The Effects of Hearing Impairment and Aging on Spatial Processing

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Objectives: Difficulty in understanding speech in background noise is frequently reported by hearing-impaired people despite well-fitted amplification. Understanding speech in the presence of background noise involves segregating the various auditory stimuli into distinct streams using cues such as pitch characteristics, spatial location of speakers, and contextual information. One possible cause of listening difficulties in noise is reduced spatial-processing ability. Previous attempts to investigate spatial processing in hearing-impaired people have often been confounded by inadequate stimulus audibility. The present research aimed to investigate the effects of hearing impairment and aging on spatial-processing ability. The effect of cognitive ability on spatial processing was also explored. In addition, the relationship between spatial-processing ability and self-report measures of listening difficulty was examined to investigate how much effect spatial-processing ability has in real-world situations.

Design: Eighty participants aged between 7 and 89 years took part in the study. Participants' hearing thresholds ranged from within normal limits to a moderately severe sensorineural hearing loss. All participants had English as their first language and no reported learning disabilities. The study sample included both hearing aid users and non–hearing aid users. Spatial-processing ability was assessed with a modified version of the Listening in Spatialized Noise-Sentences test (LiSN-S). The LiSN-S was modified to incorporate a prescribed gain amplifier that amplified the target and distracting stimulus according to the National Acoustic Laboratories-Revised Profound (NAL-RP) prescription. In addition, participants aged 18 years and above completed the Neurobehavioral Cognitive Status examination and the Speech, Spatial and Qualities questionnaire. Participants aged under 18 years completed the Listening Inventory for Education questionnaire.

Results: Spatial-processing ability, as measured by the spatial advantage measure of the LiSN-S, was negatively affected by hearing impairment. Aging was not significantly correlated with spatial-processing ability. No significant relationship was found between cognitive ability and spatial processing. Self-reported listening difficulty in children, as measured with the Listening Inventory for Education, and spatial-processing ability were not correlated. Self-reported listening difficulty in adults, as measured by the Speech, Spatial and Qualities questionnaire, was significantly correlated with spatial-processing ability.

Conclusions: All hearing-impaired people will have a spatial processing deficit of some degree. This should be given due consideration when counseling patients in regard to realistic expectations of how they will perform in background noise. Further research is required into potential remediation for spatial-processing deficits and the cause of these deficits.

(Ear & Hearing 2013;34:15–28)

INTRODUCTION

The process of understanding speech in simultaneous background noise involves separating the acoustic information into discrete streams. This process is referred to as auditory stream segregation (Bregman 1990). This can be done based on many different elements including the location of the sound source, intensity differences, spectral differences or contextual information (Alain 2007). Cameron and Dillon (2008) have shown that spatial-processing disorder, defined by the authors as a reduced ability to segregate streams based on their location in space, is a major reason why some children with apparently normal hearing nonetheless have difficulty understanding speech in noise. Investigation of the prevalence of spatial-processing disorder in hearing-impaired people is therefore warranted to establish whether reduced spatial-processing ability contributes to the difficulty understanding speech in noise that is commonly reported by hearing-impaired people, even after audibility has been restored with hearing aids.

The ability to selectively attend to sounds arising from one direction in space, although simultaneously suppressing sounds arising from another, is in part reliant on the detection and interpretation of small differences in the intensity and timing of the signals between the ears. When a sound originates from any point in space, other than one at 0-degree or 180-degree azimuth, it will arrive at one ear earlier than it reaches the other, creating interaural time differences (ITDs) (Bamiou 2007). Interaural intensity differences (IIDs), which are caused by the head shadow effect, also assist listeners in localizing sounds in space (Bamiou 2007). These interaural differences are interpreted in the central auditory nervous system, but for this interpretation to take place the differences have to be faithfully relayed by the peripheral auditory system. It can be hypothesized that the presence of a sensorineural hearing loss can degrade the signal that reaches the central auditory nervous system.

A number of researchers have previously investigated spatial-processing ability in hearing-impaired people, with mixed and widely variable results (see Glyde et al. 2011 for review). Many studies have reported that spatial-processing abilities seem to be reduced for hearing-impaired people when compared with normally hearing individuals (Gelfand et al. 1988; Dubno et al. 2002; Arbogast et al. 2005; Ching et al. 2011). However, attempts to unravel whether reduced spatial-processing ability is a cause of poor speech understanding in complex listening environments have often been hampered by a range of factors. For example, some researchers have chosen to limit investigations to the elderly population, in which hearing impairment and problems of hearing in noise are most common. By choosing an older subset of hearing-impaired people factors that occur with aging, regardless of peripheral hearing ability, such as declining cognition, must also be considered as possible contributors to difficulty in understanding speech in noise.

