Optimizing Sound Localization with Hearing Aids

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INTRODUCTION

At a grant application interview the authors were greeted by the interview panel's spokesman who said: "I'm an eye doctor. Since reading your application, I've been asking my patients: 'Does it matter whether you can tell where sounds are coming from?' and they say it doesn't." This attitude may epitomize how many people regard sound localization. It is such a natural part of living that this ability tends to be taken for granted. Even when problems arise from impaired localization, the affected people may not recognize the source of their difficulties.

Before discussing localization with hearing aids, it is appropriate to briefly review the significance and mechanisms of sound localization and how this ability is affected by hearing impairment. This general discussion will be followed by more specific information about the effects on localization of type of hearing aid, unilateral versus bilateral fitting, choice of earmold type, and possible effects of directional microphones and compression. The issue will conclude with a set of recommendations for how clinical audiologists should consider sound localization and how hearing aids should be fitted to optimize this ability.

Localizing Sounds Does Matter

In the animal world, the ability to localize sounds has obvious survival value. It is vitally important to many animals for avoiding danger and/or finding food. Masterton et al (1969) ascribe a central role to localization in the evolution of hearing systems in animals and humans. They present a good argument for the view that the evolution of auditory systems has been driven primarily by the need to provide effective sound lo-

calization for animals with varying head sizes and living in different environments (air or water). Mammals with small heads and those living in water (e.g. dolphins) receive little interaural time difference information but they hear much higher frequencies than man which provides greater opportunities for localization on the basis of interaural intensity differences. The cues for localization are discussed below. Human survival in urban environments continues to depend on sound localization. There will still be occasions when we need to jump the right way when we hear an approaching car or when we hear a tree or wall starting to fall over. Localization is important for hunting which is still part of survival for some civilizations. If we extend the concept of "survival" to include all forms of responding effectively to other people and our environment, then there are many situations where localization is essential. If we hear someone call, we may need to locate the person quickly. It may be important for their well-being or even survival. If we are awakened by a noise, we may want to know which neighbor to complain to. If we are looking for someone or something, the sounds we hear may be helpful if we can tell where they are coming from. For example, sounds of movement in another room suggest that may be a good place to look for a family member who is wanted on the phone. Knowing where a sound is coming from may help us to identify the sound, just as the reverse is true.

In another context (in relation to experiencing loudness variations), Killian (1997) has aptly pointed out that auditory sensations are essential to aesthetic experience. Localization is a vital part of that experience. We like to locate the bird that is singing in the tree or the animal that is rustling in the bush, even though it is not a danger to us and we have no intention of eating it. Another au-

ditory experience, almost totally ignored, is the externalization of sounds and a natural feeling of spatial orientation. If we wear a pair of earplugs, or tightly fitting earmolds, a common sensation is that somehow sounds are not “out there” in their proper places. This can bring a disconcerting feeling of being isolated from the environment and this is not attributable simply to the attenuation of sound. Localization is part of experiencing the environment in a natural way and this may be very important subjectively, in addition to the more obvious utilitarian purposes of localization.

Under difficult listening conditions, or for a hearing-impaired person, localization can play a vital part in understanding group conversations. When the conversation switches from one person to another, the listeners need to locate the new speaker instantly or they will miss the first part of each segment of the conversation, which may seriously reduce understanding. This is especially so for people with substantial hearing loss who typically rely on a lot of help from speechreading. Impaired localization probably plays a more significant role in speech communication difficulties than is usually appreciated.

It has been suggested (e.g. Hirsh, 1950) that there is a direct connection between the ability to localize sounds and the ability to hear speech in noise. The basis of this argument is that interaural phase differences are cues for both localization and release from masking (i.e. masking level differences). However, no strong link between these abilities has ever been demonstrated and a recent study showed only weak correlations between localization and the ability to separate speech from noise (Noble et al, 1997). This issue requires further investigation and, at present, it seems an open question whether there is any direct connection between impaired localization and difficulty in recognizing speech.

HOW DO WE LOCALIZE SOUNDS?

Mechanisms of Sound Localization

In order to appreciate the experimental results discussed later, it is necessary to understand the mechanisms of sound localization. Therefore, these mechanisms will be reviewed together with indicating how acoustic cues are somewhat interchangeable and how people can adapt to receiving abnormal acoustic information. Localization has a horizontal (azimuth) and a vertical (elevation) component. That is, is a sound to the right or the left

(horizontal) and is it above or below (vertical)? These components need to be considered separately because, for the most part, we use different kinds of information to detect azimuth and elevation.

Horizontal localization depends mainly on interaural difference information, as shown in Figure 1. A sound on the right side of the head will reach the right ear (near ear) a bit sooner than it will reach the left ear (far ear). It will also be slightly louder in the right ear and will have a slightly different spectrum because the head shadow will selectively attenuate the higher frequencies at the left ear. Interaural time differences are usually the most dominant cue for horizontal localization (Wightman and Kistler, 1992) provided that the signal has audible components at frequencies below 1500 Hz. At higher frequencies, phase and time differences in the waveform become ambiguous. However, interaural intensity differences, which occur mainly for frequencies above 1500 Hz, may become the dominant localization cue when time differences are unavailable.

Spectral cues also have some role in horizontal localization especially in discriminating front from rear sound sources (Musicant and Butler, 1984). For example, if a sound is on one side and in front of a listener, the high frequency components of the signal received at the near ear will have a relatively greater intensity than they would if the sound were at the same distance from but to the rear of the listener. Thus, for sounds located at the same elevation, changes in azimuth (horizontal direction) result in changes in the spectrum of the sound received at the near ear because of reflections and shadowing caused by the pinna. Similarly, direction-dependent spectral changes occur at the far ear because of head shadow as well as pinna effects. These spectral changes can provide

Figure 1. Main cues for localizing sounds in the horizontal plane: interaural time and intensity differences. Signals arrive later and are softer in the far ear when compared to the near ear.

a monaural cue for horizontal localization in addition to the binaural cue provided by the interaural difference in the spectra of signals received at the two ears.

The main cue for median plane vertical localization (i.e., facing the sound source) is illustrated in Figure 2. When a sound strikes the pinna (external ear) it is subjected to a complex pattern of reflections which alter the high frequency spectrum of the sound reaching the eardrum. These pinna reflections, and hence the spectrum of the sound in the ear canal, vary with the elevation of the sound source. For example, the most pronounced notch in the ear canal sound spectrum tends to become higher in frequency as the elevation of the sound source becomes greater (Hebrank and Wright, 1974). These elevation-dependent changes in spectrum occur at frequencies above 4000 Hz and provide the major vertical localization cue. When sounds are not in the median plane, interaural time and intensity differences provide additional cues for elevation.

In some circumstances, localization (horizontal and vertical) may be improved if the person's head is moving while listening to a sound. Such head movement provides variations in interaural differences and this is helpful if other cues are missing or ambiguous (any particular interaural time or intensity difference can arise from a range of locations). This dynamic cue (changes in interaural differences) was suggested many years ago (Wallach, 1940) but has been largely discounted in recent literature. However, a recent investigation has demonstrated the reality of the dynamic "Wallach" cue (Perrett and Noble, in press). Such a cue may be useful to people with ski-slope au-

diagrams and good low frequency hearing (Noble, Sinclair and Byrne, 1998).

From the above information it follows that accurate horizontal localization depends primarily on binaural functioning whereas accurate vertical localization depends on having an unobstructed pinna, to permit pinna reflections, and on having sufficient high frequency hearing to be able to detect changes in the spectrum at frequencies above 4000 Hz. These are the essential facts to bear in mind for understanding the effects of different types of hearing aid fittings on localization. More extensive discussions of the mechanisms of auditory localization may be found in various texts including Mills (1972), and Middlebrooks and Green (1991).

Interchangeability of Localization Cues

As indicated above, the cues for horizontal and vertical localization are largely different but they are interchangeable to some extent (Butler, 1987). Thus, spectral cues have some role, although a minor one, in horizontal localization and interaural difference cues have some role in vertical localization. Furthermore, in horizontal localization, intensity differences may become the most dominant cue if time differences are absent or reduced. The dynamic difference cue resulting from head movements appears to assume some importance for certain types of hearing loss, as indeed it does for normal hearing people for determining the elevation of low pass filtered sounds (Perrett and Noble, in press). Thus, for localization, as for some other aspects of auditory functioning, notably speech recognition, there is some redundancy in the auditory information used.

Figure 2. Main cue for localizing sounds in the vertical plane: elevation dependent differences in the high frequency spectrum resulting from pinnae reflections.

Acclimatization Effects in Sound Localization

Do people perform differently with a certain type of sound stimulation after they become used to listening to it? This subject, termed "acclimatization", has received much recent attention especially in relation to speech recognition with different types of amplification (Gatehouse, 1993; Turner et al, 1996). Byrne and Dirks (1996) reviewed the evidence for acclimatization with respect to non-speech abilities, including sound localization. While there are no studies directly examining acclimatization in relation to aided localization, there is reasonable evidence suggesting that some acclimatization can occur. That is, people tend to localize

better with the type of amplification they are accustomed to wearing than with other types of amplification.

