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The effects of hearing impairment, age, and hearing aids on the use of self motion for determining front/back location

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Abstract

Background—There are two cues that listeners use to disambiguate the front/back location of a sound source: high-frequency spectral cues associated with the head and pinnae, and self-motion-related binaural cues. The use of these cues can be compromised in listeners with hearing impairment and users of hearing aids.

Purpose—To determine how age, hearing impairment, and the use of hearing aids affects a listener's ability to determine front from back based on both self motion and spectral cues.

Research Design—We utilized a previously published front/back illusion: signals whose physical source location is rotated around the head at twice the angular rate of the listener's head movements are perceptually located in the opposite hemifield from where they physically are. In normal hearing listeners the strength of this illusion decreases as a function of low-pass filter cutoff frequency; this is the result of a conflict between spectral cues and dynamic binaural cues for sound source location. The illusion was used as an assay of self-motion processing in listeners with hearing impairment and users of hearing aids.

Study Sample—We recruited 40 hearing impaired subjects, with an average age of 62 years. The data for three listeners were discarded because they did not move their heads enough during the experiment.

Data Collection and Analysis—Listeners sat at the center of a ring of 24 loudspeakers, turned their heads back and forth, and used a wireless keypad to report the front/back location of statically presented signals and of dynamically moving signals with illusory locations. Front/back accuracy for static signals, the strength of front/back illusions, and minimum audible movement angle was measured for each listener in each condition. All measurements were made in each listener both aided and unaided.

Results—Hearing impaired listeners were less accurate at front/back discrimination for both static and illusory conditions. Neither static nor illusory conditions were affected by high-frequency content. Hearing-aids had heterogeneous effects from listener to listener, but, independent of other factors, on average listeners wearing aids exhibited a spectrally dependent

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increase in “front” responses: the more high-frequency energy in the signal, the more likely they were to report it as coming from the front.

Conclusions—Hearing impairment was associated with a decrease in the accuracy of self motion processing for both static and moving signals. Hearing aids may not always reproduce dynamic self-motion-related cues with sufficient fidelity to allow reliable front/back discrimination.

MeSH Keywords

Head movements; sound localization; hearing loss; hearing aids

Other Keywords

Front/back confusion

1 Introduction

1.1 Auditory/vestibular integration

Sound sources can and do move in the world. While this “source motion” does occur often, our own “self motion” is practically continuous: we are rarely perfectly still. Even when the only task given to subjects is to remain still, they still move by a small but readily measureable amount (König and Sussmann 1955; Wersényi and Wilson 2015). Both speaking and listening are associated with yet larger movements (Hadar et al. 1983; Hadar et al. 1985). Any head movement, be it rotation (Wallach 1940) or translation (Martens et al 2011) is associated with a change in spectral cues at the eardrums because of the shape of the pinnae and with changes in binaural cues because of the movement of the ears. Provided one can take advantage of it, the constant movement of the auditory world constitutes a source of information on the spatial location of signals. Listeners with sufficient acuity may, for example, compare subtle head movements to the resulting subtle acoustic motion of an approaching car to determine if it is ahead or behind them.

It has been demonstrated that dynamic binaural cues can be used to help with sound localization (Perrett and Noble 1997; Thurlow and Runge 1967), particularly in resolving the front/back location of signals (Kim et al. 2013; Wightman and Kistler 1999; Brimijoin and Akeroyd 2012), but to make ideal use of them in conjunction with the spectral cues to direction requires that three conditions be satisfied: 1) that the listener has sensitivity to the frequencies where spectral pinna cues are most informative to spatial location, 2) that the listener be able to accurately determine the way in which binaural cues change over time, and 3) that the listener have accurate information on their own movement. Hearing impairment is associated with changes in each of these three conditions: it typically involves a decrease in sensitivity to high-frequency sounds, poorer processing of binaural cues, and is frequently co-morbid with vestibular and balance disorders (Zuniga et al. 2012). Thus it is reasonable to suppose that listeners with hearing impairment may have significantly greater difficulty utilizing localization cues while they are moving their heads.

The goal of the current study was to measure how well listeners with hearing impairment can utilize spectral and dynamic binaural cues for front/back sound source localization while moving their heads, and how the use of hearing aids interacts with these abilities. To do this, we used as our assay of self-motion processing a previously published spatial phenomenon – the front/back illusion (Brimijoin and Akeroyd 2012; Wallach 1940) – to induce controllable front/back confusions in our participants.

1.2 Front/back confusion

Front/back confusions, i.e., mistaking the location of a signal in front as being behind, or vice versa, are among the most common types of spatial processing errors (Wightman and Kistler 1999). The primary cause of a front/back confusion is that the binaural cues of interaural level difference (ILD) and interaural time difference (ITD) are ambiguous front to back (Blauert 1983). For instance, a signal at 0° straight ahead and a signal at 180° straight behind both arrive simultaneously at the two ear canals with an equal sound pressure level (SPL), and binaural comparison either level or time cannot, in principle, distinguish them. Indeed the location of any pair of signals that share the same subtended angle off the acoustic midline are, at least in purely binaural terms, readily confusable with each other. Thus this ambiguity extends also into the vertical axis, and the generalization of this problem is known as the “cone of confusion,” an arc that describes all the angles in 3D space that share approximately the same ILDs and ITDs (Blauert 1983).

1.3 Cues for resolving front/back confusion

There are two major sources of information that may be used to disambiguate the direction of a sound source along the cone of confusion. The first is high-frequency spectral cues. The outer ear acts as a directionally dependent spectral filter that creates peaks and notches in a sound’s spectrum that change as a function of source position (Blauert 1983). By analysing the spectral content of the signal at the eardrum and comparing that spectrum to a set of learned spectral filtering patterns it is possible for the listener to establish the likeliest signal location along the cone. There are complications in making such an assessment, e.g., for brief signals the method would in principle require some level of a priori knowledge of the signal’s original spectrum (that is, before it had been filtered by the outer ear). Nonetheless the perceptual effect is robust enough that it can be exploited to present signals over headphones that appear to emanate from sound sources from specific directions out in the world (Brimijoin et al. 2013; Durlach et al. 1992).

The second major source of information on front/back location is found in how binaural cues change as the head moves (Wallach 1940; Wightman and Kistler 1999; Kim et al. 2013). The direction of a signal moves in opposition to any head movements: when the signal is directly in front of a listener, for example, it moves to the listener’s left when the head is turned to the right. Signals from the rear, however, move to the right when the listener turns to the right. Thus by turning the head and noting the direction in which the signal appears to move, a listener can make a reliable front/back determination (Brimijoin and Akeroyd 2012). Furthermore, the *rate* at which the sound source appears to move is a cue to the elevation of the sound source, since the gain with which the signal moves relative to the head is determined by the cosine of the angle of elevation (Wallach 1940). Signals directly above the listener, for example, do not change in their angle of incidence when the head turns. Thus the direction and rate at which binaural cues changes a function of head angle can also provide an unambiguous solution for sound direction along the cone of confusion (Wallach 1940), at least above the auditory horizon.

1.4 Hearing impairment, hearing aids, and front/back confusion

Hearing impaired listeners and users of hearing aids are both especially vulnerable to front/back confusion (Van den Bogaert et al. 2006; Akeroyd and Whitmer in press). There are two possible causes for this increase in errors; first, hearing loss may prevent listeners from accessing the high-frequency spectral cues that that help in resolving signal location. The issue is not resolved by providing hearing aids, because while they may restore high-frequency audibility, because of the typical behind-the-ear placement of the microphones the high frequencies restored may lack the relevant pinna cues required to disambiguate location. Second, hearing impairment may be associated with a decrease in the ability to process dynamic binaural cues. As a corollary to the above, it may be the case that hearing aids do not faithfully reproduce the binaural cues needed to make direction discriminations (Wiggins and Seeber 2011).

