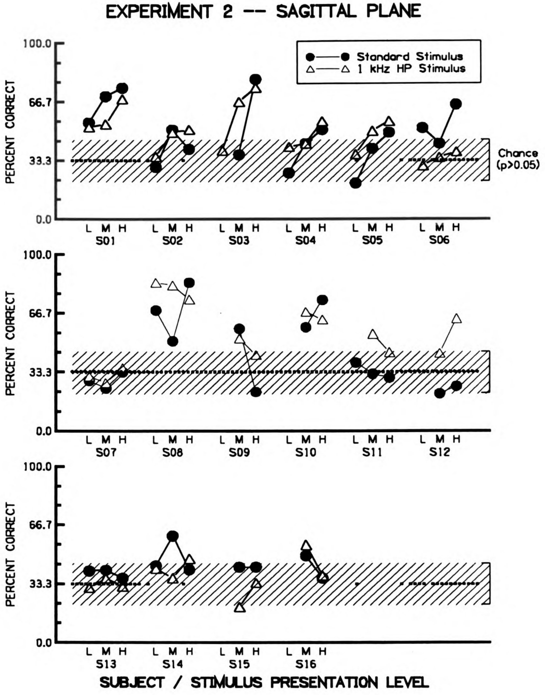


Figure 20: Individual localization results for presbyacusic subjects localizing the broad-band standard stimulus and 5 kHz high-pass stimulus in the sagittal plane.

All subject groups, on average, performed the ELV test less well with the 5 kHz HP stimulus than with the standard broad-band stimulus. This consistent decline in localization performance, across subject groups, was subjectively confirmed by most listeners, who offered in comments that the 5 kHz HP stimulus was more challenging to localize. This finding suggests that in elevational tests, these listeners were able to make use of some lower frequency spectral information when listening to the broadband (standard) stimulus.

Two-Source ELV

The second of the new conditions incorporated in the localization tasks was the introduction of the two-source elevational test(ELV2). Results for ELV2 are shown for both the standard stimulus and 5 kHP conditions in Figure 21. Note that chance performance is now 50% correct. The shaded area in the figure shows a 5% confidence interval around chance.

Standard Stimulus

NH Subjects: A concern in Experiment 1 was that even the NH subjects did not perform the ELV3 test especially well. The ELV2 test resolved that concern, with NH subjects performance improving to greater than 98.6% accuracy in all conditions tested.