The possible significance of acclimatization was revealed in a study with three groups of bilaterally fitted hearing aid wearers, a behind-the-ear (BTE) group, an in-the-ear (ITE) group, and an in-the-canal (ITC) group (Noble and Byrne, 1990; 1991). Localization was evaluated for each subject wearing their own hearing aids and wearing stock versions of the other two types of aids. Acclimatization was evidenced by the fact that the BTE wearers localized best with the BTE (i.e. their own) hearing aids whereas the ITE wearers localized best with the ITE (their own) hearing aids. Byrne and Dirks (1996) review and compare several other studies which, taken together, provide indirect evidence that people adapt to, and localize best with, their own type of hearing aid fitting.

Three studies show how subjects can adapt, or can be trained to adapt to distorted localization cues. Bauer et al (1966) tested localization (horizontal) of normal hearing subjects who wore an earplug in one ear for the duration of the experiment. Initially, localization was severely disrupted; all sounds tended to be perceived as being on the side of the unplugged ear. However, by the end of three days, the listeners' localization had returned to normal or partially so. Furthermore, when the plug was removed, localization was again disrupted, although only slightly, with the majority of sounds being perceived on the previously plugged side. A further period of listening experience was required before localization returned to normal.

The Bauer et al study (1996) showed that adaptation to abnormal intensity differences (i.e. when one ear was plugged) could be reduced from about three days to about half a day when training was provided in the form of repeated localization testing with feedback about the accuracy of responses. Butler (1987) also demonstrated that monaural localization (achieved by wearing an earplug and earmuff combination) can be improved by training. Training on one noise band resulted in improved localization for only that frequency band which suggests that adaptation occurs to a specific type of auditory input, such as might be provided by a particular type of hearing aid fitting.

Florentine (1976) studied median plane lateralization (achieving a centered image) for normal hearing subjects with plugged ears and for listeners with asymmetric hearing losses. She measured (under earphones) the interaural intensity differ-

ence required to produce the perception that the sound was in the center of the head and that required to produce a perception of equal loudness in the two ears. For normal hearing listeners (listening without earplugs), the sound was perceived as being in the middle of the head when the sound was equally loud in both ears. For the hearing-impaired listeners, the sound was perceived as being in the center of the head when the sound was less loud in the more impaired ear. When the normal hearing listeners were tested with one ear plugged, a centered image was achieved initially with equal loudness but, after the people had worn the plug for a time, the centered image was obtained with less loudness in the plugged ear. When the plug was removed, centralization required greater loudness in the ear which had not been plugged but, after a period of adjustment (7–14 days), the lateralization/loudness relationship returned to normal (i.e. centralization required equal loudness in both ears).

The Bauer et al (1966) and Florentine (1976) studies show that normal localization (or lateralization) does not require normal interaural intensity (loudness) differences. Apparently, listeners can adapt readily to receiving substantially abnormal intensity (and possibly abnormal time) difference information. This is consistent with aided localization research, with listeners with mild to moderate hearing losses, which shows that the advantages of bilateral fitting largely disappear at high presentation levels where the listeners can combine the aided hearing in one ear with unaided hearing in the other (Dermody and Byrne, 1975). From the viewpoint of hearing aid fitting, it is very fortunate that it is not necessary to accurately match interaural loudness levels to provide good localization; such matching, across a wide range of input levels, would be very complicated to achieve. The practical implications are that bilateral fittings do not need to provide equal loudness in the two ears and, for mild hearing losses, unilateral fittings may provide good localization because there may be sufficient audible signal in the unaided ear to permit binaural functioning.

EFFECTS OF HEARING IMPAIRMENT ON SOUND LOCALIZATION

Do Hearing-impaired People Experience Localization Difficulties?

The next section will be concerned with how different types of hearing loss affect sound local-

ization, as shown by experimental studies. But first, if localization is so important, why aren't people bursting through the clinic doors complaining of difficulties in localizing sounds? Although there have been some reports of complaints of localization difficulties (Barcham and Stephens, 1972; Hausler et al, 1983), such problems do not often figure prominently in the spontaneous complaints of hearing-impaired people. It was suggested above that impaired localization may often contribute to difficulties hearing in group situations. However, the complaint will probably be something like: "I have difficulty hearing in meetings" rather than the more analytical comment that "I have difficulty at meetings because I miss things while trying to locate who is talking." Localization difficulties do become apparent when people are asked about them specifically. In studies with questionnaires containing localization questions (Noble and Atherley, 1970) scores on those questions correlate highly with other aspects of hearing disabilities and handicap, as measured by the rest of the questionnaire. When people with various types of hearing aids are asked about localization, differences favoring certain types may emerge (Mueller et al, 1995; Kochkin, 1996), suggesting that hearing aid wearers do notice differences in localization ability.

Localization difficulties, as experienced by hearing-impaired people, were assessed by administering a questionnaire to groups of hearing aid users and normal hearing people (Noble et al, 1995). The questionnaire included items about localizing sounds in various situations and about the ability to hear speech, mainly in group or noisy situations. An example of a "localization" question is: "You are outside. A dog barks loudly. Can you tell where it is without having to look?" An example of a speech hearing question is: "You are at a gathering or in a club. There are many people about and it is noisy. You are with a group of people having a conversation. Can you follow the conversation?" The complete questionnaire is reported as an appendix to Noble et al (1995). Abilities were rated on a scale with "4" representing little or no difficulty (can nearly always localize) and "1" representing little or no ability to localize or hear speech (almost never) in the stated situation. The hearing-impaired people rated their abilities for both aided and unaided listening. The localization results are summarized in Figure 3 which shows mean ratings for eight questions, for three groups of subjects. There were 10 normal hearing subjects and 104 subjects with bilaterally

Figure 3. Ratings (mean and + 1 SD) of sound localization ability on eight tasks by groups of people with normal hearing and two degrees of hearing-impairment (four-frequency average HTLs less than or greater than 50 dB). Bars indicate one SD and arrows show where the mean rating plus one SD exceeded the maximum rating of "4". Reprinted with permission from *J Am Acad Audiol* (Noble et al, 1995).

symmetric hearing loss. The hearing impaired group was divided into those with four frequency average (4FAHL - 500, 1000, 2000, 4000 Hz) hearing levels (HL) of less than 50 dB and greater than 50 dB.

It is evident from Figure 3 that, for every situation, the hearing-impaired groups rated their localization as poorer than the normal hearing group and that the more severely impaired group (4FAHL >50 dB) rated their localization as poorer than the less severe group (4FAHL <50 dB). This study confirms that hearing impaired people do experience localization difficulties and that the degree of difficulty increases for increasing hearing loss. An intriguing finding, but one which is open to varying interpretations, was that the ratings of localization difficulty (mean rating for eight questions) showed a moderate correlation with ratings of speech hearing difficulty (mean rating for nine questions), once the effect of hearing level had been controlled for (partial $r = .56$).

A further finding of the Noble et al (1995) study is that increased localization disability was associated ($r = 0.55$) with greater experiences of "handicap"—for example, nervousness in, avoidance of, and desire to escape from situations in which sounds were confusing. This finding echoes one reported by Eriksson-Mangold and Carlsson (1991) in which bodily symptoms of anxiety were associated with localization disability as assessed using the Hearing Measurement Scale (Noble and Atherley, 1970).

Experimental Studies of Localization Difficulties

Measuring the Ability to Localize Sounds

Many studies have measured the sound localization abilities of normal hearing and/or hearing impaired people. A few studies have examined specifically how sound localization ability is affected by hearing loss (reviewed in Noble et al, 1994). Measurement methods have varied in detail but such variations do not alter any of the general findings to be reported in the following sections. The arrangement used in some recent studies (Byrne et al, 1998; Noble et al, 1998) is shown in Figure 4.

The main item of special equipment is an array of 20 loudspeakers. These are arranged in a horizontal arc and a vertical arc which form the circumference of a sphere. When the subject is seated

with his or her head in the center of the sphere, the mid-point of the head is 1.1 m from each loudspeaker. The horizontal arc contains 11 loudspeakers positioned from 90 degrees to the left of the subject to 90 degrees to the right. The vertical arc has only 10 loudspeakers as there is no loudspeaker in the position directly below the subject. Loudspeaker #15 is common to both arcs. The other items of equipment are: 1) a tape recorder and a recording of interrupted pink noise (random noise with equal energy in each third-octave band), 2) an amplifier, 3) an attenuator, 4) a computer-controlled switching box, and 5) a personal computer. Other equipment consisted of an intercom unit and a video camera and monitor for observing and communicating with the subject. A test run consisted of presenting a 0.83 sec burst of pink noise

Figure 4. Test array used in several localization studies (e.g. Byrne et al, 1998; Noble et al, 1998). A horizontal arc of 11 loudspeakers forms the circumference of a circle with a radius of 1.1 m. The subject is seated on a chair with its height adjusted so that the subject's ears are level with the horizontal loudspeakers. There is a vertical arc of the same size but containing only 10 loudspeakers as there is no loudspeaker directly below the subject. Bursts of noise are presented in random order from each loudspeaker and the subject judges which location was the sound source. For some testing, the subject faces the array and for other tests is turned sideways to the array. In this picture the subject (right) is being prepared for aided testing. The cross shaped "map" to the left of the array is an aid to remembering the loudspeaker positions when the subject is sideways to the array.