Previous work in our lab has demonstrated that in normal hearing listeners signal spectrum and dynamic binaural changes are roughly equally weighted for resolving front/back location (Brimijoin and Akeroyd 2012). There we produced front/back illusions using motion tracking of the head and realtime digital signal processing to move signals as a function of head movements. Signals whose source location is rotated around the head at twice the angular rate of head rotations are perceptually located on the opposite side of the head from where they are physically located. In normal-hearing listeners, this illusion is strongest for lowpass filtered sounds and weakens as the cutoff frequency is increased. The weakening of the illusion is the result of high-frequency pinna cues indicating a location opposite to that indicated by the self-motion cues (e.g., the movement of the head-tracked signals behind the listener would indicate a position in front, but the pinna cues would indicate a position in back). Such a pattern of response can only happen if the listener is able to make use of high-frequency cues for spatial location, that the listener can accurately process dynamically changing binaural cues, and that the listener has robust information on the direction of his/her own head rotations.

We used the front/back illusion paradigm from Brimijoin and Akeroyd (2012) to test the specific hypotheses that for hearing impaired listeners the strength of the illusion would be lower due to a decrease in binaural accuracy, that it would remain unaffected by spectral content due to a lack of high-frequency audibility, and that the use of hearing-aids would reduce its overall strength due to spectral and/or binaural cue distortion. Also, to determine the underlying ability of our listeners to process auditory source motion we measured the minimum audible movement angle, as for the illusion to occur a listener must presumably be capable of determining the motion of the signal.

2 Methods

2.1 Participants

We recruited 40 hearing impaired listeners. Three listeners were excluded from the analysis because in the experiment they turned their heads on average less than 15° (one loudspeaker interval). We collected complete data sets for the remaining 37 listeners, the mean unaided audiogram for whom is shown in Figure 1. All participants regularly used behind-the-ear hearing aids. On average these listeners exhibited a high-frequency roll-off in hearing threshold. The average age of the listeners was 62, ranging from 43 to 82 years old. The data shown for young normal hearing listeners (N = 7) is a subset of data previously published in Brimijoin and Akeroyd (2012). The measurement of the audiogram and all the experiments described below took roughly 1 ½ hours of testing and were accomplished in a single testing session.

2.2 Stimuli and Presentation

For stimuli, we used sentences drawn from the Adaptive Sentence List corpus (ASL - MacLeod and Summerfield 1987), lowpass filtered with cutoffs of 0.5, 1, 2, 4, or 8 kHz, and presented at a comfortable listening level (between 70 and 85 dB SPL). Each possible pair of condition/cutoff frequency was repeated 36 times with condition type and lowpass filter frequency fully randomized (see section 2.4.1 below). The signals varied in duration, with a mean duration of 1.53 ± 0.2 seconds (S.D.).

2.3 Motion tracking

Listeners were seated in a 1.8 m diameter circular ring of 24 loudspeakers placed at intervals of 15° (see Figure 2). Using six infrared motion tracking cameras (Vicon MX3+) running at 100 Hz, we measured the 3-D location of retro-reflective markers attached to a head-mounted crown (for more detailed motion tracking methods, see Brimijoin et al. (2010)). The marker locations were acquired from the hardware over TCP/IP by Matlab R13 (Mathworks, Natick MA, USA) at a rate of 100 Hz with a latency of less than 1 msec. Arctangent transforms of the XY coordinates of the front and back markers gave the azimuthal angle of the listener’s head. Similar to the techniques used in Brimijoin and Akeroyd (2012) the listener’s head angle was used to dynamically and smoothly move the location of a signal around the loudspeaker ring (Figure 2). The signals were panned between loudspeakers using sine/cosine panning to ensure equivalent level. For the purposes of the current experiment, 0° is defined as straight ahead with respect to the starting position of the listener, 180° is defined as the back, positive angles to the right, and negative angles to the left. All audio, both static and dynamic, was buffered in 24-channel 10 ms chunks of 441 samples in Matlab using the open source dynamic link library “playrec” (www.playrec.co.uk). Buffer segments were linearly cross faded over 64 samples from one to the next to prevent audible switching artefacts. Playback varied between double and triple buffering depending on Matlab processing requirements meaning that the overall latency from a head movement to a change in the signal varied between 11 and 31 msec (1-3 buffers plus overall processing latency of 1 ms).

2.4 Experimental Paradigm

2.4.1 Front/Back Illusion—Four conditions were run: (1) "static front," in which a signal was fixed in space, presented at an azimuth of 0°; (2) "static back," in which a signal was presented at 180°; (3) "front illusion," in which signals were presented from behind the listener, but panned between loudspeakers to locations 2 times the listener's head angle (Θ); and (4) "back illusion," in which signals were presented from the front but again moved at a rate of 2Θ (illustrated in Figure 2). Listeners were seated in the center of the ring and were asked to turn their heads gently back and forth between the loudspeakers at ±15°. This resulted in a roughly sinusoidal motion with a mean excursion across listeners of 38 ±17°. After the presentation of each sentence, listeners used a wireless keypad to report whether the signal was ahead or behind them.

The strength of the front/back illusion was computed as follows: For the two lowest filter cutoff frequencies (500 and 1000 Hz), the proportion of "front" responses in the front illusion condition was averaged together with the proportion of "back" responses in the back illusion condition. Under these rules, a value of 1.0 would indicate 100% front responses for the front illusion and 100% back responses for the back illusion. A value of 0.0 would indicate the opposite, i.e., a complete failure of the both illusions. The rationale behind using only the lowest frequency conditions was that it is at these conditions where the illusion is strongest for normal hearing listeners (Brimijoin and Akeroyd 2012).

2.4.2 MAMA test—We also performed a test of the minimum audible movement angle (MAMA) (Strybel et al. 1992). In this test a moving signal was presented at the front of the listeners and they were asked to report the direction (left or right) in which it appeared to move. The signals were unfiltered ASL sentences cropped to durations of either 0.75 or 1.5 seconds and moved either 1, 4, 16, or 32°. The angular movement of each signal was centered on 0° plus or minus a random offset between -7.5° and +7.5°. Signals were presented at the same comfortable listening level (between 70 and 85 dB SPL) as the signals in the front/back task. Both the order of the various conditions and actual left/right direction were randomized on a trial to trial basis. Listeners were given a wireless keypad to report the direction of movement. The psychometric functions were individually fit with a logistic function that was then solved for the movement angle resulting in 75% accuracy; this value we defined as the MAMA. The MAMA for 0.75 and 1.5 second movements were analysed separately, but since they were not statistically different from one another, the average of the two are presented in subsequent figures.

2.5 Statistics

All statistics were performed with SPSS 21 (IBM Armonk, NY, USA). The analysis consisted primarily of three way ANOVAs on cutoff frequency, stimulus condition, and hearing level with alpha set to 0.05. Three way ANOVAs were used as above to test differences between hearing aid conditions; these were run in a repeated-measures design. All post-hoc comparisons used Bonferroni corrected alpha.

2.6 Ethics

The experiment was conducted in accordance with procedures approved by the West of Scotland Research Ethics Service.

3 Results

For all lowpass filter cutoff frequencies, normal hearing listeners reliably identified static signals from the front as being from the front and signals from the back as being from the back. Hearing impaired listeners, on the other hand, were less accurate at determining front from back for statically presented signals. The difference between normal hearing and hearing impaired listeners was significant ($F_{(1, 245)} = 9.13$, $P = 0.003$) and can be observed in the dotted lines in Figures 3A versus 3B. For normal hearing listeners the strength of the front and back illusions tended to decline as a function of lowpass filter cutoff frequency. This is illustrated by the solid line plots trending towards a “front response” proportion of 0.5 in Figure 3A. However, this pattern was not observed in hearing impaired listeners. For this group, the salience of the front and back illusions did not decrease at any filter cutoff frequency (solid lines in Figure 3B). The apparent difference between the two groups is supported by a significant interaction between hearing status and ‘static’ versus ‘illusion’ stimulus condition ($F_{(1, 490)} = 35.65$, $P < 0.001$). Post hoc tests confirmed that filter cutoff frequency affected illusion strength for normal hearing listeners ($F_{(1, 30)} = 4.79$, $P = 0.004$) but not for hearing impaired listeners ($F_{(1, 215)} = 0.10$, $P = 0.982$).

