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Bilateral amplification and sound localization: Then and now

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Abstract—This article is concerned with the evolution and pros and cons of bilateral amplification. Determining whether a bilateral hearing aid fitting is superior to that of a monaural hearing aid is a long-standing question; for this reason, the trend toward bilateral amplification has been slow. However, it is now assumed that bilateral amplification has significant advantages over monaural amplification in most cases, a view that is supported by our localization results. In this article, we will address the advantages of bilateral hearing aids and reveal some new localization data that show that most listeners with bilateral amplification, when tested unaided, as well as normal-hearing listeners manifested very high degrees of symmetry in their judgments of perceived angle while listeners who routinely use monaural amplification and those with asymmetric hearing loss had relatively large asymmetries. These data show that asymmetry in localization judgments is a much more sensitive indicator of abnormal localization ability than the magnitude of localization errors.

Key words: asymmetric hearing loss, bilateral amplification, binaural advantage, directional hearing, hearing aids, localization asymmetry, monaural amplification, sensorineural hearing loss, sound localization, speech intelligibility.

INTRODUCTION

There is an ebb and flow in the development of sensory aids. Each new advance is met with considerable fanfare and much anticipation. Glowing papers are published and skeptics are held at bay. With time, enthusiasm wanes as expectations are not met and new studies illuminate newer insights and more realistic outcomes. A gradual settling down follows in which both the potential and limitations of these developments are recognized; this results in a new generation of sensory aids that embody significant, albeit undramatic, improvements. The pattern is essentially one of evolution rather than revolution. In some cases, evolution can be very rapid, as in the case of the cochlear implant; in other cases, the evolutionary development is slow and spans many decades.

The evolution of bilateral amplification has occurred at a slow pace. This has important implications for those patients who receive monaural amplification during the ebb phase. The common assumption that two optimally fit monaural hearing aids constitute an optimum binaural fit is not necessarily true [1–5].

Abbreviations: ASYM = asymmetric hearing loss, BIA = bilaterally aided, BMLD = binaural masking level difference, CI = confidence interval, CROS = contralateral routing of signals, HL = hearing level, IID = interaural intensity difference, ITD = interaural time difference, LAI = Localization Asymmetry Index, MOA = monaurally aided, NH = normal hearing, OME = otitis media with effusion, SE = standard error, SEM = standard error of the mean, SNHL = sensorineural hearing loss, SNR = signal-to-noise ratio, SPL = sound pressure level, WDRMCC = wide dynamic range multichannel compression.

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Some interaction between both hearing aids is necessary to access the binaural advantage. The importance of true binaural and the insufficiency of simple bilateral hearing aids have been emphasized. Since a true binaural hearing aid is not yet available, we will refer to all hearing aids fit for two ears as bilateral [4–5].

Initially, a great deal of excitement existed over the prospect of improvement in speech intelligibility and localization with the use of bilateral hearing aids [6]. This excitement was fueled by the studies of Hirsh [7–8] and Licklider [9] and the theoretical and clinical arguments of Bergman [10], Carhart [11], and DiCarlo and Brown [12]. Following the initial enthusiasm, a down period occurred in the 1960s because of the lack of objective studies on improvements in speech intelligibility with bilateral hearing aids and the reluctance of consumers to wear two of the bulky instruments. However, the enthusiasm for bilateral amplification has resurfaced and in the past decade more bilateral than monaural hearing aids have been dispensed [13].

Two key advantages of bilateral amplification are directional hearing and improved intelligibility of speech and noise from different directions. Directional microphone hearing aids can also improve speech intelligibility under these conditions, and enthusiasm is growing for this form of amplification as discussed in the article by Todd Ricketts [14]. This article is concerned with localization ability and the pros and cons of bilateral amplification.

THE EBB AND FLOW OF BILATERAL HEARING AIDS: A BRIEF HISTORY

Whether bilateral is superior to monaural amplification is a long-standing question. Almost since the development of the wearable electronic hearing aid (one that encompassed high gain, good reliability, and design flexibility), the issue of monaural versus bilateral fittings has been debated. Knudsen [6] wrote positively about the potential value of bilateral amplification and created innovative variations of bilateral hearing aids such as the contralateral routing of signals (CROS) and split-band systems [15]. In the CROS system, signals that reach the poorer ear are routed to the better ear. The split-band system routes some frequencies to one ear and some to the other [6,16–18].

Hirsh noted that the first true stereophonic hearing aid system was developed and patented by Soret in 1915 [7]. The seminal work of Hirsh [19] and Licklider [9] precipitated the initial interest in bilateral amplification by specifying the gains in signal detectability and speech intelligibility that are produced by an interaural difference between the signal and the noise.

However, the reception of bilateral hearing aids has not always been positive. In the 1950s, Hirsh reported that the hearing aids available at the time were “pseudo-binaural,” had little or no advantage, and might even provide poorer hearing than monaural hearing aids [7]. A hearing aid that would permit the listener to separately localize the speech and the noise and to attend separately to the desired signals was recommended; this would be possible if microphones were mounted on both ears. Otherwise, hearing-impaired listeners would continue to find their hearing aids useless in noisy situations [8].

The first verifiable positive evidence of the bilateral advantage was found by DiCarlo and Brown [12]. They found that localization of a noise burst improved with bilateral amplification, although correlation of localization ability and speech intelligibility had not been demonstrated [20].

By the 1960s, wearable bilateral hearing aids were readily available and with the introduction of ear-level hearing aids, interest in bilateral hearing aids was renewed [21]. However, no consensus existed regarding the additional benefits of bilateral amplification. Theoretical arguments such as those by Hirsh [7] and clinical observations by others [10,22] supported the benefit of bilateral amplification; however, after six years of experimentation, no objective demonstration existed of the advantage of bilateral amplification for speech intelligibility in quiet and noisy situations [19,23]. An exception to the fitting of bilateral hearing aids was made with children who, in the late l960s, were routinely fit with two body-worn hearing aids or, at worst, a Y-cord arrangement.