(pulsed four times) from each of the 20 loudspeakers in a random order. The subject's task was to say which of the loudspeakers, each identified by a number, was judged to be the source of the sound.

Various forms of scoring have been used to characterize localization ability. The most simple method is to count the number (or percentage) of correct responses (e.g. see Figure 6). A "horizontal" percent correct score is the percent of correct responses when sounds were presented from the loudspeakers in the horizontal arc. Similarly, the vertical score is the percent of correct responses when sounds were presented from the vertical arc of loudspeakers. This form of scoring takes no account of the size of errors. Therefore, a subject who makes small errors, i.e. selects loudspeakers just one or two positions removed from the sound sources, will get the same score as someone who makes an equal number of larger errors, i.e. is incorrect by three or four loudspeaker positions. To make the scoring more sensitive, most studies have used a scoring system that takes account of both the number and size of errors. The systems used have varied from study to study and are complicated to describe. Therefore, the reader should consult the relevant references for details. For the data shown in the figures of this article, except for Figures 6 and 13, "0" error score indicates perfect localization and 30–40 is a chance score (i.e. the score to be expected from guessing). The chance score varies from one study to another as the scoring method was varied and the chance score may also vary for horizontal compared to vertical localization because there is one more loudspeaker in the horizontal arc.

The array shown in Figure 4 can be varied to include more or fewer loudspeakers or by the addition of dummy loudspeakers to provide more response options (Noble et al, 1997). In some test arrangements (e.g. Markides, 1977) the loudspeakers have been hidden by a curtain to avoid limiting the number of response options. Other arrangements have used a single hidden loudspeaker that is mounted on a boom and is moved between sound presentations. In some studies (e.g. Orton and Preves, 1979) loudspeakers have been placed in a horizontal circle around the subject. That arrangement permits errors in judging sounds from the front to be from behind or vice versa. Such front/rear confusions can also be studied with the array shown in Figure 4 but with the subject turned sideways to the array instead of facing it. The above information is not an attempt to review localization testing methods but it may help the

reader to understand some of the data presented in the following sections.

Effects of Hearing Loss on Sound Localization

As indicated above, people with hearing losses experience difficulties with localizing and those with greater hearing loss experience greater difficulty than those with milder hearing loss. Several experimental studies (testing only horizontal localization) confirm that hearing impaired listeners have reduced localization ability (reviews in Durlach et al, 1981; Hausler et al, 1983; Noble et al, 1994). The effects of hearing loss for 66 subjects with sensorineural hearing losses and 21 subjects with conductive or mixed hearing losses were examined by Noble et al (1994). The findings, which have been confirmed by later research (Noble et al, 1997), are summarized schematically in Figure 5.

The effects of hearing loss on localization differ for horizontal (left graph) and vertical (right graph) localization and depend on degree of hearing loss, which frequency regions are affected (low or high frequencies), and type of hearing loss. Horizontal localization deteriorates with increasing hearing loss at the low frequencies (below 1500 Hz). The Noble et al (1994) study showed

Figure 5. Schematic summary of the effects of sensorineural and conductive/mixed hearing loss on horizontal and vertical sound localization. The main trends are: horizontal localization decreases as hearing loss at the low frequencies (<1500 Hz) increases (left panel); vertical localization decreases as hearing loss at the high frequencies (>4000 Hz) increases (right panel); horizontal localization is poorer for conductive/mixed hearing loss than for sensorineural hearing loss (left panel). The figure provides only a broad indication of the trends shown by data reported in Noble et al (1994; 1997). The correlations between hearing level and localization are only moderate and data for conductive mixed loss are limited.

a correlation of about .4 between horizontal localization and hearing level at 500 Hz or 1000 Hz. This is consistent with the theory that the low frequencies are most important for detecting interaural time differences and that the mid frequencies (1500–4000 Hz) are more important for detecting intensity differences. For mild sensorineural hearing losses (<50 dB HTL), horizontal localization is usually only slightly impaired but it may become severely disrupted for greater hearing losses.

People with conductive or mixed hearing loss have significantly greater localization difficulties than people with a similar degree of sensorineural hearing loss. This is illustrated schematically in Figure 5 and with data in Figure 6 which compares localization performance for 13 pairs of subjects with conductive/mixed hearing loss versus subjects with sensorineural hearing loss, matched with respect to four-frequency average (500, 1000, 2000, 4000 Hz) hearing level. The data are reported as the percent of correct responses when sounds were presented from the horizontal loudspeakers and when sounds were presented from the vertical loudspeakers, with the central loudspeaker (#15) counted as being in the vertical arc. The poorer performance of the subjects with conductive/mixed loss arises because a larger proportion of sound is transmitted to the cochleas by bone conduction, compared with air conduction, than occurs for people with normal hearing or

sensorineural hearing loss. As bone conducted sound travels to both cochleas, regardless of the site of stimulation, there is a reduction of the normal interaural time and intensity difference information. In other words, both cochleas tend to receive the same information rather than different information.

As Figure 5 illustrates, vertical localization decreases as hearing loss at the high frequencies (6000 Hz and 8000 Hz) becomes greater. For the test procedure described above, the percent correct score of normal hearing listeners is usually 70–75% and there is typically very little vertical localization ability when hearing level at 6000 Hz exceeds about 30 dB. This is true for sensorineural and conductive/mixed hearing loss. This suggests that people with hearing loss will usually have much poorer vertical than horizontal localization, the only likely exceptions being people with normal hearing at the high frequencies (above 4000 Hz) and a significant hearing loss at the lower frequencies. It has been a consistent finding (Byrne et al, 1992; Noble et al, 1994) that vertical localization is significantly (and greatly) poorer than horizontal localization for most subjects with hearing loss. This is shown in Figure 6 and in some of the later figures.

The comments above are based on tests in which sounds were presented at the most comfortable listening level (MCL) (i.e. at clearly audible levels). In real life, localization difficulties are compounded by the fact that some sounds will be inaudible or barely audible. Furthermore, localization of audible sounds is only moderately predictable from hearing level. The correlations between localization and hearing level at various frequencies are only low or moderate, never exceeding .65 and mostly being <0.5 (see Figure 3 on Noble et al, 1994). The lines shown in Figure 5 give only a general indication of trends. They involve a considerable degree of extrapolation and interpolation especially for conductive/mixed hearing loss as there are limited or no data for some hearing level ranges. Despite these cautions, the general trends seem clear as the Noble et al (1994) findings have been confirmed by Noble et al (1997). They are consistent also with earlier research showing moderate correlations between localization performance and hearing level (Hunig and Berg, 1990; Proschel and Doring, 1990) and with earlier conclusions that localization is more adversely affected by conductive/mixed loss than by sensorineural loss (Durlach et al, 1981; Hausler et al, 1983).

Figure 6. Comparison of sound localization ability for pairs of people with sensorineural versus conductive/mixed hearing losses, matched for four-frequency average hearing level.

HOW HEARING AIDS AFFECT SOUND LOCALIZATION

General Effect of Aiding

Some effects of wearing a hearing aid are due to providing amplification. Other effects are the result of factors such as precluding the normal pinna reflections by obstructing the ear with an earmold. In the following sections, the particular effects of different factors will be discussed. In other places, the term “aiding” will be used when discussing the overall effects of wearing a hearing aid. When listeners are asked to rate unaided and aided localization, aided localization is usually rated better (Noble et al, 1995). Apparently, improved audibility is an important factor because this finding is at variance with tests of unaided versus aided localization when all sounds are presented at clearly audible levels. For listeners with predominantly sensorineural hearing loss, aided horizontal localization tends to be somewhat poorer than unaided (Markides, 1977; Orton and Preves, 1979; Noble and Byrne, 1990; Byrne et al, 1992) and aided vertical localization is much poorer for those listeners who have reasonable unaided vertical localization and are fitted bilaterally with occluding earmolds (Noble and Byrne, 1990; Byrne et al, 1992).

From the previous discussion, it should be obvious why aiding eliminates vertical localization ability. The main reason is that the earmolds fill the structure of the outer ears and distort the pinna reflections which provide the main cue for vertical median plane localization. Furthermore, there is little possibility of hearing the high frequency sounds which are most affected by the pinna reflections; hearing aids provide little amplified sound above 6000 Hz and the earmolds tend to attenuate any unamplified high frequency sound. The slight deterioration in aided horizontal localization, found across several experiments, is more difficult to explain and apparently occurs only for some hearing aid wearers (Noble, Sinclair and Byrne, 1998). The most likely explanation is a distortion of interaural time difference information. In particular, when low frequency hearing is reasonably good, the audible signal will be a mixture of amplified and unamplified sound. In this situation, the small time delay occurring while the sound passes through the aid may result in a difference in the phase between the amplified and unamplified sound, and hence possible gross distortions of interaural time differences (Noble, Sinclair and Byrne, 1998).