Although we found a difference in illusion strength between normal hearing and hearing impaired listeners, we found no evidence for a consistent statistical relationship between illusion strength and degree of hearing loss among hearing impaired listeners ($R^2 = 0.02$). This relationship is plotted in Figure 4A. Similarly we found no correlation between illusion strength and age ($R^2 = 0.02$) (Figure 4B).

For a front or back illusion to exist, the listener must be capable of determining the direction in which the signal moved relative to the head. As an alternative measure of whether our listeners were capable of such direction discrimination, we also measured the MAMA for all listeners with and without their hearing aids. We found no evidence for a statistical relationship between MAMA and hearing impairment (Figure 5A) or age (Figure 5B) while listeners wore their hearing aids (R^2 values were 0.03 and 0.10, respectively) or when they unaided (R^2 values were 0.004 and 0.07, respectively (not depicted in the figure)). Furthermore we found no clear relationship between illusion strength and MAMA aided or unaided ($R^2 = 0.003$ and 0.01, respectively).

All listeners were also tested on the front/back illusion while wearing their hearing aids set to their self-identified most commonly used program. There was great heterogeneity in hearing aid type and fitting parameters from listener to listener, and as such these results may serve only to illustrate a general phenomenon, namely that hearing aids did not return hearing impaired listeners to normal listener performance. Figure 6 presents the grand average illusion response for listeners wearing their hearing aids. Similar to the results found in unaided listeners, we found no frequency dependent decrease in illusion strength as a function of filter cutoff frequency. Filter cutoff frequency did, however, appear to be associated with an increase in the likelihood of a “front” response. This conclusion is bolstered by a main effect of frequency on response across conditions ($F_{(1, 720)} = 9.52$, $P < 0.001$).

We further present the data split into two basic grouping conditions: unilateral versus bilateral fits, and open versus closed moulds. Figure 7 shows that there is difference in the pattern of response when the listeners were fitted unilaterally (N = 20, Figure 7A) versus bilaterally ($F_{(1, 720)} = 11.76$, $P = 0.001$) (N = 17, Figure 7B). This difference takes the form of a significant interaction between the fitting type (unilateral versus bilateral) and condition (illusion versus static) ($F_{(1, 720)} = 4.41$, $P = 0.036$). Post hoc testing showed that this interaction was due to the fact that bilaterally fitted listeners were poorer at identifying the front/back location of static signals ($F_{(1, 360)} = 25.80$, $P < 0.001$), but the strength of both front and back illusions was not different in listeners who were bilaterally fitted from those who were unilaterally fitted ($F_{(1, 360)} = 0.88$, $P = 0.35$). It is understandable that the distortion of spectral cues for spatial location in bilaterally fit listeners would make static source localization worse. But by the same logic this would be accompanied by an increase in the apparent strength of the illusion, due to a reduction in the salience of the veridical spectral cues for location, which we did not observe. We cannot currently explain this discrepancy.

The listeners were also subdivided into two groups based on the type of hearing aid mould they used, open (N = 17) and closed fits (N = 20). These results are plotted in Figures 8A and B, respectively. We found a main effect of mould type ($F_{(1, 720)} = 25.80$, $P < 0.001$). While the identification of static signals appeared to remain similar between the two types of mould, post hoc testing suggested that the differences were significant ($F_{(1, 360)} = 8.00$, $P = 0.005$). Closed fits were also associated with a decrease in the strength of the front and back illusions ($F_{(1, 360)} = 18.92$, $P < 0.001$). This change may be due to these listeners being denied uncontaminated low frequency ITD cues that have been shown to play an important role in front/back localization (Macpherson 2013).

The MAMA for our hearing impaired listeners was 12.9 ± 5.8° SD. While wearing hearing aids, this number was 13.1 ± 6.9° SD. This difference was not significant ($F_{(1,63)} = 0.35$, $p = 0.81$). Thus we found no impact of wearing hearing aids on a hearing-impaired listener’s threshold for motion direction judgements. We did not measure the MAMA for our normal hearing listeners.

4 Discussion

4.1 Hearing impairment and self-motion processing

There are three primary results from this experiment that provide information on the relationship between hearing impairment and the processing of self motion: first that hearing impaired listeners were less accurate than normal hearing listeners at identifying the front/back location of statically presented signals when they were turning their heads, second that they were less consistent in the identification of the front/back location of the illusion signals; and third that they did not experience a spectrally dependent decrease in illusion strength. These findings are argued to be primarily the result of 1) a change in dynamic binaural sensitivity, and 2) high-frequency hearing loss affecting the audibility of pinna cues.

4.1.1 Hearing impairment and dynamic binaural cues—

It has been repeatedly demonstrated that hearing impairment is associated with a decline in the spatial processing of static signal locations (Angell and Fite 1901; Tonning 1975; Hausler et al. 1983; Lorenzi et al. 1999; Akeroyd and Whitmer in press). One primary reason for this decline is thought to be binaural in nature. A reduced sensitivity to binaural temporal fine structure is seen in hearing impaired listeners (Neher et al. 2012) suggesting that one would see a concomitant decrease in acuity for interaural phase differences, and indeed listeners with hearing impairment often demonstrate deficits in ITD discrimination (King et al. 2014; Hawkins and Wightman 1980). There are few published studies on the effect of hearing impairment on ILD discrimination. One study reported just noticeable differences in ILDs of 2-8 dB (Gabriel et al. 1992), which are larger than the 1 dB typically seen in normal-hearing listeners, but the experiment was conducted with only four listeners. Changes in ILD discrimination could be at least roughly equivalent to a impairment-associated change in monaural (or diotic) level discrimination ability. Unfortunately, evidence of this in the literature is also scant, apart from gross differences between young normal hearing listeners and older hearing impaired listeners (Whitmer and Akeroyd 2011). Regardless of the fact that it is unclear whether access to and/or processing of the basic binaural level cue is affected by hearing impairment, demonstrable effects have been found on ITD.

Little research has been done on changes in auditory motion processing in hearing impairment, but by extrapolation one could assume that if static binaural cue processing is affected by hearing impairment, the ability of listeners to accurately determine direction and rate of source movement would be similarly impacted. For a signal to appear to move it must change in location by an angle as large as or larger than the minimum detectable separation, and so it could be argued that the MAMA (at least within a certain range of velocities) is simply a temporal extension of the minimum audible angle (MAA). The MAA is a measurement known to change with hearing impairment (Hausler et al. 1983; Brimijoin and Akeroyd 2014). Despite a lack of published work on the subject (c.f. Akeroyd and Whitmer, in press, for review), we argue that the observed deficit in static front/back localization and in illusion strength is due primarily to a hearing-impairment related decrease in binaural processing acuity.

4.1.2 Hearing impairment and high-frequency spatial cues—

Our listeners were asked to turn their heads back and forth during the whole course of the experiment, so in neither the illusion nor in the static conditions did any signals actually remain static with respect to the head. Thus the static and illusion conditions are related to each other in that they both require a listener to identify changes in the spatial location of signals with respect to the head as a function of time. The only difference between the two conditions was that in the static condition the dynamic binaural and spectral cues were congruent with each other, whereas in the illusion condition the binaural cues indicated a location opposite to that indicated by the spectral cues. We did not observe a difference between static and illusory conditions in our hearing impaired listeners; this is in contrast to normal hearing listeners and is most likely due simply to high-frequency audibility.