By the late ’70s and early ’80s, impaired localization was considered one of the biggest problems consistent with hearing loss [24] and improved sound localization was reported the most universally accepted benefit of a bilateral fitting [25]. However, few people were willing to wear two bulky hearing aids and very few professionals were recommending them. One reason for this may have been a 1975 hearing aid industry ruling by the Federal Trade Commission [26]. This ruling stated that “no seller shall prepare, approve, fund, disseminate, or cause the dissemination of any advertisement which makes any representation that the use of two hearing aids, one in each ear, will be beneficial to persons with a hearing loss in both ears, unless it is clearly and conspicuously disclosed that many persons with a hearing loss in both ears will not receive greater benefits from the use of two aids, one in each ear, than the use of one hearing aid."

This ruling, as well as the difficulty in objective demonstration of the binaural advantage with bilateral hearing aids, resulted in a decrease in recommendations for bilateral hearing aids as compared with monaural hearing aids. A fundamental weakness of early attempts to solve the monaural-bilateral controversy was that no well-established methodology existed to demonstrate the binaural advantage with bilateral hearing aids, especially with regard to speech intelligibility. For example, one of the first studies with positive results from bilateral amplification compared two ear-level hearing aids with a body-worn instrument [27], which was an inadequate control. Levitt suggested that contrasting the subject's performance with optimally prescribed ear-level monaural versus optimally prescribed bilateral hearing aids would be a reasonable comparison [28]. Other methodological issues that contributed to the long-standing controversy about the benefits of bilateral amplification (see Byrne [25] for an excellent review of the controversy) included lack of research on acclimatization [29–30], selection of appropriate tests sensitive to differences in hearing aid conditions, selection of methodologies that demonstrate binaural advantages [27], and choice of presentation level [31].

Thus, as late as 1980, the view was that solid evidence for bilateral fitting was minimal and justification for the practice rested mainly on favorable subjective reports [25]. The limited conclusive or compelling scientific evidence in support of bilateral hearing aids [32] has caused them to be used infrequently around the world [28,33].

For these reasons, the trend toward bilateral amplification has progressed slowly. As recently as 2001, 29 percent of hearing aid fittings were still monaural [13]. Dillon states that this average fitting rate indicates what is being done, not what should be done [34], although the number of bilateral hearing aid fittings has risen. He cautions that for various reasons not everyone who receives two hearing aids wears them. In a 1999 National Acoustic Laboratories of Australia study of 4,000 patients, only 48 percent had been fitted with bilateral hearing aids [35]. Three months after fitting, 20 percent of the patients that were fit bilaterally reported wearing only one hearing aid. Still, Dillon states there is now overwhelming evidence that two hearing aids provide better performance than one in most situations [34].

PROS AND CONS OF BILATERAL AMPLIFICATION

Many advantages exist for binaural hearing, although the advantages of bilateral hearing aids have not always been easy to prove objectively. As outlined recently by Dillon, the major claims of the advantages of bilateral amplification and the binaural advantage are similar: increased speech intelligibility, especially in noisy situations; improved sound quality; ability to "tune in" to a wanted signal and minimize the effects of unwanted background noise (the squelch effect) [22]; and superior localization ability [34]. Markides, in an early classic hearing aid study, found that listeners with two ear-level aids had superior performance in speech discrimination, the squelch effect (3.39 dB), head shadow effects, and localization compared with listeners with one hearing aid [21]. The summation of the two signals also permits reduced amplifier gain, which results in fewer potential feedback problems. People with severe hearing loss may have difficulty achieving appropriate loudness for speech with the lack of summation inherent to a monaural fitting.

The advantages of bilateral amplification have traditionally been weighed against financial cost, self-image, listening needs, hearing aid management ability, and binaural interference, i.e., poorer speech discrimination when a user listens binaurally as opposed to monaurally [34]. However, a very important additional cost that is often overlooked is the deleterious effects of long-term monaural amplification.

ACCLIMATIZATION AND BILATERAL HEARING AIDS

In the past two decades, two findings have altered some of the traditional views of amplification. First, Silman and colleagues, in a series of studies, reported significant changes in auditory function, specifically speech recognition ability, as a result of long-term monaural amplification or lack of bilateral amplification in people with symmetrical hearing loss [36–37]. These studies have focused on only one aspect of the problem, speech perception. It is likely that other stimulus or input deprivation effects are subtler, yet at least as significant, and they may be manifested by changes in binaural as well as monaural processing, such as localization.

Second, Gatehouse found an improvement in speech recognition performance after some period of hearing aid use that was not noticeable immediately following the hearing aid fitting [38–39]. This effect was attributed to acclimatization of the aided ear to the speech cues made available by the hearing aid. Even if hearing aid benefit does increase over time, other sources of variability may still influence the measured change, such as the speech recognition material and/or the statistical limitations of the procedures and measures the researchers used [40].

However, controversy exists concerning the extent to which a first-time hearing aid user must acclimate to hearing aids. Some studies suggest that acclimatization occurs very rapidly or not at all since performance soon after the receipt of a new hearing aid is equivalent to that measured after months of experience [41–44]. Studies that do show an acclimatization effect indicate that it is incomplete even 10 to 18 weeks postfitting [39,45–46]. All of these acclimatization studies, however, were performed with conventional linear hearing aids.