For conductive and mixed hearing losses, aiding may improve horizontal localization (Byrne et al, 1995; Byrne et al, 1996). Recall that these types of hearing losses create special difficulty for localizing because the higher proportion of bone conducted sound reduces interaural time and intensity difference information. Apparently, aiding can improve localization by increasing the proportion of air conducted sound relative to that of bone conducted sound. In one study of 19 subjects with conductive or mixed hearing losses, aided localization was significantly better than unaided localization for about half of the subjects, and was about the same for the other half (Byrne et al, 1996). Furthermore, for some subjects the effect of aiding was dramatic. For two of these 19 subjects, there was virtually no unaided horizontal plane localization ability (i.e. their scores were equivalent to what would be expected by chance) whereas aided localization was nearly perfect.

How is Sound Localization Affected by Type of Fitting (Unilateral versus Bilateral)?

When audiologists consider sound localization, it is usually as a justification for bilateral aid fitting. Although bilateral fitting frequently does optimize localization, it is naive to assume that two aids will always mean good localization and one aid will always mean poor localization. The situation is more complicated than that; unilateral fittings can sometimes provide good localization and the advantage of bilateral fitting may depend on using a particular type of earmold. In the following discussion hearing aid fittings will be designated “unilateral” and “bilateral” rather than “monaural” and “binaural”. A fitting with one hearing aid (i.e. a unilateral fitting) does not necessarily result in monaural hearing and a fitting with two hearing aids does not necessarily provide binaural hearing. For example, fitting both ears will not provide binaural hearing if one ear is “dead” and may not do so if one ear is greatly poorer than the other. There may also be cases where central auditory problems preclude effective combination of information from the two ears or, in fact, where the information from one ear interferes with, rather than complements, the information from the other ear. Furthermore, binaural hearing is possible with a unilateral fitting provided there is reasonably good hearing in the unaided ear. Our aim should be to provide binaural hearing rather than simply to fit two hearing aids. This may affect the choice of unilateral or bilat-

eral fitting and it may affect the specific ways the hearing aids are fitted.

This section will summarize what research shows about the relationships of type of fitting to aided localization. It should be stressed that this is not a discussion of unilateral versus bilateral fitting as such. That decision will consider factors additional to localization, notably the importance of avoiding head shadow effects. It is probably true, however, that optimizing localization should tend to optimize other abilities that depend on binaural processing.

A number of studies have shown that bilateral fitting typically provides superior horizontal plane localization when compared to a unilateral fitting (DiCarlo and Brown, 1960; Byrne and Dermody, 1975; Dermody and Byrne, 1975; Heyes and Ferris, 1975; Markides, 1977; Sebkova and Bamford, 1981; Noble and Byrne, 1991). Such studies have not analyzed the effects of hearing level and have not controlled for possible acclimatization effects. As the same subjects were tested with bilateral and unilateral fittings, there may have been a bias in favor of the bilateral fittings because this is what the subjects had experienced, in most instances. Mindful of possible acclimatization effects, we compared the localization performance of groups of experienced unilateral and bilateral hearing aid wearers, all tested with their own hearing aid fittings (Byrne et al, 1992). As the results of this comparison depended on hearing level, each of the hearing aid fitting groups was divided into two, according to whether the four-frequency average (4FA) hearing level (500, 1000, 2000, and 4000 Hz) was less than or greater than 50 dB. There were eight groups (4–20 listeners in each group) derived from two types of fitting (unilateral, bilateral) times two aid types (BTEs, ITEs) times two degrees of hearing level (<50 4FA, >50 4FA). Each subject was tested at two presentation levels (MCL, and midway between threshold and MCL) for horizontal and vertical localization facing a loudspeaker array (forward orientation) and turned sideways to the array (lateral orientation). Figure 7 shows the results for the horizontal forward orientation condition.

Consider the left panel of Figure 7. This shows the results for the listeners with 4FA hearing levels less than 50 dB. As the data are in error scores, "0" indicates perfect performance. It can be seen that for both the unilateral and the bilateral groups, for ITE and BTE fittings at both presentation levels, horizontal localization is good but not perfect (scores are ≤ 10). In the present con-

Figure 7. Comparison of horizontal localization ability for bilateral versus unilateral fittings, for BTE versus ITE hearing aids, and for two presentation levels. Reprinted (modified) with permission from *J Am Acad Audiol* (Byrne et al, 1992).

text, the most significant point is that, on average, the unilateral groups localized just as well as the bilateral groups. The right panel of the figure reports a different finding. For listeners with hearing levels over 50 dB, the unilateral groups had substantially impaired localization whereas the bilateral groups localized much better, indeed almost as well as the listeners with less impairment. The relatively good performance of the unilateral ITE group at the higher presentation level (1/2 MCL) probably occurs because the ITE groups had less severe hearing loss (53 and 54 dB compared with 62 and 64 dB) than the BTE groups.

The interaction of hearing level with the effect of unilateral versus bilateral fitting is illustrated in Figure 8. This shows how horizontal localization deteriorates (i.e. error score increases) with increasing hearing level for unilateral and bilateral fittings. The data are for BTE fittings and the MCL presentation level. Similar findings were reported for ITE fittings and/or the lower presentation level (Byrne et al, 1992). For mild hearing loss (up to 40–50 dB), localization is relatively good for most subjects, whether fitted unilaterally or bilaterally. For greater hearing loss, localization deteriorates rapidly with increasing hearing level for unilateral fittings but deteriorates more slowly for bilateral fittings. Thus, only bilateral fitting maintains fairly good horizontal localization for moderate or severe hearing loss.

The most surprising result of this study is that, for mild hearing loss, unilateral fittings provided equivalent (excellent for most individuals) localization compared to bilateral fittings. This is in

Figure 8. Illustration of how type of fitting (bilateral versus unilateral) affects horizontal sound localization (for BTE aids with sounds presented at MCL) as HTL increases. The closed and open circles show individual data (localization error score versus 4FA HTL) for 35 bilaterally and 23 unilaterally fitted subjects, respectively. The solid and broken lines are the regression lines for predicting error score from HTL for bilateral and unilateral fittings, respectively. Reprinted (modified) with permission from *J Am Acad Audiol* (Byrne et al, 1992).

contrast to previous studies, some of which (e.g. Dermody and Byrne, 1975) involved mainly subjects with mild to moderate hearing losses. This suggests that acclimatization was a factor; the experienced unilateral hearing aid users performed better than would be expected from previous research with subjects who were not experienced with unilateral fittings. The unilateral and bilateral mild hearing loss groups of the present study had, on average, equivalent aided localization as well as being equivalent with respect to hearing loss and unaided localization. This suggests that, given aided listening experience, either all listeners with mild hearing loss will localize similarly with unilateral or bilateral fittings or that some will localize better with a unilateral fitting while others will localize worse. This, in turn, suggests that if there are some benefits from bilateral fitting, then there must also be disadvantages for some people. Such disadvantages may be related to some distortion of time difference information occurring more when both ears, rather than one,

are aided. A deterioration in vertical localization is understandable if there is reasonable unaided localization and a bilateral fitting results in blocking both pinnae with earmolds. These comments apply to fittings with closed (occluding) earmolds. Later it will be explained how it may be possible to overcome any disadvantage of bilateral fitting (while retaining the advantages) by using open earmolds.

The localization results support the already strong case for bilateral fitting of people with moderate or severe hearing losses. With a unilateral fitting, such people will almost certainly suffer a significant loss of horizontal localization. The localization findings are less clear-cut for people with mild hearing losses. For such people, localization may not be the main consideration when deciding whether to fit bilaterally.

Which Types of Hearing Aids Provide Best Localization?

There is considerable research on localization performance with body, BTE, ITE aids, and ITC aids. Also, there is a small amount of information on localization with completely-in-the-canal (CIC) hearing aids. Which type of hearing aid provides the best localization? Does it make any difference?

Some of the earlier studies examined localization with body worn aids. Such aids were in common use 20–25 years ago especially with hearing impaired children. Owing to the position in which the aids were worn and the absence of head shadow, it was not self-evident that bilaterally fitted body worn aids could provide effective localization. However, studies by Byrne and Dermody (1975), Heyes and Ferris (1975) and Markides (1977) showed conclusively that relatively good horizontal localization could be achieved by moderately and severely hearing impaired listeners wearing two body-worn aids. For best results, the aids should be separated by 6–7 inches (i.e. about as far apart as the ears) and, when this was done, localization performance was similar to that with bilateral BTE aids (Byrne and Dermody, 1975). If the aids are positioned too close together, all sounds tend to be perceived as being directly in front, whereas, if they are positioned too far apart (only possible on a large body), a disproportionate number of sounds are perceived as being to the extreme right or left. In the Byrne and Dermody (1975) study, localization was always poor with a unilateral body worn fitting although there was a tendency for it to improve at high presenta-

tion levels. This indicated that even these moderately to severely hearing impaired listeners had some capacity to combine the aided information with any audible signal in the unaided ear.