High-frequency hearing loss affects a listener's ability to make use of pinna cues for front/back location: that range of frequencies most informative for spatial location tend to be those that are lost. For normal hearing listeners, high-frequency content helps with sound localization (for a review see Middlebrooks and Green (1991)), particularly in the vertical plane (Roffler and Butler 1968; Butler and Humanski 1992). The role of high-frequency information can also be demonstrated in normal-hearing listeners in that using ear defenders and/or ear plugs as hearing protection is associated with a significant decrease in localization ability (Simpson et al. 2005; Noble 1981). High-frequency cues can also help to reduce front/back confusions (Musicant and Butler 1984). It is this reduction in front/back confusions that is of particular relevance to the current work. Our previous work demonstrated that the front/back illusion becomes less salient as high-frequency information is added. More accurately stated, owing to an irresolvable conflict between spectral cues and motion cues, the perceived location of full band front/back illusion signals is a bimodal percept, flickering front and back as either motion cues or spectral cues temporarily dominate (Brimijoin and Akeroyd 2012). In our hearing impaired listeners, we did not see an effect of high-frequency content on illusion strength. The absence of a role of high frequency in our hearing impaired listeners is entirely predictable given that the stimuli were presented between 70 and 85 dB SPL; this would suggest that the high-frequency energy in the signals was not audible for a substantial portion of the participants (see Figure 1). Thus the fact that we did not see a frequency-dependent drop in illusion strength is due to the fact that the disambiguating role of spectral content is likely not applicable for these listeners.

4.2 Hearing aids and self-motion processing

Individuals with hearing impairment are often given hearing aids to restore audibility to high frequencies. This increase in audibility helps with speech understanding in hearing impaired listeners. It is less clear what help they provide in terms of sound localization (Akeroyd and Whitmer in press). For normal hearing listeners it has been demonstrated that hearing aids significantly impair localization ability (Noble and Byrne 1990). For hearing impaired listeners, on the other hand, the relationship between hearing aids and spatial hearing is less clear. A few studies show some positive spatial acuity benefit (Byrne et al. 1992; Van den Bogaert et al. 2011) particularly when listeners use open-mould fittings (Noble et al. 1998; Byrne et al. 1996) or completely in-the-canal fits (Best et al. 2010; Jensen et al. 2013). A number of other studies, however, show no improvement or even a decline in localization ability (Noble and Byrne 1990; Dermody and Byrne 1975; Keidser et al. 2009). Given the heterogeneity of these conclusions, it is reasonable to suppose that the effect of hearing aids on localization performance, if any, is small. The one unambiguous conclusion that can be drawn is that hearing aids do not return a hearing impaired listener to normal listener performance in a front/back discrimination task (Byrne et al. 1998; Best et al. 2010). The possible reasons for this are potential distortions of binaural cues and a lack of spatially informative spectral cues.

4.2.1 Hearing aids and dynamic binaural cues—That hearing aids did not restore normal performance on the front/back illusion test may be in part attributed to the fact that hearing aids could interfere with binaural cues (Wiggins and Seeber 2012, 2013). Although prototype hearing aids that use gyroscopes and accelerometers to determine their own movement in space may be able to show some promise in being able to counteract the distortion of movement-induced spatial cues (Archer-Boyd et al. 2015), the current generation of devices do not take such information into account. The ILD cues that are generated by the head shadow are altered by the use of binaurally unlinked compression and this leads to a change in ILD discrimination performance (Musa-Shufani et al. 2006). A high level signal at the right ear, for example, will tend to engage the compressor more strongly in the right hearing aid than in the left hearing aid, reducing the magnitude of the ILD and effectively shifting the perceived sound location towards the midline. This constitutes a distortion of auditory space (Van den Bogaert et al. 2006). With these static spatial distortions in mind it would be reasonable to suppose that the spatial distortion of moving signals would be at least as impacted. High frequency ITDs are unlikely to be strongly affected by hearing aid processing, but compressors that alter level would necessarily distort envelope ITD cues, potentially leading to a temporal misrepresentation of acoustic space. Nevertheless, it should be noted that the use of bilaterally linked compression has been shown to improve speech perception in noisy, spatially complex environments (Wiggins and Seeber 2013). Further work is necessary to determine whether such benefits extend to listening while in motion.

4.2.2 Hearing aids and high-frequency spatial cues—A second potential reason that hearing aids do not return listeners to normal hearing performance on processing of auditory self motion is that they may not always be providing the listener with spatially informative high-frequency information. All the listeners in our study used the most common form of hearing aid, the ‘behind-the-ear’ hearing aid. The microphones on such hearing aids are located above and behind the pinnae. This location means that the signal arriving at such microphones largely bypasses the outer ear and its associated directionally dependent filtering, and is thus at least somewhat stripped of the corresponding spectral cues for sound direction. So while hearing aids restore the audibility of high-frequency information, the relevance of this high-frequency information for spatial location may be reduced.

4.2.3 Hearing aids and the heterogeneity of self motion processing—Our data suggests that aids in their most commonly used modes may not always provide the listener with spatially-informative spectral cues, and they may in some cases interfere with the perceptual weighting or indeed availability of dynamic self-movement-related cues. Both ILD and spectral distortions are potentially at play for statically presented signals, and by simple extension it follows that they must be similarly involved in a perceptual distortion of space for moving signals. It has been shown that hearing aids in different modes can affect the ability of listeners to turn their heads smoothly to new targets in a field of distractor noises (Brimijoin et al. 2014). Such findings are related to the fact that the type of microphones used can interact with spatial auditory localization (Ching et al. 2009; Chung et al. 2008; Keidser et al. 2006; Kuk et al. 1999). As for the current experiment, we made no attempt to control for differences in the make, model, or settings of the participants' hearing aids. All listeners were tested with their hearing aids set to the self-identified most commonly used program. In this way we hoped to determine whether the listener would typically receive any benefit on our task with their current hearing aids. The degree of heterogeneity in the effect of hearing aids cannot be understated, nor, however, can it be simply ascribed to the variety of hearing aids used by our listeners. Even in cases in which listeners used the identical brand and model of hearing aid we found that their effect on the strength of the front/back illusion could vary dramatically from listener to listener, ranging from no effect to a shift to an association of any high-frequency content with a front location. The two robust conclusions that can be drawn in the face of the observed heterogeneity are: 1) that the more high-frequency content in the signal, the more likely listeners were to report it as coming from the front. This could be either due to a simple mapping of frequency content onto front/back response options (the pinna does act as a low pass filter for signals from behind (Middlebrooks and Green 1991), or a genuine shift in their percept of the source location. We cannot currently distinguish between these two possibilities. And 2) that in no instance did the use of hearing aids return a hearing impaired listener to a performance resembling that of a normal-hearing listener.

Given the variability of responses of hearing aid users, we argue that the front/back illusion could be useful in the creation of sensitive tests for dynamic spatial hearing in moving listeners and the response of hearing aids in dynamic spatial scenarios. The role of bilaterally linked compression, for example, could be assessed with such measures. These tests would include acoustic measurements of both the spectrotemporal distortions and interaural level difference distortions introduced by hearing aids, potentially allowing one to determine the relative contribution of (and interaction between) these distortions to any observed deficits in dynamic spatial hearing performance. In combination with simple vestibular and/or balance assays, such sensitive tests for dynamic spatial hearing could lead to a more detailed understanding of the role of self-motion cues in dynamic spatial hearing and speech intelligibility, and an in-depth acoustic and phenomenological analysis of the effect of current hearing aids on the availability and usefulness of such cues. Such information could inform the next generation of hearing devices.

4.4 The relationship between the front/back illusion and the MAMA

The lack of a significant correlation between illusion strength and MAMA suggests that in this instance the threshold measurement (the MAMA) may be unrelated to suprathreshold motion processing (the illusion). The smallest amount of detectable motion would seem to be inextricably tied to the ability of listeners to integrate their own movements with the movements of the acoustic environment. They are however, in principle, two different phenomena. A potential second explanation for the lack of a consistent relationship between the MAMA and illusion strength is that it is due to unrevealed vestibular or balance issues (see section 4.6 below). That is, the ability of listeners to process moving binaural cues was preserved and the deficits observed were the result of an inability to accurately determine head movement and successfully integrate it with the movement of the world. We cannot resolve these questions with the current data set.