A recent study by Yund et al.[*] showed that the listeners' average syllable discrimination improved over their first 8 weeks of hearing aid experience and that acclimatization was significantly greater for hearing aids with wide dynamic range multichannel compression (WDRMCC) than for those with linear amplification. It had been previously suggested that longer periods of acclimatization might be required for hearing aids with more complex signal processing [47–48]. However, these were the first data to directly support this hypothesis.

Although the term "deprivation" is normally viewed as the absence of stimulation, many instances of deprivation involve different stimulation, i.e., exposure to low rather than high sound levels. Gatehouse and colleagues showed that the unaided ear of a hearing aid wearer tends to process low-intensity stimuli better than the aided ear [39–40,46]. Thus, the range of levels that can be optimally processed can be extended [49].

Most of the research to date on acclimatization and deprivation has focused on speech perception. In one of the few studies on nonspeech auditory abilities, Robinson and Gatehouse [50–51] showed that acclimatization and deprivation effects exist for intensity discrimination [38–39,49]; binaural tasks, such as the binaural masking level difference (BMLD); and auditory localization and lateralization (the latter being the apparent location of the sound source in the listener's head when earphones are worn) [52]. For example, deprivation has been demonstrated in studies of both children and adults; results from these studies show that long-term reduction in auditory stimulation can affect the BMLD. Reduced BMLDs have been observed in children who had normal hearing when they were tested but who had a history of hearing loss associated with otitis media with effusion (OME) [53]. Although the BMLDs of these children returned to expected levels, which presumably demonstrates their incorporation of normal binaural auditory cues with experience [54], this finding suggests a slow recovery of binaural function after deprivation. Reduced BMLDs have also been observed in children and adults years after corrective surgery for both OME and otosclerosis has equalized the hearing levels (HLs) in the two ears [55–57].

Acclimatization to input asymmetries has not been studied in great depth, which is surprising considering the widespread use of monaural amplification and the large number of individuals with asymmetric hearing loss (ASYM). The possibility that long-term input asymmetries may affect binaural processing was suggested by Moore [58] based on the following evidence: human adults can adapt to altered binaural cues that are produced by real or artificial asymmetries [4,59], the physiological responses of neurons in the higher levels of the central auditory system of animals remain plastic into adulthood and can be altered by lesions in the peripheral auditory system, and the bilateral balance of anatomic connections between auditory and brain stem nuclei continues to change in animals after unilateral peripheral lesions, at least into adolescence.

HEARING LOSS AND LOCALIZATION ABILITY

The question of how well someone with hearing loss can localize sound (with or without amplification) is still not fully resolved. It is well known that normal-hearing (NH) listeners can localize well in both the horizontal and

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[*] Yund EW, Roup CM, Simon HJ, Lotze A. Changing speech perception and localization in new hearing aid users with wide-dynamic range multichannel compression and linear fittings. Unpublished observations; 2005.

vertical planes. The smallest error for broadband sounds in a study by Makous and Middlebrooks [60] was 2° in the front and 9° at 60° azimuth in a two-dimensional head pointing task. Bronkhorst [61] observed a mean absolute error of 3° and Seeber [62] of 1.6°. However, controversy exists regarding how well hearing-impaired listeners can localize sound.

Accurate sound localization is a complex perceptual process that requires the integration of multiple acoustic cues [63]. Localization on the horizontal or azimuthal plane depends primarily on binaural difference cues, interaural intensity differences (IIDs), and interaural time differences (ITDs) [64]. The dual mechanism theory of binaural localization, sometimes referred to as the "duplex" theory [65], states that low frequencies are localized on the basis of ITDs and high frequencies on the basis of IIDs. Thus, a lateral shift of the auditory image is produced by ITDs in low but not high frequencies. However, ITDs can still be used in the high frequencies when there are discernible features in the signal envelope. The fact that localization on the basis of interaural timing information is possible for complex, high-frequency stimuli, such as transients, noise, and amplitude-modulated signals, has challenged the duplex theory [66–68]. Also, when wideband stimuli are produced with conflicting IID and ITD cues, listeners follow the direction of the ITD cue as long as the stimuli include low frequencies [63].

Vertical localization and front-back discrimination rely on high-frequency spectral cues (>5 kHz) that are created by reflection and diffraction of sound by the external ear and, in particular, the pinna [69–70]. These cues are often referred to as "monaural spectral cues" since the analysis depends only on a signal being present in one ear, although the spectral cues would be available to both ears [71]. Directional shaping of the spectrum at low frequencies is also salient because of the effects of the torso [72]. Listeners with high-frequency hearing loss have more difficulty than NH listeners when tested in the sagittal plane and with elevation [73].

Investigators also argue that based on monaural listeners' ability to localize sound in the horizontal plane, spectral cues contribute to horizontal localization [70,74–75]. Source or head movement cues, cognitive cues [76], and visual cues [77] are also relevant in sound localization.

Recent studies of localization (or lateralization) abilities in sensorineural hearing loss (SNHL) listeners have been designed to either describe binaural deficits [4,78–82] or evaluate the effects of hearing aids and various amplification strategies [3,83–85], ear-mold configurations [3,83–86], and ear protectors [87].

Durlach et al. extensively reviewed studies of this type prior to 1981 and noted a general lack of agreement about the ability of listeners with SNHL to use interaural cues [88]. This finding was attributed to inconsistent methodology between studies (presentation levels, stimuli, paradigms, listener practice levels) [89] and an inadequate separation of age, degree, type, and etiology of the hearing loss. Aside from these methodological issues, general localization and lateralization performance was not easily predicted on the basis of the audiogram, although it was degraded in listeners with SNHL and, in particular, those with presbycusis, unilateral hearing loss, and bilateral asymmetry [88].