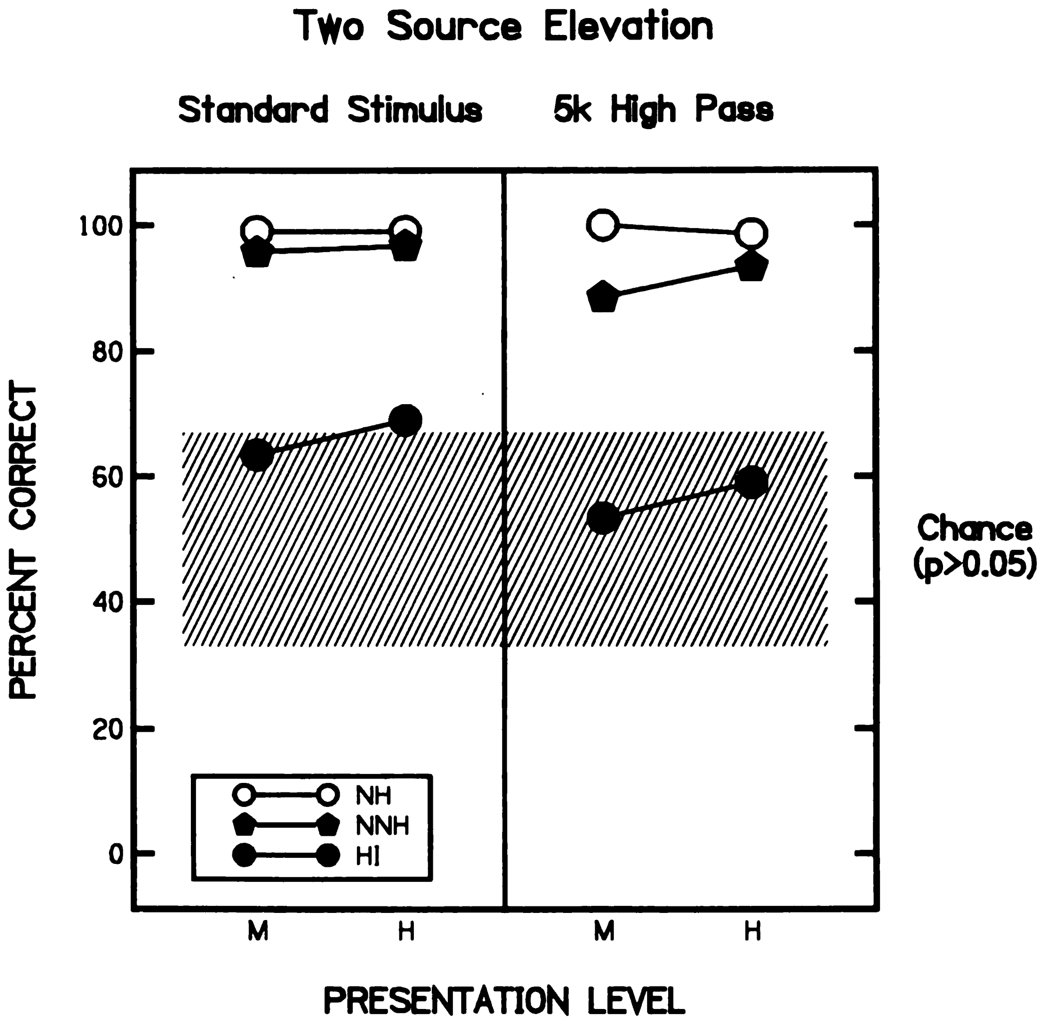


Figure 21: Mean localization performance of the normally-hearing (n=5), near-normally-hearing (n=5), and hearing-impaired listeners (n=16) in the two source elevation tests. The hashed area represents a 5% confidence interval about chance performance (50% correct). The hearing-impaired 5 kHz high-pass means are based on 12 subjects.

<u>NNH Subjects:</u> NNH subjects were generally successful at the ELV2 test, with mean percent correct scores of 95.7% and 96.7% on mid and high presentation levels, respectively, when presented with the standard stimulus. Their performance diminished slightly with the HP noise, but remained well above chance.

<u>Elderly HI Subjects:</u> HI subjects performed ELV2 little or no better than they did ELV3. As a group they were at or near the margins of chance performance with both the standard and HP stimuli.