4.5 Age and self motion

In terms of static sound localization, some age related changes have been observed in spatial acuity (Abel et al. 2000) and in the ability to process binaural temporal fine structure (Neher et al. 2012), but age has been shown to far more greatly affect localization in elevation than azimuth (Otte et al. 2013). This finding was attributed to a decrease in high-frequency resolution and a concomitant loss of pinna cues for spatial location, which are more informative in the vertical dimension. We did not observe a strong correlation between age and either MAMA or illusion strength. It is possible that the range of participant ages was not large or distributed uniformly enough to make such an assessment, but since our experiment was conducted exclusively in azimuthal space it may be that age did not play a significant role.

4.6 Caveats and unknown factors

In order to accurately process self motion, one must not only have robust information on dynamic spatial acoustic cues, one must also have robust information on one’s own movement. Thus the function of the vestibular, proprioceptive, motor-planning, and/or visual systems also play an integral role in self-motion processing. We did not measure the vestibular health, sensitivity to proprioception, motor control ability, or visual motion acuity of our participants. Apart from clear co-morbidities between hearing loss and vestibular dysfunction in conditions like Meniere’s disease and auditory neuropathy (Starr et al. 1996), there is evidence of a significant association between hearing impairment and vestibular processing. In children with severe to profound hearing loss, for example, it is estimated that roughly one-fifth (Brookhouser et al. 1982) to one-third (Cushing et al. 2008) have some form of vestibular dysfunction, though other estimates put the percent of hearing impaired children with some degree of vestibular impairment as high as three-quarters (Maes et al. 2014). The variability in results may be due to a correlation between the extent of hearing impairment and extent of vestibular dysfunction (Sandberg and Terkildsen 1965). In adults the data is similar, abnormal vestibular-evoked myogenic potentials and/or caloric response can be found in about 70% of adults with noise-induced hearing loss (Tseng and Young 2013; Wang and Young 2007), and there is a significant correlation between hearing loss and saccular dysfunction in listeners 70 and older (Zuniga et al. 2012). This link between hearing and balance leaves open the distinct possibility that a sizeable number of our listeners may not have had a normal ability to estimate their own motion. This deficit, independent of any issues with spatial hearing, would manifest itself as a change in a listener’s ability to identify front/back location for both static and dynamic illusion signals. After all, inaccurate estimation of one’s own motion would have as great an impact on the ability to make use of acoustic self motion cues as would poor binaural processing. There is also the issue that vestibular signals are not the only information listeners have on their own motion, there are also proprioceptive inputs, motor efference copy, and visual cues to name a few (Harris et al. 2002), so more work is needed to address these aspects of multi-sensory integration in dynamic sound localization.

4.5 General Summary

Listener motion challenges the auditory system by requiring integration of both acoustic and non-acoustic cues. Further investigation into self-motion processing may be able to reveal spatial processing and possible knock-on intelligibility deficits that might be invisible when measured in standard, static ways. Since listeners are essentially in constant motion, we argue that such investigations are needed to assess the true impact of hearing impairment on and true benefit of hearing devices for listening in typical, dynamic situations.

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Abbreviations

ASL	Adaptive Sentence List
dB	Decibel
ILD	Interaural Level Difference
ITD	Interaural Time Difference
MAA	Minimum Audible Angle
MAMA	Minimum Audible Movement Angle
SPL	Sound Pressure Level

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Statement of Originality

Some of the data presented in this manuscript was presented as pilot data on a poster at the British Society of Audiology Meeting 4th – 6th September, 2013. The manuscript also contains means of some normal hearing data presented in Brimijoin & Akeroyd (2012) iPerception.

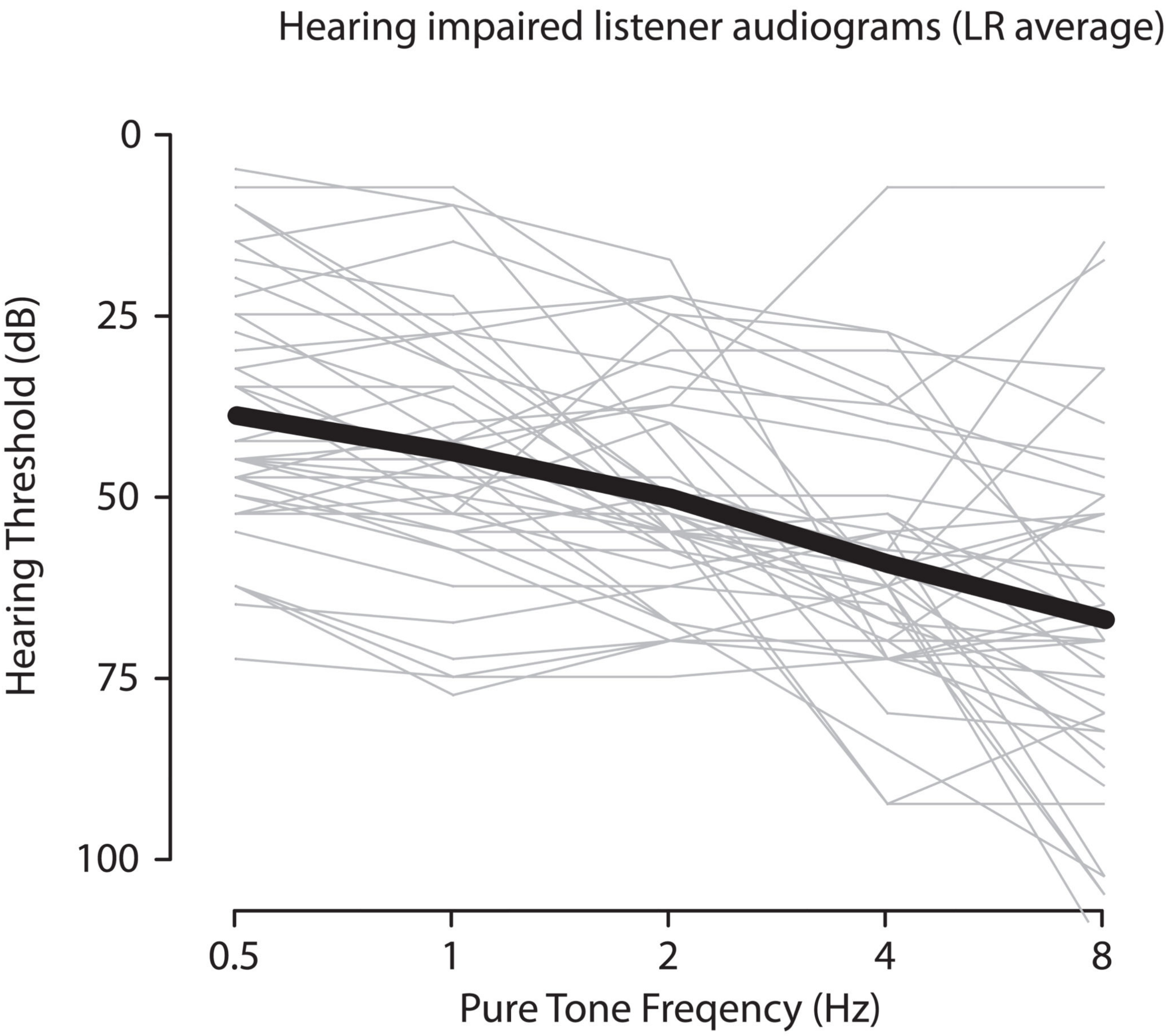

Figure 1.

Mean audiograms for our hearing impaired listeners (N = 37). Individual audiograms are shown in grey, mean in black. The typical profile was that of a sloping loss.