Others [4,79,89] have attempted to answer the concerns of Durlach et al. [88]. These studies found large intersubject variability in binaural performance for listeners with a similar degree, configuration, type (e.g., cochlear), and etiology of hearing loss. Studies by Koehnke and colleagues advocate that the audiogram of the SNHL listener is neither a good predictor of binaural abilities (not localization per se) nor is performance predictable from one binaural test to another [3,79,90].

Byrne and colleagues [49,81] found a moderate correlation between the severity of the hearing loss and the localization difficulty, and they concluded that unaided localization by SNHL listeners is affected by degree and type of hearing loss [91]. They further found an interaction between degree of hearing loss and localization advantage with bilateral hearing aids [83]. Flamme et al. confirmed this finding and showed that individuals with severe hearing loss, who were fit bilaterally, reported slightly fewer localization disabilities in comparison with monaurally fit listeners [92]. However, Noble et al. found that in listeners with pure-tone averages of less than 50 dB HL, no clearly demonstrable advantage of bilateral over monaural fittings existed for localization performance in real-world settings [93].

Aided localization has been shown to be better with the listener's own hearing aid(s) [84], which may be due to acclimatization [39,45–46]. As previously mentioned, numerous studies have compared aided localization among various hearing aid fittings and types of hearing aids. Earlier studies showed that when sounds are presented at clearly audible levels, aided localization was worse than unaided localization [21,83]. In addition, Byrne et al., reporting on various studies done in their laboratory over the years, found that aided localization in the horizontal plane for listeners with SNHL was either the same as unaided localization or "distinctly poorer" [91]. These studies used various hearing aid configurations, including monaural fittings. However, in the Byrne study, no correlation existed between aided and unaided localization score and frequency pure-tone average, although it should be noted that half of the fittings in the study were monaural [91].

Two studies tested localization in both quiet and noisy settings in listeners with bilateral, symmetric, high-frequency hearing loss [87,94]. The SNHL listeners exhibited poorer localization performance than the NH listeners [87]. Noise decreased performance in both listener groups but only with low-frequency narrowband signals, which suggests that audibility ensures the availability of high-frequency IID but not ITD cues.

Lorenzi et al. tested listeners with a broadband click-train signal in quiet and noisy settings at three different azimuths (0°, ±90°) and six signal-to-noise (SNR) ratios [95]. Localization performance was only slightly poorer for SNHL listeners than for NH listeners with noise at 0° azimuth. At ±90° azimuth, localization performance of the SNHL listeners decreased at a higher SNR than for NH listeners and was less consistent at ±90° than at 0° azimuth. Reduction of the stimulus audibility to NH listeners did not simulate the poor localization of the SNHL listeners, which suggests that characteristics other than audibility (i.e., distortion) might affect localization in quiet and noisy settings.

Some caution is in order because, until recently, a multichannel expansion hearing loss simulation has not been used for evaluating the effects of the audibility of all frequency components of the localization stimuli [96]. Preliminary data suggest that the use of bilateral WDRMCC hearing aids does not interfere with localization in new hearing aid users; results for listeners tested with WDRMCC showed no significant difference in localization abilities from those of a group tested with bilateral linear hearing aids [97].

Even with the benefit of WDRMCC, high-frequency hearing loss would limit access to higher frequency IID and spectral cues and force listeners to rely mostly on low-frequency ITD cues, which are more salient than IID cues [98]. If the population is an older one, it is noted that the ITD cues are less salient [59,99–100]. If wideband stimuli are produced with conflicting IID and ITD cues, listeners follow the direction of the ITD cue as long as the stimuli include low frequencies. Alternately, Middlebrooks found that responses to narrowband noise (1/6-octave bandwidth at center, frequencies of 6–12 kHz) were as accurate as those to broadband stimuli in the horizontal plane, while the vertical and front-back responses exhibited systematic errors [71]. Middlebrooks suggested that accurate horizontal localization was basically unaffected by the imposition of the narrowband spectral peak and that horizontal judgment depended almost entirely upon IID cues because of the high center frequencies of the stimuli [71].

CURRENT RESEARCH ON SOUND LOCALIZATION AND SENSORINEURAL HEARING LOSS

Recent studies have raised the awareness of the importance of acclimatization in acoustic amplification. As noted earlier, relatively little is known regarding acclimatization to asymmetric inputs such as from ASYM or long-term monaural amplification. A series of investigations has been undertaken at The Smith-Kettlewell Eye Research Institute for determining the effects of long-term asymmetric inputs on sound localization [4,59]. Localization in the horizontal plane is of particular interest because of the remarkable sensitivity of the auditory system to small differences in angle of azimuth.

Investigators used the continuous-pointer method of measurement, which in experiments with NH listeners has been found to be superior in overall accuracy, response time, and error to other methods [101–102]. Previous studies of localization accuracy with SNHL listeners used experimental paradigms in which the listener identified the sound source from a finite set of possible locations that were usually visible to the listeners. Imposition of a finite response set introduces quantization error that can reduce accuracy. The visual cues provided by readily visible reference points (especially a set of speakers that correspond to the sound sources) can powerfully influence apparent sound position [103]. In the continuous-pointer method, the number and location of loudspeakers are unknown to the subject who manually moves a visual pointer with a slider potentiometer to the perceived location of the auditory signal. This is a more natural response since no mental transformation of the target is required and listeners can use their own anatomical reference points [101]. The continuous range of possible responses eliminates the context effects of identification paradigms. These significant advantages make this paradigm an important contribution to the accurate measurement of the localization percept.

Simon et al.[*] used the continuous-pointer method to study the localization of broadband and narrowband stimuli in the horizontal plane. We assessed the frequency-dependence of localization ability with five NH and five bilaterally aided (BIA) SNHL listeners with symmetric, bilateral hearing loss. Stimuli were presented at a sound pressure level (SPL) of 80 dB, which was audible to all the SNHL listeners.