Several studies have compared localization with BTEs and ITEs and some have found ITEs to be superior (Orton and Preves, 1979; Westerman and Topholm, 1985; Turk, 1986). The superiority has been attributable to one type of localization error, namely that there are fewer front/rear confusions with ITEs. The better performance with ITEs occurs because the shadow effect of the pinna changes the spectrum and loudness of sounds from rear sources relative to that of sounds from the front. This assists performance in a test where all sounds are presented at the same intensity. This "advantage" may not occur in real life because, when people are trying to locate a sound, they do not know how loud it would be if it came from a different direction. One study compared BTEs and ITEs in a situation which permitted front/rear confusions but in which the intensity difference cue was removed by varying presentation levels by ± 3 dB around the nominal level (Byrne et al, 1992). The results of this comparison are summarized in Figure 9. Performance was equivalent for both types of aids (BTE and ITE) when differences in unaided performance were

Figure 9. Comparison of sound localization ability, horizontal and vertical, for BTE and ITE hearing aids. (ITE scores adjusted by the difference between unaided scores for the two aid types.) The numbers of subjects with each type of fitting are: unilateral BTE = 23; unilateral ITE = 17; bilateral BTE = 35; bilateral ITE = 12.

accounted for. (i.e. the ITE wearers had better unaided performance and the aided scores were adjusted by the difference in unaided scores for the two aid types.) A previous study had also shown no difference for aid type (Noble and Byrne, 1990) but the test procedure did not permit front/rear confusions. That study included a group of ITC aid wearers as well as groups of ITE and BTE wearers.

From surveys, Mueller et al (1995) and Kochkin (1996) concluded that CIC hearing aid users were significantly more satisfied with sound localization than were users of other aid types. Mueller and Ebinger (1997) summarize data from a study that showed superior vertical localization with CIC hearing aids compared to ITE hearing aids. Figure 10 presents average data for four CIC hearing aid users for whom localization was tested with their own hearing aids and with temporarily fitted BTE aids.

The left panel of the figure suggests that, for horizontal localization, the CIC is slightly poorer than unaided performance but better than BTE performance. All three conditions are equivalent for vertical localization. Considerable caution is needed in drawing any conclusions from these data. First, although the CIC appears distinctly better than the BTE for horizontal localization, the difference is not statistically significant at the 95% confidence level. (Note, there were only four listeners in the sample; the effect of aid condition [unaided, BTE, CIC] had a "p" value of .085). Second, any acclimatization is in favor of the CICs as these subjects had all worn CICs for at

Figure 10. Comparison of sound localization ability, horizontal and vertical, for unaided, CIC and BTE hearing aids. (Note: there are only four listeners and all were experienced CIC wearers. Because of large individual variability, the difference in horizontal localization between the CIC and BTE condition is not significant at the 95% confidence level.)

least several months and did not use the BTEs except for the experiment. Third, the lack of any difference in vertical localization is understandable as all these subjects had fairly poor high frequency hearing. It is possible that the CIC might show an advantage if used with listeners with better high frequency hearing. However, it is doubtful whether the frequency response of most current CIC aids extends to sufficiently high frequencies to provide good vertical localization.

In summary, a possible localization advantage for CIC aids, over other aid types, merits further study. Otherwise, hearing aid type does not appear to affect localization ability.

OPTIMIZING AIDED SOUND LOCALIZATION

Choice of Earmold: Conductive and Mixed Hearing Loss

As noted above, aiding can improve horizontal sound localization for people with conductive or mixed hearing loss, presumably by increasing the proportion of air-conducted to bone-conducted sound transmitted to the cochleas. This effect could vary for different types of earmolds, depending on the rigidity of the coupling to the ear and the proximity of the tip of the mold to the eardrum. To examine this possibility, 19 subjects with conductive or mixed hearing loss were evaluated for unaided localization and when aided, bilaterally, with three types of earmolds (Byrne et al, 1996). One earmold was made from hard acrylic and had a canal length of about 8 mm. This was designated the “hard/ short” (HS) earmold. A second earmold had the same length canal, but was made from silicone rubber. This was the “soft/short” (SS) earmold. The third earmold was made of silicone rubber and had a canal length of 16 mm. This was the “soft/long” (SL) earmold. The results of this study are summarized in Figure 11.

The left panel of Figure 11 shows the average results for the nineteen subjects and the right panel shows the results for Subject 8. On average, aided localization with any of the three earmolds resulted in only about half as many errors as unaided (UA) localization. Also, for the group, aided performance was equivalent for the three earmold types. However, for some subjects, performance varied across earmold type. Such a case is illustrated in the right panel of this figure. This also illustrates that aiding can make a very dramatic difference for some subjects. For this sub-

Figure 11. Effects of earmold type (UA = unaided; HS = hard material, short canal; SS = soft, short; SL = soft, long) on horizontal localization by subjects with conductive/mixed hearing loss. Left panel shows group average results ($n = 19$), right panel presents an illustrative case. (Chance performance is an error score of 40.) Reprinted (modified) with permission from *Ear Hear* (Byrne et al, 1996).

ject, unaided localization was no better than chance performance whereas aided localization was perfect with the SL earmold and satisfactory with the other two earmolds.

From a practical viewpoint, it is not possible from present knowledge to predict which earmold type will be best to improve localization for each individual. This is not surprising considering that the proportion of air conducted to bone conducted sound reaching the cochleas is probably determined in a very complex manner by interactions of properties of the earmold, properties of the ear canal and skull, and hearing loss. It is not clear whether there will be any practical way to make the desired predictions. This issue will be pursued in future research. Audiologists should bear in mind that any change in earmold may significantly affect localization, for better or for worse. Although it would incur some trouble and expense, there may be circumstances where experimentation with different earmolds should be considered to optimize localization for people with conductive or mixed hearing losses.

Choice of Earmold: Sensorineural Hearing Loss with Good High Frequency Hearing

As mentioned earlier, some listeners with sensorineural hearing loss have reduced localization ability when aided, compared with unaided localization, for sounds at clearly audible levels. Furthermore, experienced hearing aid users with mild hearing loss localize just as well, on average, with

a unilateral fitting as with a bilateral fitting. Probably some of these listeners do better with the unilateral fitting while others do worse. These findings suggest that, in some respects, unaided localization is superior to aided localization. We reasoned that it might be possible to get “the best of both worlds” (i.e. the advantages of aided and unaided hearing) by using open earmolds. Such a mold will provide both an amplified and unamplified signal within the one ear or, with a bilateral fitting, in both ears. The possible advantages of open earmold fittings were evaluated for two types of sensorineural hearing losses which, for different reasons, might be expected to achieve improved localization.

One group are listeners with moderate low frequency and mid frequency hearing loss combined with good hearing at frequencies above 4000 Hz. In contrast to other types of hearing loss, such listeners usually have good unaided vertical localization (Noble et al, 1994). When aided, they lose this ability, presumably mainly because the earmold fills the ear and thereby precludes any pinna reflections, but possibly partly because the earmold provides some attenuation of unaided high frequency sounds. As a non-occluding earmold could permit pinna reflections and normal, unamplified high frequency sound, this type of fitting should restore vertical localization to the unaided performance level. At the same time, a bilateral fitting with open earmolds would provide the benefits of bilateral amplification of the low frequency and mid frequency sounds. An open earmold results in reduced low frequency amplification but this can be offset by increasing the electrical gain of the hearing aid to provide the required real-ear gain.

In one study, localization with open earmolds was evaluated for 22 hearing impaired subjects with good high frequency hearing (Byrne et al, 1998). Aided localization was tested for bilateral BTE fittings with a commercial “open” earmold, which partly occludes the ear canal and concha, and with a specially developed “sleeve” earmold which is completely non-occluding. The “open” earmold, a modified form of what is sometimes called a “G-mold”, consisted of a half-ring shaped structure that fits within the concha and an 8 to 10 mm canal section just thick enough to contain a length of 2 mm tubing connecting to the hearing aid. This type of earmold obscures the lower part of the ear canal entrance and part of the concha bowl. The “sleeve” earmold was a thin plastic ring about 4 mm long that fitted into the outer end of the ear canal. This secured the sound delivery tube that extended 8 to 10 mm into the ear canal.

Figure 12. Illustration of the clinical version of the sleeve earmold. (This is slightly different from the earlier research version.) The earmold fits entirely within the ear canal except for a 1 mm wide flange at the outer end. This earmold has walls that are only 0.5 mm thick and provides no significant occlusion of the ear. (Construction details are at the end of this section.)

A sleeve earmold is illustrated in Figure 12 and details of its construction will be described at the end of this section.