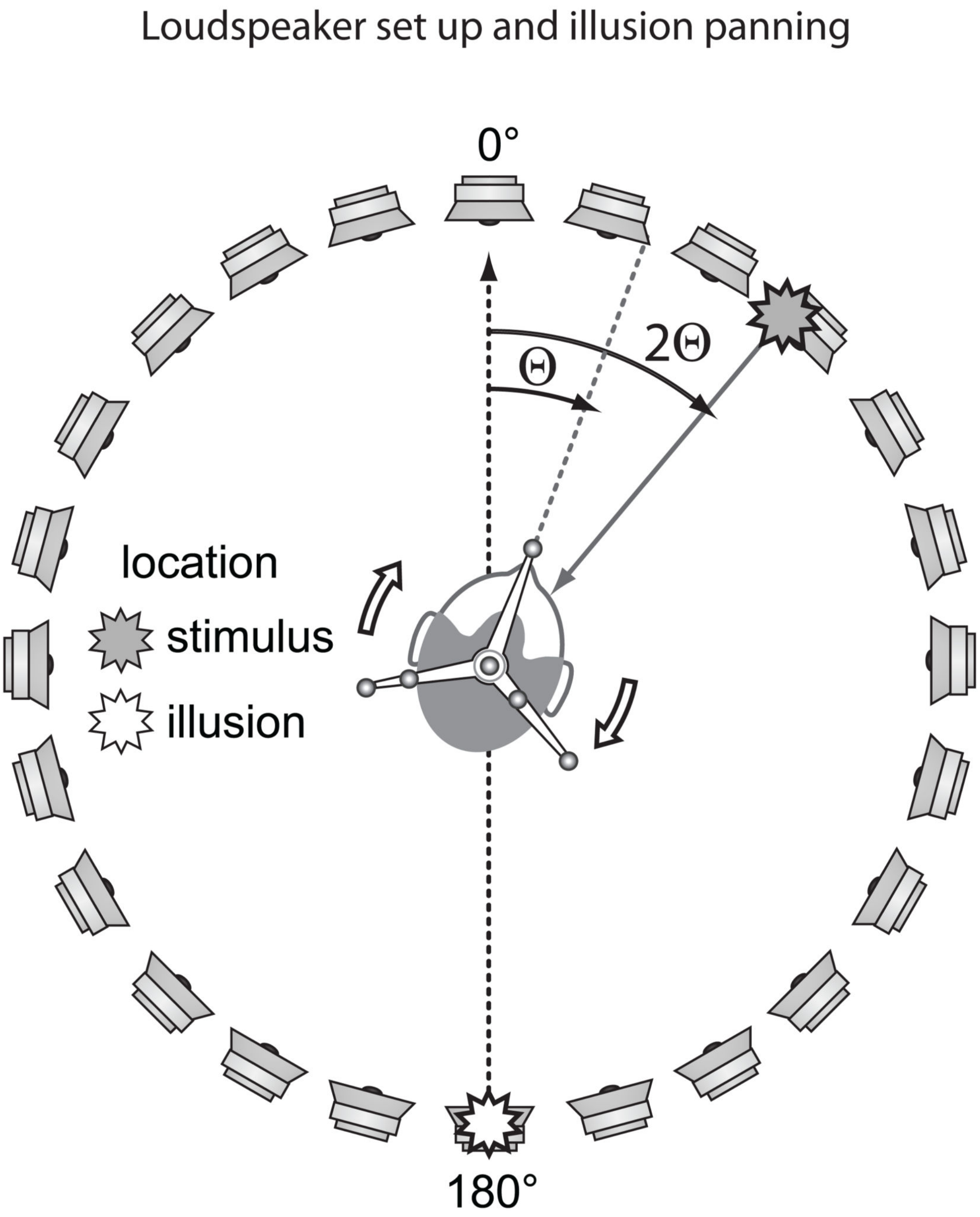

Figure 2.

Front/back illusion method. This figure illustrates the method for generating a front-to-back illusion. The head was tracked with infrared cameras measuring the position of retro-reflective markers mounted to a crown. The position of the signal (grey star) was smoothly panned across loudspeakers so as to be always exactly twice the angular position of the listener's head. At least for low-pass filtered signals, the perceptual location of this moving signal was that of a static signal located at 180° (white star). Although not pictured, a back-to-front illusion can be generated in a complimentary manner.

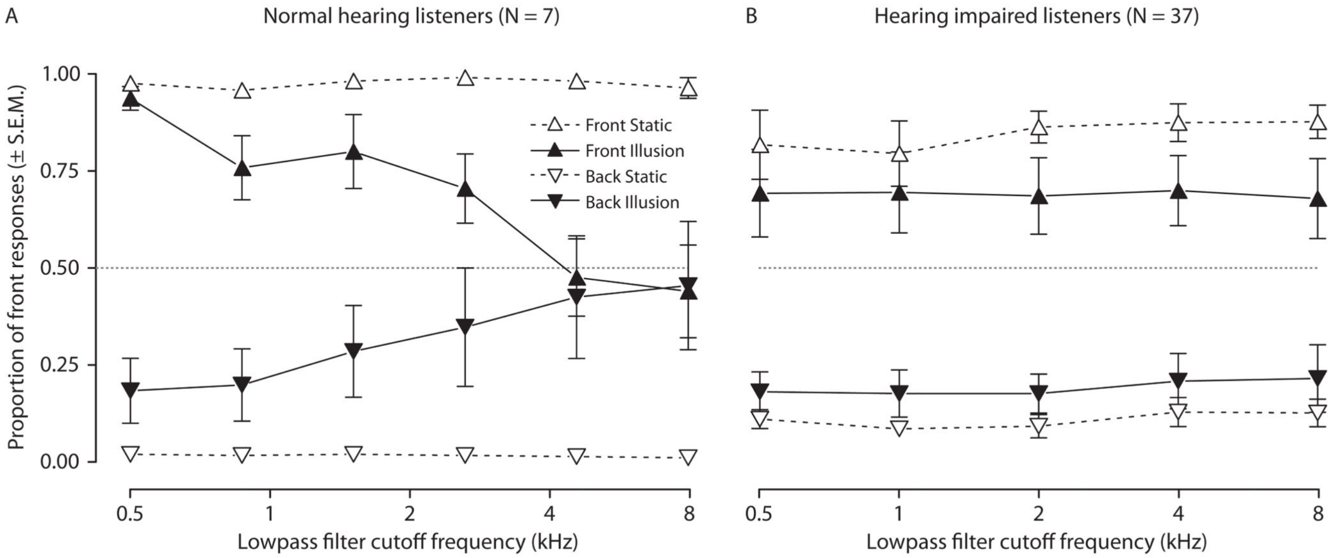

Figure 3.

Self-motion results for normal (A) and hearing impaired listeners (B). The dotted lines are mean proportion of “front” responses for static signals located in the front (open up triangles) and in the back (open down triangles). The solid lines represent illusion conditions, in which the signals were located in back but moved to simulate front locations (filled up triangles) or located in front but moved to simulate back locations (filled down triangles). The strength of the illusion decreased as a function of lowpass filter cutoff frequency for normal hearing listeners (A) but not for hearing impaired listeners (B).