Figure 1 shows perceived angle as a function of target angle for a broadband speech signal (multitalker babble, 250–4,000 Hz) for one NH and one BIA listener. The accuracy of localization was measured without amplification, i.e., in the unaided condition. The listeners are typical in that their localization errors fell in the middle of the range for each group. The test-retest standard errors (SEs) for the NH and BIA listeners were 1.6° and 1.1°, respectively. These listeners were consistent in their judgments as shown by the relatively small test-retest SEs. They also showed distinct patterns in their localization errors. The consistency of these errors reflects a perceptual bias (target angle-perceived angle) on the part of each listener in sound localization (i.e., the NH listener perceived the sound coming from an angle that was further away from the midline than the true angle while the BIA listener perceived the sound coming from an angle closer to the midline than the true angle). Typical for localization errors, these errors increased with increased target angle for both listeners; the magnitude of the error was greater for the BIA listener. Although there were significant individual differences in the magnitude of the localization biases, the majority of listeners in each group showed biases in the same direction, away from the midline for the NH group and closer to the midline for the BIA group.

A striking feature of the data is the high degree of symmetry of the localization bias on either side of the midline. For both listeners, localization bias on the right of the midline was roughly the same in magnitude (but opposite in sign) to the bias on the left of the midline. For example, the NH listener showed an average bias of +7.9° at a target angle of +16.5°. At a target angle of –16.5°, the bias was –6.3°, which is not significantly different in magnitude from 7.9°. A useful measure of the degree of symmetry or lack of symmetry in localization errors is the average difference in localization bias on either side of the midline.

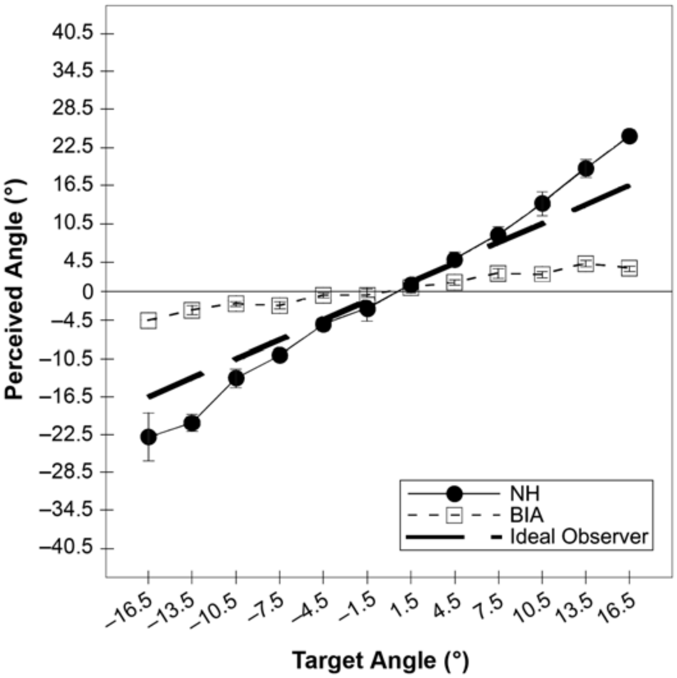

Figure 1.
Perceived angle as a function of target angle for normal hearing (NH) and bilaterally aided (BIA) subject. Results are for broadband signal (250–4,000 Hz). Negative values indicate targets left of midline; positive values indicate targets right of midline. Perceived angle is shown on ordinate with negative values indicating perceived angles left of midline and positive indicating angles right of midline. Each point is mean of 5 replications for each listener and standard deviation of 1 observation is $\sqrt{5}$ larger than these standard errors (error bars).

This measure of symmetry is called localization asymmetry and defined as (bias right of midline – bias left of midline)/2, where bias = perceived angle – target angle; this value is averaged over sufficient replications that the standard error of the mean (SEM) is much smaller than the bias. Note that bias to the left of the midline needs to be reversed in sign in order to maintain symmetry.

Figure 2 shows localization asymmetry as a function of target angle for the NH listener. Perfect symmetry in localization errors results in a localization asymmetry of zero, as shown by the solid horizontal line. As is evident from the figure, localization asymmetry does not differ significantly from zero at any of the target angles at which localization data were obtained for the NH listener.

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[*] Simon HJ, Levitt H, Lotze A. Localization ability using a continuous paradigm: symmetric sensorineural hearing loss. Unpublished observations; 2005.

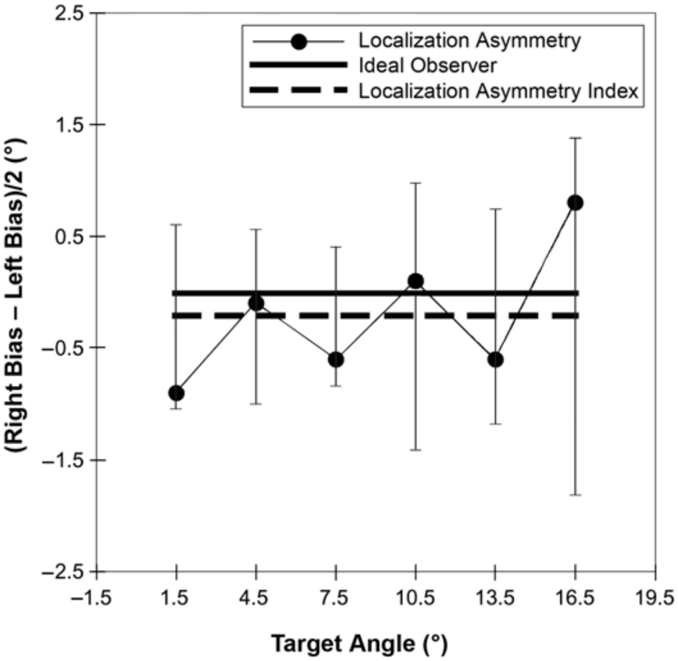

Figure 2.
Localization asymmetry as a function of target angle for normal-hearing listener. Target angles ranging from 1.5° to 16.5° are shown on abscissa, and localization symmetry ([right bias – left bias]/2) is shown on ordinate. Error bars show standard error of each localization asymmetry value.