The right panel of Figure 13 presents the test results for horizontal and vertical plane localization for 22 listeners facing the loudspeaker array and for a presentation level of 65 dB SPL, which was audible to all listeners unaided. The results are shown for all 22 subjects (solid line) and the 11 listeners (dashed line) who had the best high frequency hearing (≤ 20 dB HL at 4000–8000 Hz). The average audiograms of the two groups are shown in the left panel of Figure 13. The data are plotted as mean error scores and the results of most interest are for vertical localization, shown by the two highest lines of the right panel of Figure 13. As a group, vertical localization is significantly poorer for the closed earmold than unaided performance; it is improved, compared with the closed condition, for the open earmold (OP) and even more so for the sleeve earmold (SL). These trends are stronger for the group of 11 listeners (dashed line), indicating that the subjects with the best high frequency hearing received the most benefit from using the open and

Figure 13. Effects of earmold type (UA = unaided; CL = closed; OP = open; SL = sleeve) on horizontal and on vertical sound localization for subjects with moderate low-frequency hearing losses and good high frequency hearing. Localization data and audiograms are shown (solid lines) as a group ($n = 22$) and for those listeners with high frequency average 6000 Hz and 8000 Hz) HTLs of 20 dB or less (broken lines).

sleeve earmolds. Note that, even for these subjects, the sleeve earmold did not restore localization to the unaided level. To investigate this, a few of the listeners were tested with the sleeve earmold and hearing aids in place but with the hearing aids turned off. Under this condition, performance was the same as unaided and was slightly better than with the sleeve earmold and the aids turned on. This indicates that the sleeve earmolds were not causing any disruption of localization cues. There was, however, a slight effect of amplification, possibly because of upward spread of masking from the amplified mid frequency sounds.

For horizontal localization, the two lowest lines of Figure 13, for the group of 11 listeners, there is a suggestion that the sleeve earmold fittings may be better than closed earmold fittings. This suggestion is stronger in the results for horizontal localization with a lateral orientation of listeners to the array (reported in Byrne et al, in press). This issue was examined for a different subject group and will be discussed below.

An obvious clinical question is: does improved vertical localization, as demonstrated experimentally, result in any everyday benefits to the hearing aid wearer? We are investigating this with a field trial of sleeve earmold fittings for some of the participants in the present experiment. Currently, only five people have completed the trial but all expressed a preference for the sleeve earmold over the closed earmold they had been fitted with previously. One subject felt the closed earmold was better under some conditions and was finally fitted with a special type of earmold that, in terms of its acoustic effects, is a compro-

mise between a sleeve and a closed earmold. The reported reasons for the preference for the sleeve earmold related to more natural sound quality, better externalization of sound and more comfortable listening. All five people report that they wish to use the sleeve earmold fittings (or the modified molds, for one person) regularly, which is in contrast to more limited use of their previous fittings. The type of subjects studied (moderate low and mid frequency hearing losses combined with good high frequency hearing) tend to be variable in the extent to which they use hearing aids, in spite of having considerable difficulties hearing unaided. Twenty of the 22 subjects had been fitted with aids, but almost half made no use or very limited use of their own (closed earmold) aid fittings (see Table 1 in Byrne et al, in press). We are hopeful that sleeve earmold fittings may enable a greater proportion of people with this type of hearing loss to become successful aid users. However, further clinical trials are required to determine whether this will happen.

The sleeve earmolds that were used for research were hand-made by the investigators. However, a production version, as shown in Figure 12, was developed subsequently and used in the clinical trials. This is essentially a tube shaped to fit the outer 8 mm of the ear canal. It is made of soft and flexible plastic material and has walls only 0.5 mm thick. The part of the earmold at the entrance to the ear canal has a slight flange to assist insertion and retention of the earmold in the ear. The sound delivery tube is glued to the inside wall of the earmold at the top of the ear canal. Acoustically this earmold is equivalent to a tube fitting but with the major advantage that the tube is held securely in the desired position in the ear canal. As well as being non-occluding, the sleeve earmold is very comfortable and unobtrusive and, when made in the current material, is durable. The sleeve earmold is made using a process similar to that used for making shell earmolds. That is, the audiologist simply takes an ear impression and orders a sleeve earmold from the earmold laboratory. This fitting option is now available from Australian Hearing Services, and presumably other audiologists could make similar arrangements with other earmold manufacturers.

Choice of Earmold: Sensorineural Hearing Loss with Good Low Frequency Hearing

There is a relatively consistent (although not always statistically significant) finding that, for

sensorineural hearing loss, aided horizontal localization tends to be poorer than unaided localization (Markides, 1977; Orton and Preves, 1979; Noble and Byrne, 1990; Byrne et al, 1992). As explained above, this decrement in aided horizontal localization probably affects only some hearing aid wearers and probably occurs because of a distortion of interaural phase information resulting from a mixture of amplified and unamplified low frequency sound (Noble et al, 1998). It seemed possible that this decrement in horizontal localization in people with good low-frequency hearing might be eliminated by using open earmold fittings which would provide only unamplified low frequency sound, instead of amplified sound as well. A group was selected of bilateral BTE hearing aid wearers who had near normal low frequency hearing (<25 dB HTL at 250 Hz to 500 Hz) combined with severe high frequency hearing loss (60–70 dB HTL at 2000 Hz to 4000 Hz). These are the type of cases for whom open earmold fittings have been considered desirable for reasons other than localization. None of these subjects wore open earmolds but some had earmolds with 2 mm vents. We wanted to see whether there was any decrement in aided localization and then, if there was, whether localization could be improved by using an open or sleeve earmold fitting. In a preliminary study, nine out of 18 subjects, tested unaided and with their current earmolds, showed a decrement in aided localization and were selected to participate in the experiment.

The nine subjects were tested unaided and in closed, open and sleeve earmold aided conditions. The open and sleeve earmolds have been described in the previous section. For the closed condition, the subjects used their own earmolds but any vents were blocked. In order to avoid acoustic feedback, several subjects needed to reduce the hearing aid gain for the open and sleeve earmolds. On average, the insertion gain used by the subjects was 16 dB at 3000 Hz and 12 dB at 4000 Hz for the sleeve earmold condition (Noble et al, in press). These gain values are equivalent to those used for the closed condition although, predictably, the low frequency insertion gain was substantially reduced for the open and sleeve earmolds compared to the closed earmold.

The results of this experiment (horizontal localization only), for a presentation level of 65 dB SPL and a forward orientation, are shown in the right panel of Figure 14, together with the average audiogram (left panel) for the group. In this instance, the scores are reported simply as the num-

Figure 14. Effects of earmold type (UA = unaided; CL = closed; OP = open; SL = sleeve) on horizontal sound localization for subjects with good low-frequency hearing and poor high frequency hearing. Group ($n = 9$) audiogram is shown in left panel and localization data are shown in right panel.

ber of correct responses with the maximum score being 30 (three runs times ten loudspeakers). All listeners performed perfectly for the unaided condition, but made an average of seven errors for the closed earmold condition. Subjects made only one error, on average, for the open and sleeve earmold conditions. These data do not show any advantage for the sleeve over the open (i.e. partly occluding) condition, but any conclusion should be cautious considering that scores are almost perfect; the sleeve earmold could possibly be advantageous for listeners whose overall performance was poorer. Furthermore, it appears that 2 mm vents, as used by several listeners in the preliminary testing, are not sufficiently “open” to overcome a closed earmold aided decrement.

Can Extending the High Frequency Response Improve Localization?

Theoretically, there are possibilities for improving vertical localization by extending the high frequency response of hearing aids, and providing adequate amplification of the high frequencies, combined with using a type of earmold that does not obstruct the pinna. An experimental hearing aid has been constructed, using laboratory equipment and software, that provides excellent amplification to 10,000 Hz. The earmold is an individually molded silicone rubber plug which fits within the ear canal (like a CIC aid) and contains the microphone and earphone, with wires leading to the amplifying equipment. The earmold units, one for each ear, and connecting leads are illustrated in

Figure 15. The use of equalization software can provide flat insertion gain to 8000 Hz and a somewhat less flat response to 10,000 Hz. So far, testing has been conducted with only a few normal hearing and hearing impaired subjects having good high frequency hearing and good vertical localization when listening unaided or with BTE hearing aids with a sleeve earmold fitting. For these two groups of subjects, the prototype device has provided excellent vertical localization, thus establishing that it is working as expected in providing the required acoustic cues. This study also established that good (perfect or near perfect) performance requires the frequency range to extend to 8000 Hz but not necessarily to 10,000 Hz; there is a substantial decrement in performance when the upper frequency limit is reduced to 6000 Hz and there is very little vertical localization when the limit is reduced to 4000 Hz. The most interesting question (currently being investigated) is whether listeners with significant high frequency loss can achieve vertical localization with our “hi-fi” aid, either immediately or after a period of training.