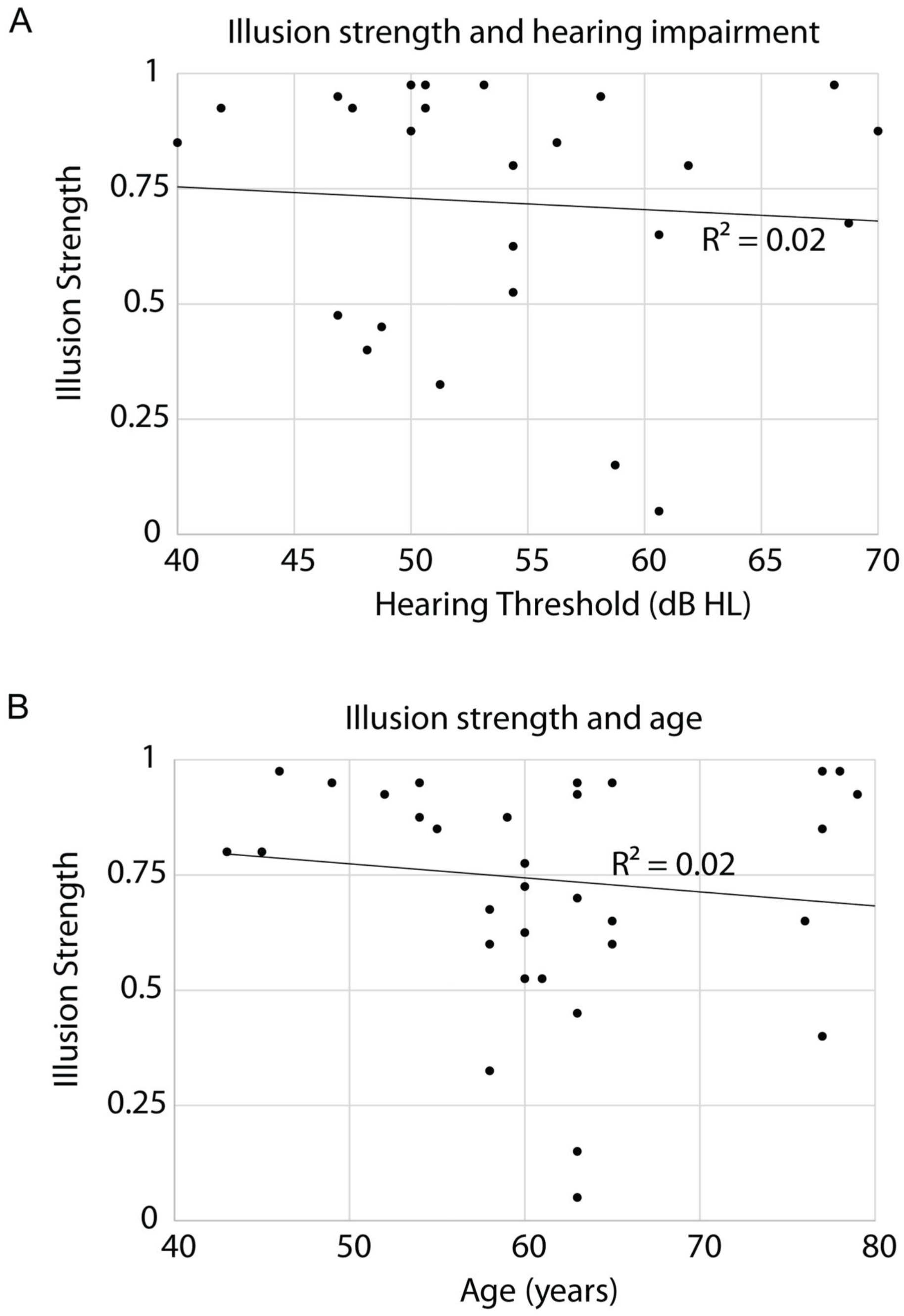

Figure 4.

Illusion strength as a function of hearing impairment (A) and age (B) among hearing impaired listeners. The dots represent individual data points for each listener. The solid lines are linear fits to the data, showing no consistent relationship between illusion strength and amount of hearing loss (A) or age (B).

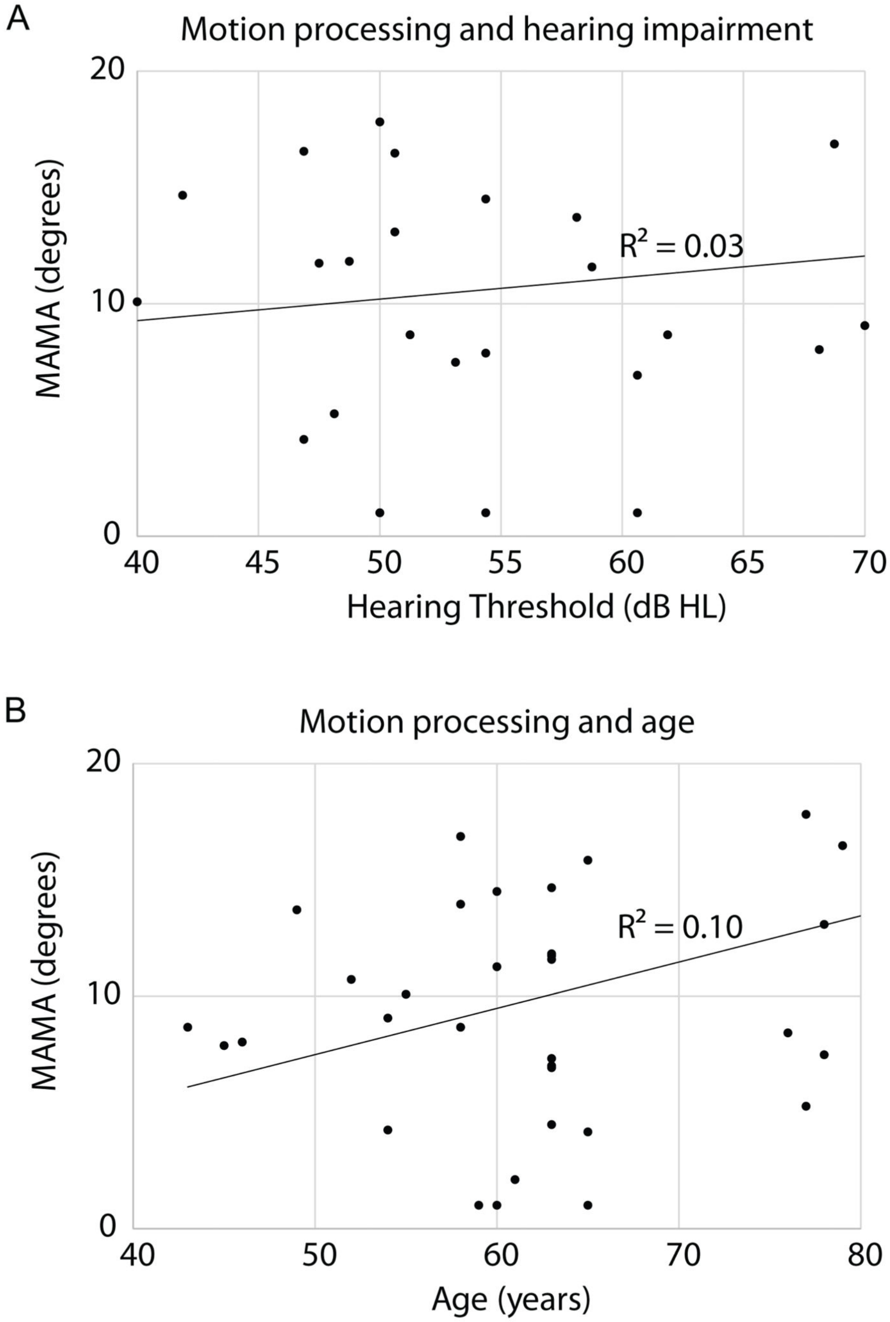

Figure 5.

MAMA as a function of hearing impairment (A) and age (B). Similar to the previous figure, the dots represent individual data points for each hearing impaired listener and the solid lines are a linear fit to the data. No consistent relationship was seen between MAMA and amount of hearing loss (A) or age (B).