The Localization Asymmetry Index (LAI) for a given set of data is defined as the average localization asymmetry over all the target angles in the study. It is important that the target angles are symmetrically located about the midline; i.e., for a target angle of *x*° there must also be a target angle of –*x*°. The dashed line in **Figure 2** shows the average LAI. The LAI for this particular listener is –0.22°. The SE of this index for the NH listener is 0.41°.

This very small SE indicates the high sensitivity of the LAI in detecting asymmetries in localization errors. An LAI as small as 0.8° indicates statistically significant asymmetry in perceived angles for this particular listener. Not only did this listener show very good test-retest repeatability in judging perceived angle, but the LAI was also very small (–0.22°), which indicates a high degree of symmetry in the subject's judgments of perceived angle. In contrast, the average bias of the subject's judgments of perceived angle was 3.3°, which is significantly greater than zero (SE = 0.41°).

All of the NH listeners and most of the BIA listeners studied by Simon et al. (see footnote p. 123) showed a high degree of symmetry in their localization errors. We found that the LAI was very sensitive to asymmetries in localization errors. In light of this result, we were very interested in examining the effects of asymmetric inputs on the accuracy of localization ability and localization asymmetries, in particular.

ASYMMETRIC INPUTS AND ACCURACY OF LOCALIZATION

Determination of localization ability, in the unaided condition, of listeners with symmetric, bilateral hearing loss and long-term monaural amplification was of interest. We hypothesized that these listeners will have poorer localization ability than the NH and BIA listeners and will demonstrate significant asymmetries in their localization judgments as a result of acclimatization to long-term asymmetric (monaural) amplification. We anticipated that the LAI would be sensitive to asymmetries in localization judgments. We were also interested in investigating asymmetries in localization of listeners with ASYM with the techniques just described.

Deprivation can be viewed as either a detrimental or a compensatory manifestation of auditory plasticity [104]. Recent work at The Smith-Kettlewell Institute has investigated input differences with the use of a number of different paradigms in asymmetric and symmetric SNHL and NH listeners. In an acoustic pointing task, when slight asymmetries at the two ears produced signals of equal sensation level but unequal SPL, lateralization was towards the ear with the greater SPL signal regardless of the ear to which the signal was delayed by an ITD [59]. In a second paradigm, a graphic pointing task, the perceived lateral position was found to linearly depend on the degree and direction of the threshold asymmetry when the listener was equalizing by sensation level [4]. Equalization by SPL showed no such dependency but produced images that were lateralized close to the midline. The results of these two studies suggest that people with asymmetric hearing, normal or otherwise, have adapted to their asymmetry for IID in lateralization tasks.

Another important consideration is the effect of monaural amplification on measures of binaural hearing. While it might be expected that people with ASYM have adapted to their asymmetries for localization and lateralization [4,88], what happens to localization abilities for a person with symmetric hearing loss after long-term monaural amplification as compared with long-term bilateral amplification?

Eight SNHL listeners were tested: four monaurally aided (MOA) listeners with bilateral, symmetric hearing loss who wore a monaural hearing aid for more than a year and four with ASYM who wore bilateral hearing aids. The continuous-pointer paradigm that was described previously was used.

Figure 3 shows the difference in hearing thresholds between the right and left ears for the BIA, MOA, and ASYM groups. The right and left ear thresholds for the MOA listeners were symmetric with very small HL differences between ears. The average difference across frequencies was very close to zero, –1.4 dB (SE = 3.4 dB).

The BIA listeners' right and left ear thresholds were also well matched, except at 4 kHz. The average difference between ears across frequencies was also –1.4 dB (SE = 4.4 dB). The ASYM listeners all had better hearing in the left ear, with an average difference between the ears and across frequencies of +11.1 dB (SE = 4.1 dB).

Figure 4 shows the perceived angle for a broadband speech signal (multitalker babble) as a function of the target angle for MOA listeners. The thick gray lines represent the 95 percent confidence interval (CI) for the BIA listeners and the bold dashed line represents the performance of an ideal observer.

The results for two of the MOA listeners were very poor, while data for one listener lies just outside the 95 percent CI for the BIA listeners. Only one MOA listener perceived angles within the BIA range, and even this listener showed some asymmetry in localization judgments on either side of the midline.

Generally, long-term use of a monaural hearing aid, even with a symmetrical hearing loss, can cause localization confusion when a listener is unaided. This may be due to partial adaptation to the MOA condition and the combination of aided and unaided listening. The use of monaural amplification, therefore, has ramifications for unaided as well as aided localization the degree that might be dependent on the duration and consistency of the use of monaural amplification. This last point has yet to be studied.