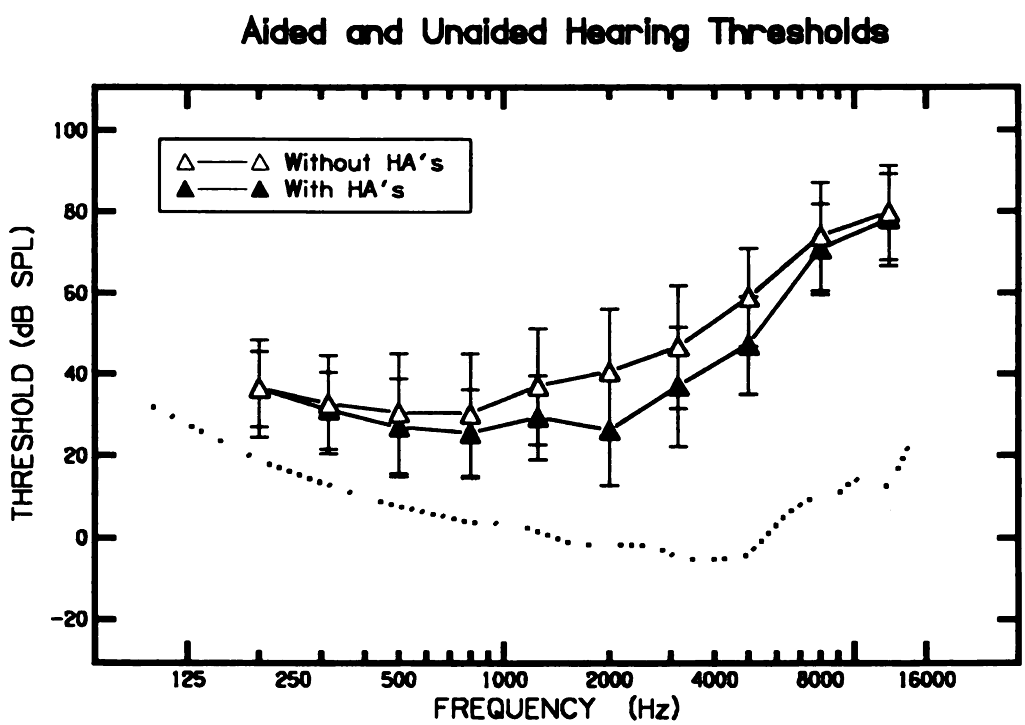


Figure 22: Comparison of (n=11) hearing aided listeners *in situ* hearing threshold measures with and without the use of their hearing aid(s). Hearing aids were adjusted to MCL.

Hearing-Aided Listening

Figure 22 displays aided and unaided group mean hearing thresholds for those subjects (n=10) tested with and without the use of their hearing aids. Subjects received the greatest functional gain at 1250 Hz, 2000 Hz, 3150 Hz, and 5000 Hz. The subjects' mean gain for these four bands was 10.9 dB. Between-subject variation in functional gain was large, with some subjects getting only a few dB of gain, and others getting nearly 20 dB of gain (see below).

Mean localization results for the hearing-impaired subjects, as tested with and without their hearing aid(s), are shown in Figure 23. These data are from the subjects' best presentation level unaided and from their performance when listening at MCL under aided conditions, as noted above. Each panel in the figure represents a different localization test (SAG, ELV3, ELV2).[2] Within each panel, unaided and aided listening group means are plotted with filled symbols for the standard stimulus and open symbols for the HP stimulus. In all, there were eight comparisons of unaided and aided listening (4 tests x 2 stimuli). Listening with a hearing aid produced no statistically significant improvement in group performance in any of the six tests (p >0.05).

---

[2] The subjects also completed FRN tests with and without their hearing aids. Their best level performance unaided was perfect, so wearing a hearing aid could not help them. In general it did not hurt either (mean percent correct hearing aided score was 98.2%).

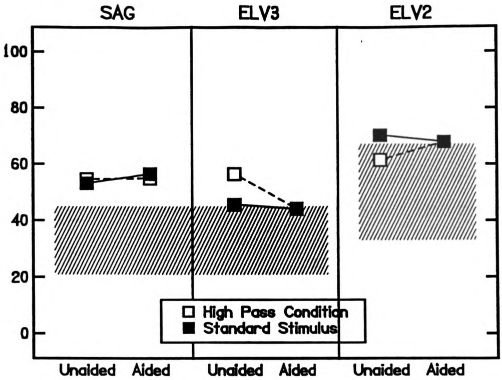


Figure 23: Mean results of hearing-impaired subjects' localization performance on three tests. Tests were done both with and without the use of a hearing aid(s).

Individual Differences. Figure 24 shows the relationship between a subject's hearing-aided functional gain and the localization benefit (if any) afforded by listening with a hearing aid. A difference score (percent correct aided minus percent correct unaided) is plotted for each subject for each of the three tests done with the standard stimulus (SAG, ELV3, ELV2). The plot makes it clear that: (1) wearing a hearing aid was at least as likely to hurt individual performance as help it; and (2) this was the case no matter what the functional gain level of the subject's hearing aid.