Despite the added complexity of assessing spatial processing in an aging population, the effect of age on spatial processing merits exploration. As Divenyi et al. (2005), among others, point out, aging leads to greater degradation of speech understanding in background noise. If worsening spatial-processing

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ability is contributing to the reported deterioration, then clinicians and researchers alike should take spatial-processing ability into account when assessing and managing patients. A research design that incorporates hearing-impaired people across a large age range will allow for the effect of aging to be differentiated from the effect of hearing loss. Such a design is preferable in several respects to one in which a group of "young adults" is compared with a group of "older adults." First, age-related changes may be gradual and could exist within each age category. Second, arbitrary decisions about what constitutes an older adult, which does not necessarily reflect the beginning of age-related deterioration, are avoided. Third, if older adults with normal hearing can be found, these individuals are not typical representations of older adults in general and their results cannot be generalized to others. It is possible that the same factors that enabled these individuals to have better hearing than is normal for their age might have caused them to also have better neural processing within the auditory system than is normal for their age.

Another factor that could explain inconsistencies in reported spatial-processing skills may be the various methods researchers have used to ensure stimuli audibility. If adequate audibility of the test stimuli is not achieved participants may not have access to the ITDs and IIDs that are used in spatial processing. One method of achieving audibility, increasing the overall intensity of the test stimuli for the hearing-impaired participants relative to the normal-hearing participants, has been used widely in studies of spatial processing (Warren et al. 1978; Divenyi and Haupt 1997; Arbogast et al. 2005; Murphy et al. 2006). For example, Gelfand et al. (1988) employed this method of achieving audibility and found that presbycusic older adults gained significantly less benefit from access to spatial cues than age-matched normal hearers (5 dB advantage for normal-hearing group, 3.5 dB for presbycusic group). Although this result provides support for the theory that spatial processing is deficient in hearing-impaired people it is possible that, given no frequency-specific adjustment was made to the stimuli to ensure that the high-frequency components of the speech were equally audible for the presbycusic group, they did not have the same opportunity to make use of IIDs (which are dominant in the high frequencies). An alternative method for achieving audibility across all frequencies was used by Ahlstrom et al. (2009) and Marrone et al. (2008). Participants' spatial-processing ability was assessed although they were wearing bilateral hearing aids fitted to within 5 dB of National Acoustic Laboratories-Nonlinear 1 (NAL-NL1) prescription targets. This approach increased the likelihood that participants had access to all the frequencies across the speech spectrum. Using this approach Ahlstrom et al. demonstrated that hearing-impaired older adults could gain more than 4 dB benefit from access to spatial cues.

It is interesting that Marrone et al. (2008) found that there was no significant difference in the amount of benefit in dB gained from access to spatial cues when frequency-dependent amplification using hearing aids was applied versus increasing the overall level of the stimulus. The authors suggested that the recorded lack of difference in benefit between amplification methods may be a result of the fact that testing with hearing aids in situ can alter ITD information and subsequently may not provide an ideal solution to the problem of how best to ensure audibility while testing spatial-processing ability.

Given the inherent limitations (inadequate high-frequency amplification or loss of ITD) in both methods used for ensuring audibility when measuring spatial-processing ability in hearing-impaired people, it is plausible that the differences observed in spatial-processing ability between normal-hearing control groups and hearing-impaired groups could be partially explained by inadequate access to IIDs or distorted ITDs. To control for these confounding factors a third method of achieving adequate audibility was used for the present study. Frequency-dependent amplification, based on the NAL-RP prescription (Byrne et al. 1990) specified for each participant, was directly applied to the prerecorded target stimuli and maskers before presentation.

The Listening in Spatialized Noise-Sentences test (LiSN-S) was specifically developed using head-related transfer functions to assess spatial processing ability under headphones (Cameron & Dillon 2007). The LiSN-S uses an adaptive sentence repetition task to establish the speech-reception threshold (SRT) of the listener in four different conditions that vary according to whether spatial, pitch, or both spatial and pitch cues are provided (Cameron & Dillon 2007). Target sentences are perceived as coming from directly in front of the listener (0-degree azimuth). Simultaneously presented distracter speech (looped children's stories) varies according to either their perceived spatial location (0-degree versus and ±90-degree azimuth), the vocal identity of the speaker/s of the stories (same as, or different to, the speaker of the target sentences), or both. This test configuration results in four listening conditions: same voice at 0 degree (or low-cue SRT); same voice at ±90 degrees; different voices at 0 degree; and different voices at ±90 degrees (or high-cue SRT).