Here we may mention some unreported work from a previous study, as it suggests that achieving vertical localization where there is a significant high frequency hearing loss probably will not be easy and, indeed, may not be possible. In that study, 20 hearing impaired subjects were tested with random noise that was shaped to follow the threshold curve of each individual. This was achieved by measuring thresholds for one-

Figure 15. Parts of the “hi-fi” experimental hearing aid. The earmolds fit entirely within the ear canal and each contains an earphone and microphone. Leads from each transducer terminate in a plug that connects with leads attached to laboratory equipment that amplifies and equalizes to provide a flat insertion frequency response to 10,000 Hz.

third octave bands to 12,500 Hz. This stimulus was presented at MCL and, thus, every frequency band of the stimulus was well above threshold. This stimulus, which ensured audibility of all frequencies, did not result in any improvement in vertical localization. The explanation for this result may lie in psychoacoustic factors, such as upward spread of masking or reduced frequency selectivity, and/or in a need for training in using previously inaudible information. This issue remains to be resolved.

Can Directional Microphones Help or Hinder Sound Localization?

Audiologists often think that directional microphones should help localization, apparently because of the connotations of the word “directional”. It is worth emphasizing that directional microphones are *not* designed to improve localization, but rather to improve signal-to-noise ratio and, hence, speech recognition in noisy conditions. However, directional microphones could improve localization when used with head movement. That is, when wearing a directional microphone, in relatively non-reverberant conditions, a cue for localization could be obtained by moving the head to ascertain the direction that results in the sound being loudest. Under conditions where little head movement is possible, such as when sounds are brief, there is no basis for expecting directional microphones to provide any improvement in localization. Furthermore, as the operation of directional microphones depends on phase cancellation, there is a possibility that directional microphones could interfere with localization by disturbing interaural phase difference information. The possible effects of directional microphones on localization need to be investigated.

Can Compression Amplification or Other Forms of Signal Processing Reduce Sound Localization?

Compression amplification may reduce interaural intensity differences. It is, therefore, pertinent to ask whether compression (or rather, any particular type of compression) can have a detrimental effect on sound localization. By definition, compression reduces the intensity differences in a hearing aid’s output compared with its input. Slow-acting compression will reduce only long-term intensity variations (e.g. reducing the differences between the overall voice levels of different

talkers) whereas fast-acting compression will reduce short-term variations, such as the intensity differences between successive syllables of speech. Furthermore, fast-acting multi-band compression may reduce the intensity differences among the different frequency components of speech that occur at the same time. These effects occur for compression systems with low or moderate compression thresholds (Automatic Volume Control and Wide Dynamic Range Compression), not to compression limiting, which affects only high intensity inputs. With respect to localization, the relevant question is whether compression can reduce interaural intensity differences compared with the differences that would be received unaided or with linear amplification. The answer to this question will depend on what types of amplification are provided to each ear but, in general, compression could reduce interaural intensity differences. To explain, consider first unaided listening. The sound that is to be localized will be received at a higher intensity at the near ear than at the far ear (see Figure 1). The interaural intensity difference, which will be frequency-dependent, will be constant regardless of the overall intensity of the sound at its source. That is, the interaural intensity difference will vary only with changes in the direction of the sound source and thus can provide a cue for localization. This is also true if one or both ears receive linear amplification. If both ears are fitted with compression hearing aids of equivalent gain, the aid on the side receiving the higher input (i.e. the near ear) will provide less gain than the other aid, assuming that compression is activated. Thus, the interaural intensity differences in input, which would be the same as the interaural differences received unaided, will result, after amplification, in smaller interaural differences in output. The effects of compression on interaural intensity differences are complicated to predict as these effects will depend on the absolute intensity of sounds, whether compression amplification is used in one or both ears, and properties of the compression system. The latter could include the compression time constants when considering brief sounds. The general point is that, under some conditions, some types of compression amplification could reduce interaural intensity differences compared to those received in unaided listening or when compression amplification is not activated. However, the research reviewed above indicates that listeners have a considerable capacity to adapt to abnormal interaural intensity differences. For this reason, it

is doubtful whether a moderate degree of compression will result in any significant long-term effect on localization. A recent (yet unpublished) study by Bakke (personal communication) found that a 2:1 reduction of interaural intensity differences, intended to simulate compression, produced no significant effect on localization.

It is also possible that some types of signal processing, that could be considered for future hearing aids, could distort interaural time difference information. This could occur if the processing involved signal-dependent delays that were different for each ear. At present, there is only a limited basis for judging whether any type of compression is likely to have significant effects on localization but, given the theoretical possibility of this occurring, coupled with the almost universal use of compression amplification, the issue warrants a thorough investigation. It would also be desirable to examine possible localization effects for any new type of signal processing that alters time, intensity or spectral information.

RECOMMENDATIONS FOR CLINICAL PRACTICE

The information reviewed above has a number of implications for how audiologists should manage hearing aid clients. At this point, we shall summarize those implications and offer recommendations for clinical practice.

Assessing Localization Difficulties

The audiologist should assess the extent and nature of difficulties each client may have with sound localization and related phenomena. As suggested earlier, although clients do not often complain spontaneously of localization difficulties, such problems may exist and be important for the client's well-being. Experimental results show that virtually all hearing impaired people have impaired localization and, when asked specifically, they rate their localization ability in everyday life as poorer than normal hearing people. Audiologists should be aware that nearly all hearing impaired people (except those with good high frequency hearing) will have little or no ability to discern the elevation of sounds. This may not often be important in itself but it will preclude a true sense of spatial orientation which may be part of experiencing the sound environment as natural. Most hearing impaired people will also

have some loss of horizontal plane localization and this ability may be severely reduced for severe hearing losses. Horizontal plane localization may also be severely reduced for people with conductive and mixed hearing loss of only moderate degree. In addition to disturbing spatial orientation, reduced horizontal localization may lead to a variety of problems related to social functioning or even survival. As discussed earlier, there are situations where it is important to be able to tell where sounds are arriving from.

Audiologists should inquire closely into sound quality issues, listening unaided and aided, and such inquiry should include specific questions related to localization and externalization of sounds and the feeling of spatial orientation. Section III (localization) of the Hearing Measurement Scale (HMS) (Noble and Atherley, 1970) has been used effectively in this regard (Chung and Stephens, 1986). More recently, Noble et al (1995) have compared unaided and aided localization abilities using a questionnaire derived in part from the HMS. That questionnaire is reported as an appendix to the Noble et al (1995) article. Another specific area for inquiry is functioning in group situations. If difficulties are experienced, as they are for most hearing impaired people, then how much of the problem is related to delays in locating each talker as the conversation switches back and forth? Such localization difficulties may well be very significant, especially for people with severe hearing losses. The above mentioned questionnaires may be used to assess the success of hearing aid fitting or other rehabilitative strategies in alleviating localization difficulties. Other pre versus post fitting measures, such as the Client Oriented Scale of Improvement (COSI, Dillon et al, 1997) could also prove to be useful.

Advising about Hearing Aids and Strategies

Localization difficulties should be considered when advising hearing impaired people about hearing aids and listening strategies. If the client has a conductive or mixed hearing loss, aid fitting will probably help overcome any localization difficulty, perhaps dramatically, unless the difficulty is related more to vertical than horizontal localization. Clients with sensorineural loss will probably also experience some localization benefit because sounds that are inaudible obviously cannot be localized and sounds that are soft are more difficult to localize than ones that are at a comfort-

able or loud level. However, for some people, certain types of fittings may increase localization difficulties and the audiologist needs to consider this in the choice of fitting. One example (discussed earlier) is the use of closed earmolds with a bilateral fitting for people with good hearing at frequencies above 4000 Hz and, in some instances, for people with good low frequency hearing (250–1000 Hz).

Furthermore, if it is realized that impaired localization is creating a problem, there may be strategies available to reduce the problem. For example, if locating talkers in a meeting is causing a problem, the leader of the meeting should be made aware of this problem and should be able to alleviate the problem by asking each talker to get the hearing impaired listener's attention before speaking. There may also be implications for the choice and use of communication equipment, as can be illustrated by an incident occurring at NAL a few years ago. A conference room was used for another organization's board meeting which included one severely hearing impaired board director. The room was equipped with a loop system to which the input was a series of microphones suspended at several positions to ensure that every participant was near a microphone. The hearing impaired person complained that this system was not satisfactory for him. He insisted that he needed a loop with a single microphone that was passed from talker to talker. That was the only way he could identify each talker before they spoke! This story is not offered as a general recipe for designing loop systems, but it demonstrates a problem that would never be suspected unless one appreciates the significance of localization for group communication.

Hearing Aid Fitting

Hearing aids should be fitted in ways that will optimize sound localization. As well as being a desirable goal in its own right, it is reasonable to presume that other benefits may follow from optimizing binaural functioning. To achieve this goal, the following specific recommendations are possible.

- Bilateral fitting should always be recommended for people with moderate or severe hearing losses unless there is some specific contraindication. A bilateral fitting will almost certainly provide better horizontal plane localization than a unilateral fitting. A unilateral fitting, to the poorer ear, is likely to

provide equally good localization, after a period of adjustment for people with mild hearing loss (<40–50 dB HL). Therefore, for such people, the choice between unilateral and bilateral fitting should be based mainly on grounds other than localization.