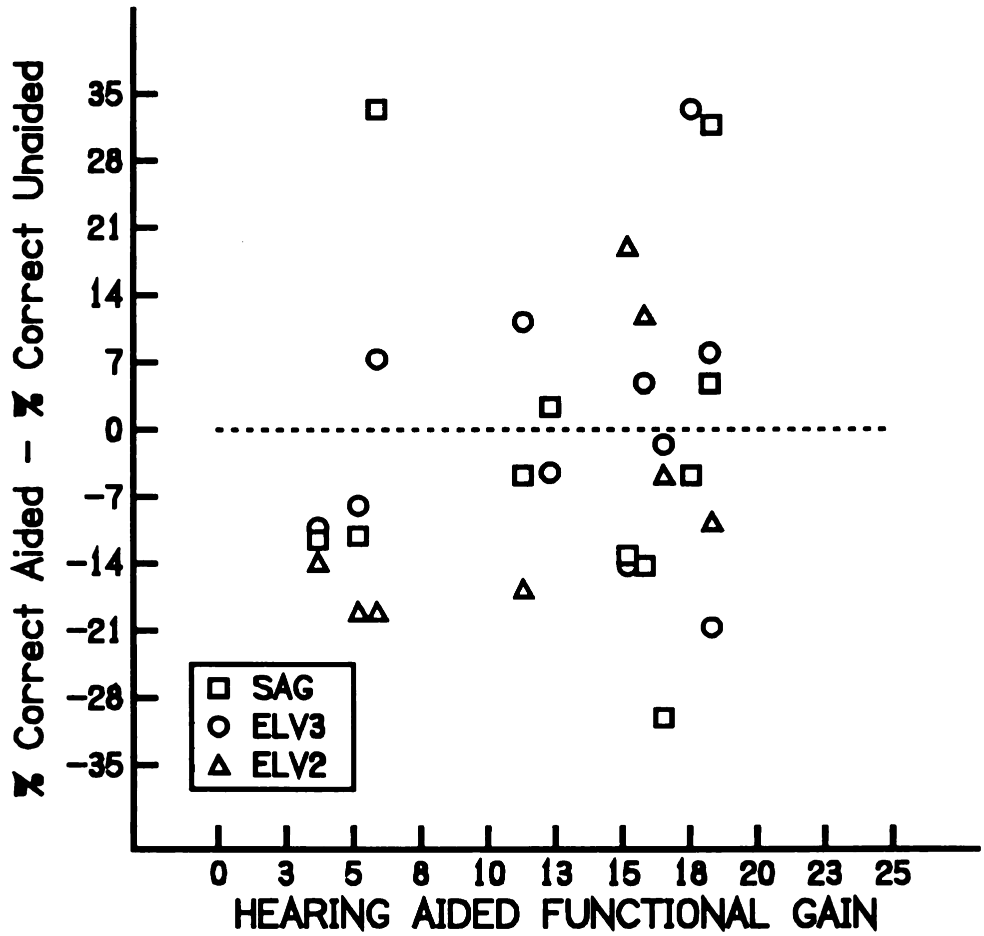


Figure 24: Relationship between hearing aided functional gain and localization performance in three tests as indicated. Functional gain measures are a four frequency average (1250 Hz, 2000 Hz, 3150 Hz, and 5000 Hz) as measured in freefield.

GENERAL DISCUSSION

A common finding among the normally-hearing listeners in both Experiments 1 and 2 was evidence of a decrease in elevation accuracy when the stimulus presentation level was increased. This *negative level effect* is discussed in detail below. Also discussed is a model of spectral localization. The model was originally advanced to account for normally hearing listeners' perceptions of simplified spectra. Its extension to the data of the hearing impaired subjects of this study is considered.