Performance on the LISN-S is summarized by the low- and high-cue SRT and on three "advantage" measures. These advantage measures represent the benefit in dB gained when either talker (pitch), spatial (location), or both talker and spatial cues are incorporated in the maskers, compared with the baseline (low-cue SRT) condition in which neither of these cues are present in the maskers (Fig. 1). The use of relative measures of performance (i.e., difference scores) minimizes the influence of higher-order language, learning, and communication skills on test performance. This allows for clearer evaluation of a participant's ability to use spatial cues to aid speech understanding (Cameron et al. 2009). This configuration allows the user to isolate how much benefit is gained specifically from access to spatial cues and makes it ideal for use in this investigation. The high-cue SRT provides the most realistic listening conditions whereas the low-cue SRT, though unrealistic, serves as a baseline score to which performance in the other conditions can be compared.

Aims

The major aim of the present research was to investigate the effect of hearing impairment and aging on processing of speech in spatially collocated and spatially separated competing signals. Sensorineural hearing loss has been linked to a reduction in the number of afferent fibers from the inner hair cells of the cochlea, leading to less-accurate temporal resolution (Schmiedt 2010). Gates and Mills (2005) explain that this reduction can lead to poorly synchronized activity in the auditory nerve. Given that spatial processing relies, at least in part, on ITD cues, it is hypothesized that hearing impairment should directly cause

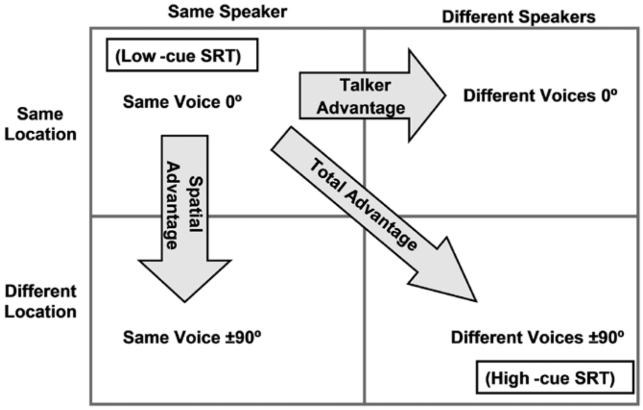


Fig. 1. The Listening in Spatialized Noise-Sentences test SRT and advantage measures. SRT, speech-reception threshold.

reduced spatial-processing abilities. Also, given that previous research with normal-hearing participants aged up to 60 years failed to show any decline in spatial-processing ability with age (Cameron et al. 2011), it is reasonable to hypothesize that age should not affect spatial-processing ability in hearing-impaired adults at least until 60 years of age.

Secondary aims were to (1) explore the effect of cognition on spatial-processing ability and (2) to examine the relationship between spatial-processing ability and self-report measures of listening difficulty.

PARTICIPANTS AND METHODS

Ethical clearance to conduct this research study was obtained from the Australian Hearing Ethics Committee and the University of Queensland Behavioral and Social Sciences Ethical Review Committee.

Participants

Eighty participants between 7 and 89 years of age were tested in a sound-attenuated booth at the National Acoustic Laboratories in Sydney or at the University of Queensland Audiology Clinic. Participants had a range of audiometric thresholds, from completely within normal limits between 250 Hz to 8000 Hz, to moderately severe in degree in the worse ear. The distribution of hearing thresholds across age is shown in Figure 2. Of the sample of 80, 35 participants reported that they were regular hearing aid users. The participants spoke English as their first language and reported no history of learning or attention disorders. A summary of participant details is provided in Table 1.

A wide range of recruitment methods was used in an effort to obtain a diverse sample of the hearing-impaired community. Participants were recruited from the National Acoustic Laboratories participant database, from family and friends of National Acoustic Laboratories staff, via flyers placed on hearing support-group web sites, and from local audiology clinics. Participants were excluded from the study if an air–bone gap of more than 10 dB was measured at one or more frequencies on a pure-tone audiogram, as conductive or mixed hearing loss may have different effects on the binaural cues used in spatial processing. Participants were also required to have type A tympanograms bilaterally.

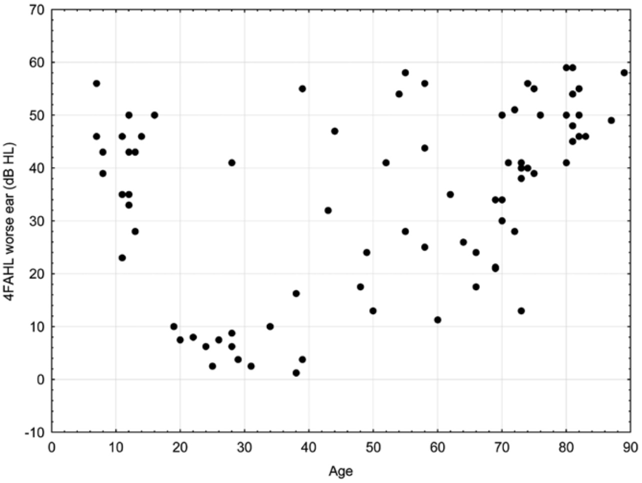


Fig. 2. Distribution of hearing thresholds by age (n = 80). 4FAHL, four-frequency average hearing loss.