Figure 5 shows the perceived angle as a function of the target angle for the ASYM listeners. The perceived angles for three of the four listeners were well outside the

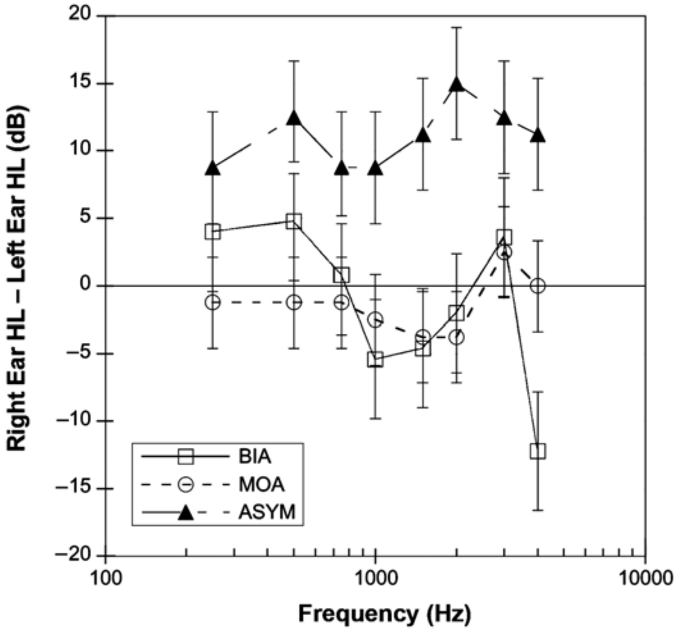

Figure 3.
Threshold asymmetry or difference in hearing thresholds between right and left ears for 3 sensorineural hearing loss groups BIA = bilaterally aided, MOA = monaurally aided, ASYM = asymmetric hearing loss. Abscissa shows frequency (250–4,000 Hz) and ordinate shows right ear hearing level (HL) – left ear HL. Error bars show standard error of mean.

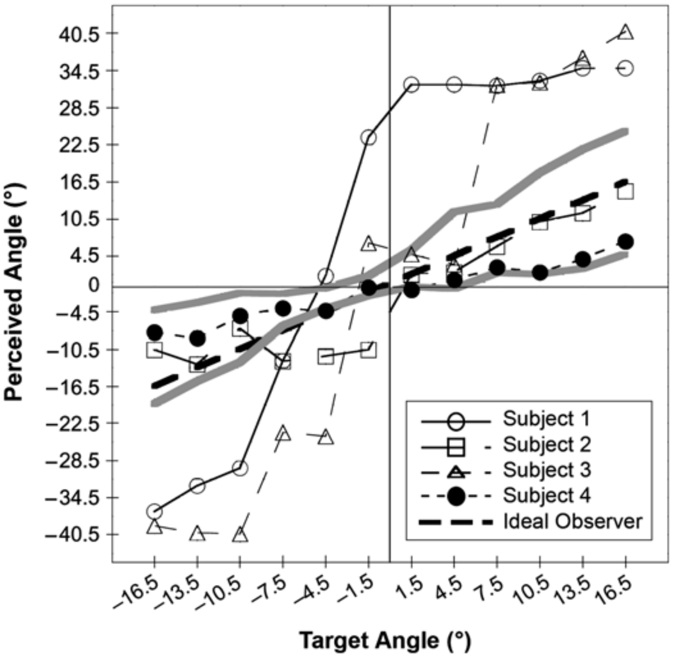

Figure 4.
Perceived angle as a function of target angle for monaurally aided listeners. Thick gray lines represent 95% confidence interval for group of 5 bilaterally aided listeners.

95 percent CI for BIA listeners. All the localization judgments were biased to the left (better) ear. Even the subject whose perceived angles were fairly close to those of the BIA listeners had significantly asymmetrical localization judgments. The results for the MOA and ASYM listeners show large individual differences that were not previously seen with either the BIA or NH listeners.

Figure 6 shows the LAI for four groups of listeners (seven NH and five BIA listeners from a previous study in addition to the four MOA and four ASYM listeners of this investigation). The data for each listener group are plotted in order of increasing LAI (absolute value). The error bars show the SEM for each group. All statistical tests that evaluated the significance of the LAI values were conducted with the use of the Bonferroni adjustment to account for multiple comparisons. We tested a total of 20 LAI values to determine if they differed significantly from zero.

The lowest curve in **Figure 6** shows the LAI values for the seven NH listeners. The largest LAI for this group was 1.6°, which was statistically significant ($p > 0.95$). The second lowest curve shows the LAI values for the five BIA listeners. Two of these listeners had LAIs that were significantly greater than zero (1.8° and 5.1°, $p > 0.95$), which indicates a higher degree of asymmetry among the BIA listeners than among the NH listeners. The next highest curve shows the LAI values for the MOA group. As a group, these listeners showed consistently higher LAI values than the BIA listeners. However, because the test-retest variability of the MOA listeners was much larger than either the NH or BIA groups, only one of the MOA listeners showed a statistically significant LAI of 9.3° ($p > 0.95$). This LAI is substantially larger than any of the LAIs obtained for the BIA and NH listeners. The ASYM listeners, as expected, showed the largest LAIs. All four of the ASYM listeners showed statistically significant LAIs with values ranging from 2.1° to 13.7°. Asymmetries of this magnitude are clearly evident even without the use of a sensitive asymmetry index.