NH LISTENERS: THE NEGATIVE LEVEL EFFECT

Looking across Experiments 1 and 2, eight of 10 NH control subjects displayed some sort of negative level effect at the highest stimulus presentation level. The average level of NH subjects performance declined by about 10.9% (mid-level: 91.1% correct; high-level 80.2% correct) when the stimulus presentation level increased from 66 dB to 84 dB. This effect is reminiscent of one recently reported for normally-hearing listeners localizing click stimuli in the sagittal plane (Hartmann and Rakerd, 1993). With listeners localizing click trains ranging in intensity from 68-98 dB SPL, in a similar front-overhead-rear geometry, Hartmann and Rakerd report nine of eleven listeners were more successful at lower stimulus presentation levels than at higher levels.

They speculated that this negative level effect arose due to the inability of the peripheral auditory system to resolve the spectral details of the clicks, as filtered by the listener's anatomy for front, overhead and rear sound incidence. This failure of the peripheral auditory system may be due to saturation at high levels of stimulation. Localization in the sagittal plane requires resolution of the signal spectrum which is laid out tonotopically along the basilar membrane. The dynamic range of the peripheral neurons is limited and high levels of stimulation may lead to saturation of peripheral excitation patterns, thus "smearing" the neural encoding of relevant spectral cues encoded by the body, head, and pinna transfer functions.

Hartmann and Rakerd found no effect of level on the localization of noise in the sagittal plane. Nor was an effect seen here, in the sagittal tests of Experiments 1 and 2. The negative level effect for noise showed up uniquely in the present elevation tests (ELV3, ELV2). The relevant spectral cues required for accurate elevational judgments are located in the very highest frequencies, at 7 kHz and above (Roffler et. al., 1989), while the cues to front-over-rear judgments reside in the low, mid, and high frequencies. Keeping in mind that due to the tonotopic organization of the cochlea, with higher frequency information encoded at the basilar region, and lower frequencies near the apex, it is reasonable to expect that during periods of intense stimulation, one might experience a greater signal-to-noise ratio in the higher frequencies, encoded in the basilar region, where mechanical energies are at a maximum. It would be reasonable, then, to expect that listeners would be more compromised in their ability to make accurate elevational judgments during periods of intense stimulation, which particularly require resolution of high frequency cues.

An alternative account of why elevation behaves specially is that its spectral codes may be more subtle than those for the sagittal plane overall. Changes in elevation angle produce shifts in the center frequency of a spectral peak and accompanying "notch" (Shaw and Teranishi, 1968; Kuhn, 1979). Subjects may simply find it harder to discriminate those changes than to detect more gross spectral differences associated with the sagittal plane geometry.

HI LISTENERS: A MODEL

Taken together, the results of Experiments 1 and 2 point up a significant sound localization problems for listeners with presbyacusic hearing loss when they must localize on the basis of signal spectrum. In general, the HI subjects' error patterns were consistent with a recent localization model put forth by Asano and colleagues(1990). Based on their experiments with simplified head transfer functions, 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 compromised by the experimenter--or, it appears, in the case of hearing-impaired persons when the listener cannot detect available cues--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. Hearing impaired 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 opportunity to pick-up on what Asano and colleagues call "macroscopic spectral features" that are present at much higher frequencies. When Asano et al. deleted those features from their spectra, normally-hearing listeners made numerous front-back errors. The elderly listeners in this study were clearly compromised in their ability to detect any high frequency macroscopic features present in their inputs. This would seem to explain why they had such difficulty with front and/or rear source location in the sagittal plane.

An as yet unresolved exception to the Asano et al. 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 be badly compromised in their ability to correctly localize the overhead source. But in fact they were not. On the average, the overhead source was perceived more accurately than the front source and nearly as accurately as the rear source. One explanation for this may be that listeners were able to identify the overhead "by default" in a three-alternative SAG task after ruling out the other two possibilities. Alternatively, it may be that some limited 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. This question warrants further investigation.