- With the possible exception of CICs, hearing aid type does not seem to affect localization. The potential localization advantages of CICs require further investigation. If there are significant advantages, this would be a good argument for favoring CIC fittings provided they are suitable in all other respects. From a localization point of view, it does not seem to matter whether fittings are ITEs or BTEs except that the latter fitting offers greater options for using open earmolds which are advantageous for some types of hearing loss.
- Whenever possible, use open earmolds for bilateral fittings of people with either good low frequency hearing or, especially, people with good high frequency hearing. In order of effectiveness, the fitting options are likely to rank: bilateral with open earmolds (best), unilateral with either open or closed earmolds, bilateral with closed earmolds. In other words, the use of open earmolds may make it possible to obtain the advantages of bilateral fitting without disturbing localization. In making a suitably “open” earmold, the aim is to minimize any obstruction of the outer ear (pinna) structures and to allow unaided sound to pass unimpeded into the ear canal.

A practical difficulty in using open earmolds has always been the increased risk of acoustic feedback. In our experience, this is not a problem when fitting people with good high frequency hearing as they do not need much high frequency gain. In the Byrne et al (1998) study, all 22 participants could be fitted with the NAL prescription and only a few of the subjects would have chosen to use more gain than feedback would allow. For people with good low frequency hearing, often “ski-slope” audiograms, the avoidance of feedback is more problematic because such people would usually be prescribed a moderate to high amount of gain at the high frequencies. On one hand, there are strong reasons for preferring an open earmold fitting, localization being only one of them, but on the other hand, this probably will not permit use of the prescribed high frequency gain. To what extent should audiologists accept less high frequency gain than prescribed

for the sake of using an open earmold? This has not been answered conclusively and there may not be any general answer that is applicable in every case. However, there is some doubt about the benefit of high frequency amplification for steeply sloping high frequency hearing loss and it may be that reducing the high frequency gain from that prescribed is less disadvantageous than might be supposed. For example, Murray and Byrne (1985) found that, for five subjects with audiograms sloping from normal hearing at 250 Hz and 500 Hz to 60–70 dB HTL at 4000 Hz, there was no disadvantage in reducing the high frequency limit of an amplifying system from 4500 Hz to 3500 Hz and one of these subjects performed best with a limit of 2500 Hz. Two recent studies (Hogan Hargenrader, 1996; Ching et al, in press) confirm the limited, or even negative, value of amplifying high frequencies if hearing loss is severe at those frequencies. From a practical viewpoint, we suggest that open earmold fittings may often be worthwhile even if this requires limiting gain at the higher frequencies.

Audiologists should consider the possible effects of earmold changes on the localization ability of people with conductive or mixed hearing loss. This has both a positive and a negative aspect. On the positive side, if localization difficulties are a concern, it may be worth experimenting with different types of earmolds, such as variations in canal length or material. Unfortunately, the effects of earmold changes are unpredictable but there may be significant differences for some people and, therefore, there is some prospect of improving poor horizontal localization by a change of earmold. On the negative side, there is a possibility that a change in earmold may cause a deterioration in localization. Therefore, whenever an earmold is changed for someone with a conductive or mixed hearing loss, the audiologist should enquire closely about any possible difference in auditory experience that could be related to reduced localization.

When fitting hearing aids for the first time or changing aid fittings, audiologists should be aware that localization ability may change after a few months experience (i.e. there may be acclimatization). If there is difficulty initially in localization, it may be appropriate to advise the client to keep trying the current fitting for a while longer, rather than immediately considering change. It appears there is a fair amount of capacity to adjust to interaural loudness differences arising from differing amounts of amplification in each ear or from

differences in level between an aided and an unaided ear.

Clinical Testing of Sound Localization

So far, localization testing has been almost entirely confined to the research laboratory. We have heard of simple localization tests being used in some European clinics but we are unaware of any significant attempt to introduce localization testing to Australian or American clinics. This need not remain so. It would be easy to devise a clinical procedure and, in most respects, localization testing has the features of an excellent clinical test. The great clinical virtues of a localization test are that it is relatively quick—just a few minutes for each test condition—and it will usually provide a clear-cut result. For example, in comparing a unilateral with a bilateral fitting, audiologists will not be left wondering about the significance of a few percentage points of difference on a speech discrimination test; the localization test will nearly always leave no doubt about whether the bilateral fitting is significantly better. This would be helpful in making clinical decisions, demonstrating the relative benefits of different fittings to a client, providing data for clinical research and as an outcome measure.

The equipment required for localization testing—for example, to duplicate the arrangement used in most of our research—is not very elaborate or expensive. Loudspeakers of adequate quality are relatively cheap. A supporting structure for the loudspeaker array can be readily constructed, and suitable switching equipment can be designed and made by an electronics technician. The other required items of equipment would be available in any audiology clinic. These are: a tape recorder for presenting recorded stimuli or a noise generator, an amplifier and an attenuator. Most diagnostic audiometers could provide these facilities. Testing can be controlled by using a personal computer and software or it can be done entirely manually, as it was in some of the earlier research studies (e.g. Byrne and Dermody, 1975). Furthermore, a clinically useful arrangement could be less elaborate than has been used in research. Considering the typical size of localization errors, most clinical purposes could be served reasonably well with an array of eight or more loudspeakers. An example of such an array would be eight loudspeakers in the following positions and numbered as indicated: 1) 60 degrees left; 2) 30 degrees left; 3) directly in front; 4) 30 degrees right; 5) 60 degrees

right; 6) 30 degrees below ear level; 7) 30 degrees above ear level; and 8) 60 degrees above ear level. The loudspeakers are arranged in a horizontal arc (loudspeakers #1 – #5) and a vertical arc (loudspeakers #6 – #8 and #3, which is common to both arcs). Each loudspeaker is the same distance from the center of the subject's head on a line that would pass from one ear to the other. The subject is seated at least one meter, preferably more (e.g. 1.5 meter), from each loudspeaker. The horizontal arc is at the height of a subject's ears and an adjustable chair is used to position subjects at the same height. Although an eight loudspeaker array would be very useful clinically, it would represent only a modest cost and space saving over a more elaborate array (e.g. 20 loudspeakers) which would permit a finer resolution of localization performance.

Localization testing requires a reasonable sized test room to accommodate the loudspeaker array and possibly the remainder of the equipment. Although not optimal, it is feasible to have all the equipment in the same room as, indeed, has been done in some research (e.g. Byrne and Dermody, 1975). The test room should be reasonably quiet and non-reverberant but does not need to be sound treated to audiometric standards. Localization testing is conducted at suprathreshold levels and with broadband stimuli, which would avoid any significant problems arising from standing waves (Walker et al, 1984). Furthermore, the equipment and facilities required for localization testing would be suitable for other tests such as testing speech recognition with noises from a number of separate sources. Although we are not making specific recommendations, we suggest that the use of localization testing would be a valuable addition to the assessment of auditory functioning and the fitting of hearing aids.

CONCLUDING REMARKS

We hope that the material presented in this issue has convinced the reader of the importance of considering sound localization when assessing the difficulties of hearing impaired people and in fitting hearing aids in ways that will minimize such difficulties. We also hope that the suggestions presented will help audiologists to fit hearing aids more effectively. Localization is one of a number of aspects of auditory experience that have received inadequate attention in hearing aid fitting and in appreciating the problems of hearing impaired people. Historically, the major focus has

been on assessing difficulties in speech recognition and on designing and fitting hearing aids to improve speech understanding. Considering the current state of development of hearing aids, this focus is too narrow and we largely echo some thoughts expressed fifteen years ago. Killion (1982) argued that hearing aids were generally effective in making sounds audible and had gone most of the way towards optimizing speech discrimination for most hearing aid wearers. Killion advocated that more attention should be given to quality considerations and less to striving for further improvements in speech discrimination, an area of greatly diminishing returns. Killion suggested that audiologists and research scientists should inquire about what is important to hearing aid wearers, rather than assume that speech understanding is all-important. Further, he pointed out that when speech understanding conflicts with listening comfort people do not always (probably do not usually) choose to optimize speech recognition. These comments are particularly pertinent today considering that the advantages of recently developed hearing aids, which all include some form of compression, seem more related to listener comfort and convenience than to any demonstrable improvements in speech recognition (Dillon, 1996). Over the last fifteen years, quality considerations have received far more attention from research than they did formerly. This is also true to a much lesser extent through the clinical use of benefit questionnaire measures which often include some "quality" questions. Most questionnaires, however, are still weighted heavily towards assessing speech recognition (Noble, in press). We consider that the quality aspects of auditory functioning and how they are affected by hearing aid fitting, still do not get nearly enough attention with regard to either depth or breadth of study. Localization and related phenomena, such as externalization of sound and a proper feeling of spatial orientation, form a major component of the quality of auditory experience.

In a way, our doctor friend, introduced at the beginning of this article, had the right idea in inquiring about the importance of localization. Although his inquiries were anything but adequate, audiologists do need to ask hearing impaired people about localization difficulties and how such difficulties affect their lives. We need to consider localization as a major aspect of auditory functioning and the quality of auditory experience. This is vital for extending our appreciation of hearing loss and to optimize hearing aid fittings.

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