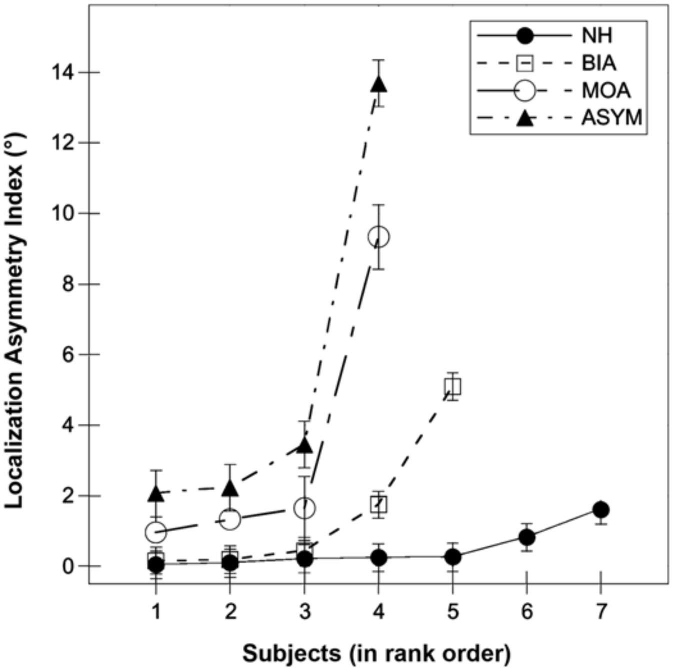

Figure 6.
Localization asymmetry index (LAI) for four groups of listeners. LAI values for listeners within a group are plotted in order of increasing magnitude. Abscissa shows listeners; ordinate shows LAI values. Error bars show standard error of mean for each group. NH = normal hearing, BIA = bilaterally aided, MOA = monaurally aided, and ASYM = asymmetric hearing loss.

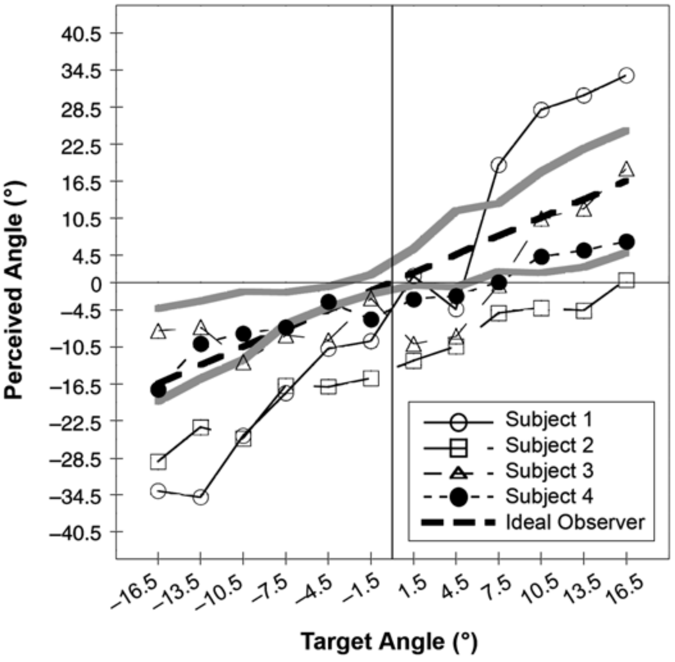

Figure 5.
Perceived angle as a function of target angle for asymmetric hearing loss listeners. Thick gray lines represent 95% confidence interval for group of 5 bilaterally aided listeners.

DISCUSSION AND CLINICAL IMPLICATIONS

The work that has been discussed in this and previous articles [104] shows that BIA and NH listeners manifest very high degrees of symmetry (and negligibly small LAI values) in their judgments of perceived angle while the MOA listeners had relatively large LAI values. Whereas plots of perceived angle showed that only two of the MOA listeners fell well outside the range for BIA listeners, LAI values were consistently higher for the MOA listeners. These data show that asymmetry in localization judgments is a much more sensitive indicator of abnormal localization ability than the magnitude of localization errors. The ASYM listeners showed substantial errors of localization in the expected direction. Since the errors were highly asymmetric, the LAI indices for this group were large, much larger than the average error (bias) in localization judgments.

As a result of recent studies and the present findings, the current practices for fitting “binaural” hearing aids have become an important issue [4]. Simon and Aleksandrovsky [4] and others [1–3] argued that the common assumption that two optimally fit monaural hearing aids constitute an optimum binaural fit is not necessarily true. The importance of true binaural and the insufficiency of simple bilateral hearing aid fitting have recently been emphasized [4–5]. Some interaction between both hearing aids is necessary to access the binaural advantage. However, what constitutes this interaction is unclear. Kimberly et al. suggest that adjustments of the interaural amplitude ratio are necessary to compensate for an asymmetric loss [105]. Jerger et al. [106] and Schweitzer [107] consider the phase relationships between the two hearing aids to be important and suggest variable phase adjusters for varying phase relationships to reflect individual differences. Thus, some relationship between the two hearing aids in either time or intensity is being advocated. Digital binaural hearing aids with considerable flexibility in controlling the signals that reach each ear have recently been introduced. The LAI, because of its simplicity and great sensitivity, should prove to be a useful tool in establishing how well a person fitted with a true binaural hearing aid is able to localize sound and in establishing fitting procedures for true binaural amplification.

CONCLUSIONS

This article has shown that in the tide of the evolution of bilateral hearing aids we are now experiencing a flow of research, technology, and clinical application for this fitting option. As recently as 1988, monaural hearing aid use for a few months, until the patient had become accustomed to wearing the aid, followed by a second hearing aid that is fit at a later date was still considered a viable option, although not necessarily the first choice [108]. In contrast, this article has shown, on the basis of recent research and clinical and theoretical arguments, that bilateral hearing aids should be the first choice for maximization of localization ability [34]. An important conclusion of this and other studies (Simon et al. see footnote p. 123) is that, although most listeners with moderate hearing loss have good to excellent accuracy of localization, some will always have difficulty localizing sound, possibly as a result of monaural amplification or poorly fit bilateral hearing aids. In addition, the decreased localization ability may be seen in the unaided situation, especially with monaurally fit individuals. Audiologists need to be alert to this possibility and the methods to deal with it. We are hopeful that basic and clinical research regarding these issues of binaural and bilateral advantages will continue on the present scale.

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