SUMMARY

The preceding localization experiments showed that elderly listeners, while generally able to make sense of binaural cues when available, are greatly compromised in their ability to make spectrally-cued localization decisions. Elderly listeners rarely performed much above chance in elevational tests, regardless of the presentation level of the stimulus. It appears that listeners with presbyacusic hearing loss have great difficulties in judging the elevation of sound sources because they have little or no access to the spectral elevation cues at commonly occurring sound levels.

Relative to their performance in the elevational tests, elderly listeners were somewhat more successful, in the sagittal plane test, but no subject was as accurate as the young normally hearing adults. A distinct deficit of either a front or a rear sensation was noted for the elderly hearing-impaired subjects in this testing paradigm.

A test of a small group of middle-aged listeners revealed, on average, both auditory thresholds and localization performance that were intermediate to those of younger and older adult subject groups. This suggest that age-related declines in localization performance on spectrally based tasks are likely to be gradual and cumulative.

The above findings make it clear that elderly persons with moderate to moderately-severe sensorineural hearing loss, manifest predominantly in the high frequencies, are very likely to be compromised in their abilities to localize on the basis of spectrum when they encounter sounds in everyday listening.

References

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

Batteau, D.W., (1967). "The role of the pinna in human localization," Proc. Roy. Soc. (Lond. B) 158-180.

Blauert, J. (1969/70). "Sound localization in the median plane," Acoustica 22, 205-213.

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

Butler, R.A., Belenduik. (1977). "Spectral cues utilized in the localization of sound in the median saggital plane," J. Acoust. Soc. Am. 61,1264-1269.

Butler, R.A., Humanski, R.A., (1992) "Localization of sound in the vertical plane with and without high-frequency spectral cues," Perception & Psychophysics, 1951, 51 (2) 182-186.

Hartmann, W.M., and Rakerd, B.S., (1993). Auditory spectral discrimination and localization of clicks in the sagittal plane," J. Acoust. Soc. Am. 94, 2083-2092.

Hausler, R., Colburn, S., and Marr, E., (1983). "Sound localalization in Subjects with impaired hearing," Acta Oto-laryngol. (Stockh), Suppl. 400.

Herbrank, J., and Wright, D.,(1974b). "Spectral cues used in the localization of sound sources on the median plane," J. Acoust. Soc. Am. 56, 1829-1834.

Kuhn, G.F., (1979). "The Pressure Transformation from a difuse sound field to the external ear and to the body and head surface," J. Acoust. Soc. Am. 65, 991-1000.

Lebo, C.P., and R.C. Reddell. (1972). "The presbycusis component in occupational hearing tests," Laryngoscope 82, 1399-1409.

Middlebrooks, J.C., and Green, D.M., (1991). "Sound localization by human listeners," Annu. Rev. Psychol. 42, 135-159.

Mills, A.W., (1958). "On the minimum audible angle." J. Acoust. Soc. Am. 30, 237-246.

Musicant, A.D., and Butler, R.A., (1984b). "The influence of pinnae-based spectral cues on sound localization," J. Acoust. Soc. Am. 75,1195-1200.

Noble, W., Byrne, D., and Bernadette, L., (1994) "Effects on sound localization of configuration and type of hearig impairment" J. Acoust. Soc. Am. 95, 992-1005.

Roffler, S.K., and Butler, R.A., (1968). "Factors that influence the localization of sound in the vertical plane," J. Acoust. Soc. Am. 43, 1255-1259.

Searle, C.L., Braida, L.A., Cuddy, D.R., Davis, M.F. (1975). "Binaural pinna Disparity: another auditory localization cue," J. Acoust. Soc. Am. 57, 448-455.

Sivian, L.D., and White, S.D., (1933). On Minimum audible Fields. J. Acoust. Soc. Am. 4 288-321.

Shaw E.A.G., 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.