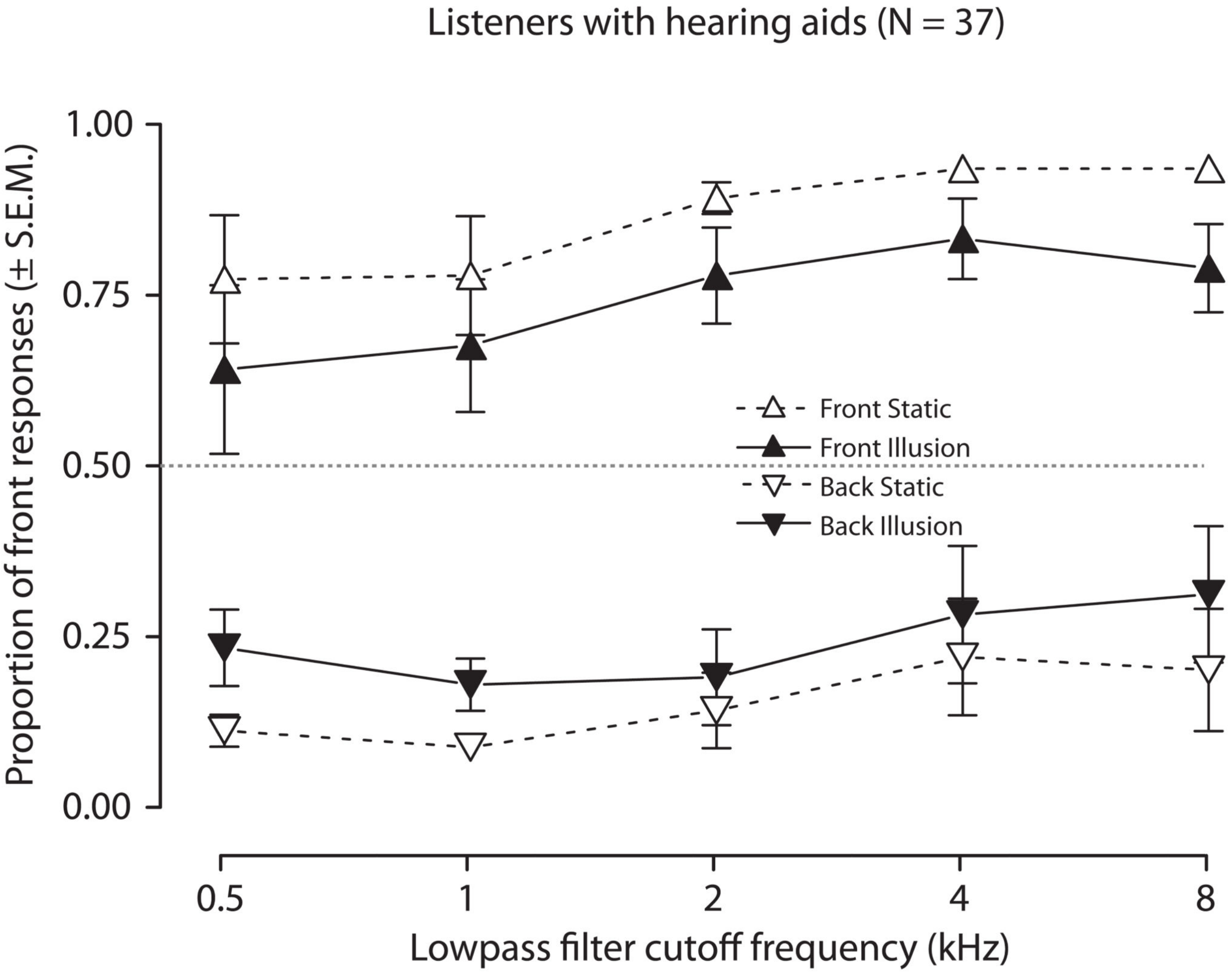

Figure 6.

Self-motion results for listeners wearing hearing aids. Symbols and lines are as seen in Figure 3. Across conditions, listeners wearing hearing aids were more likely to respond with a "front" response as amount of high-frequency energy was added to the signal.

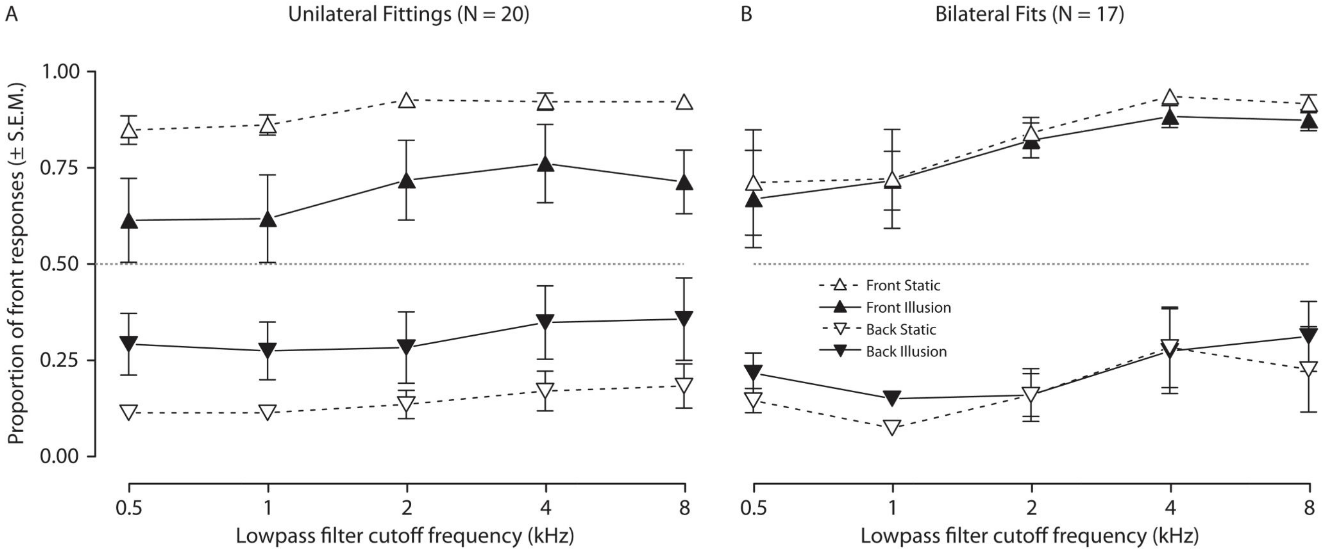

Figure 7.

Self-motion results for unilaterally fitted (A) and bilaterally fitted listeners (B). Symbols and lines are as seen in Figure 3. The accuracy of static front/back localization was lower for those fitted with two hearing aids than those fitted with only one. Response to the illusion conditions was not different between the two groups.

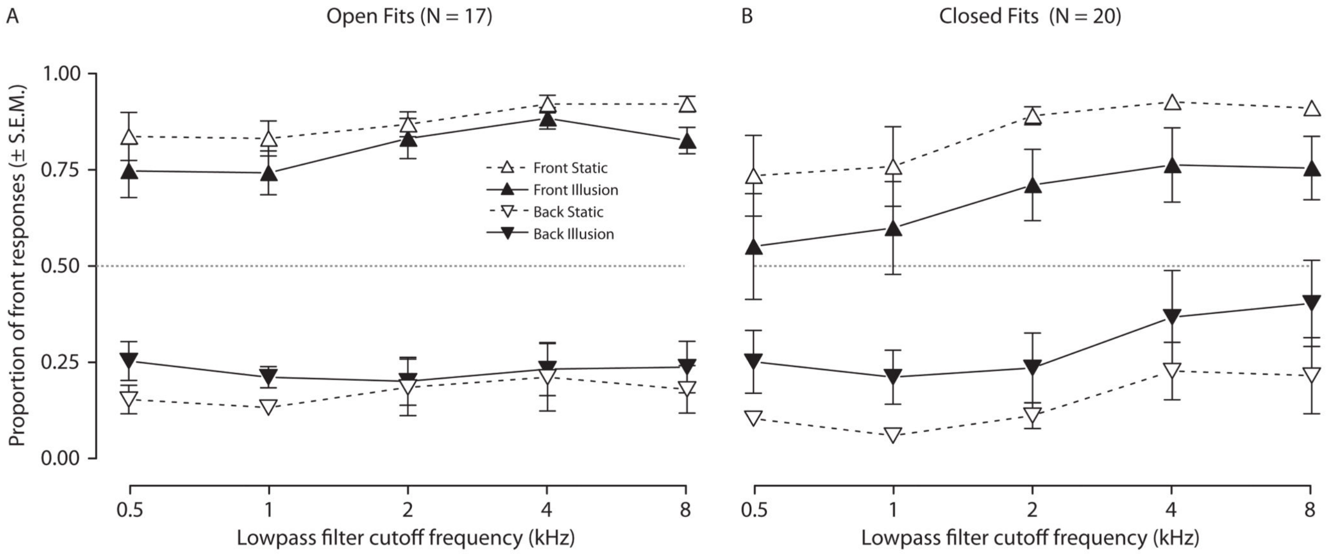

Figure 8.

Self-motion results for open fit (A) and closed fit listeners (B). Symbols and lines are as seen in Figure 3. Both illusion strength and static front/back localization accuracy were lower for those fitted with two hearing aids than those fitted with only one.