Materials

A number of tests and self-report measures were used in the study. To ensure that the materials were appropriate for use with a hearing-impaired population and would allow the research aims to be achieved some modifications to materials were required. Test materials were:

1. The LiSN-S (Cameron & Dillon 2009). The LiSN-S target stimuli comprised short sentences (average five words in length) designed to be understandable to children from 4 years of age. The two competing discourse signals were children's stories that repeated continuously during the test. Further details of the LiSN-S software are provided in Cameron and Dillon (2007). Instructions for the LiSN-S were given in accordance with those recommended in Cameron and Dillon. The target sentences and competing stories were presented simultaneously to both ears. The participants were required to repeat as many words from the target sentences as possible. The beginning of each sentence was signaled by the presentation of a brief 1000 Hz tone. Each participant completed all four conditions of the LiSN-S (different voices at ±90 degrees, different voices at 0 degree, same voice at ±90 degrees, and same voice at 0 degree), which were presented in this order for all participants, as recommended by Cameron and Dillon.

   The LiSN-S software was modified so that the speech stimuli were adjusted to suit each participant using the

TABLE 1. Summary of participant details (N = 80)

	Mean	Range	SD
Age (yrs;mos)	50;2	7;0 to 89;0	26;4
4FAHL worse ear	33.4 dB	1.3 to 58.8 dB	17.2
4FAHL better ear	29.4 dB	−3.8 to 56.2 dB	17.6
250 Hz worse ear	18.9 dB	0 to 55 dB	13.1
500 Hz worse ear	22.3 dB	−5 to 55 dB	15.3
1000 Hz worse ear	28.7 dB	0 to 60 dB	17.9
2000 Hz worse ear	38.3 dB	0 to 75 dB	20.1
4000 Hz worse ear	46.1 dB	−5 to 90 dB	25.0
8000 Hz worse ear	56.1 dB	−5 to 100 dB	29.0

4FAHL, four-frequency average hearing loss (500, 1000, 2000, and 4000 Hz).

prescribed gain amplifier software developed for the study. Processing was carried out separately for each ear. The NAL-RP prescribed insertion gain was calculated by the software, using the participant's audiogram for each ear, and based on the formula described in Dillon (2001). The average gain, calculated across the audiometric frequencies from 250 Hz to 4000 Hz, was subtracted from the gain at each frequency, to give the gain shape. This gain shape was applied to the original LiSN-S stimuli (target and distracter speech files) by applying a Fourier transform to convert the signal to the frequency domain, then applying a linearly interpolated version of the gain shape, and finally applying an inverse Fourier transform to convert the signal back to the time domain. A 2:1 overlap-add processing scheme, with a 512-point transform was used. The speech files were modified and stored before testing. The processing increased the combined gain of the sound driver and sound card above the usual LiSN-S calibrated level during testing by the average gain required for each participant.

The LiSN-S stimuli were presented on Sennheiser HD215 headphones, which were connected to the computer via a Phonak-branded Buddy 6G USB soundcard. The software automatically controlled the output level of the soundcard, removing the need for daily calibration. Before amplification was applied the distracters had a combined output level of 55 dB SPL, and the first target sentence presented had an output level of 62 dB SPL.

2. Neurobehavioral COGNISTAT (Mueller et al. 2001). The COGNISTAT is a screening tool, which evaluates eight cognitive functions with the goal of identifying cognitive deficits. The eight functions are assessed in different sections of the test, labeled: level of consciousness, orientation, attention, language, constructional ability, memory, calculations and reasoning. The number of items included in each section ranges from 4 to 29.

Given that COGNISTAT is a screening tool, the range of performance within adults with normal cognition is quite narrow (Mueller et al. 2009). Test validity has previously been found to be high for adults aged between 20 and 92 years (Mueller et al. 2009). The developers recommend that for each section of the COGNISTAT, excluding level of consciousness and orientation, a screening item is administered and the remaining questions in the section are only administered in cases in which the participant fails the screening item. For the present study the authors decided to administer each question regardless of whether the participant passed the screening item of the section. It was hoped that this would yield scores with greater variation between participants, thus increasing test sensitivity.

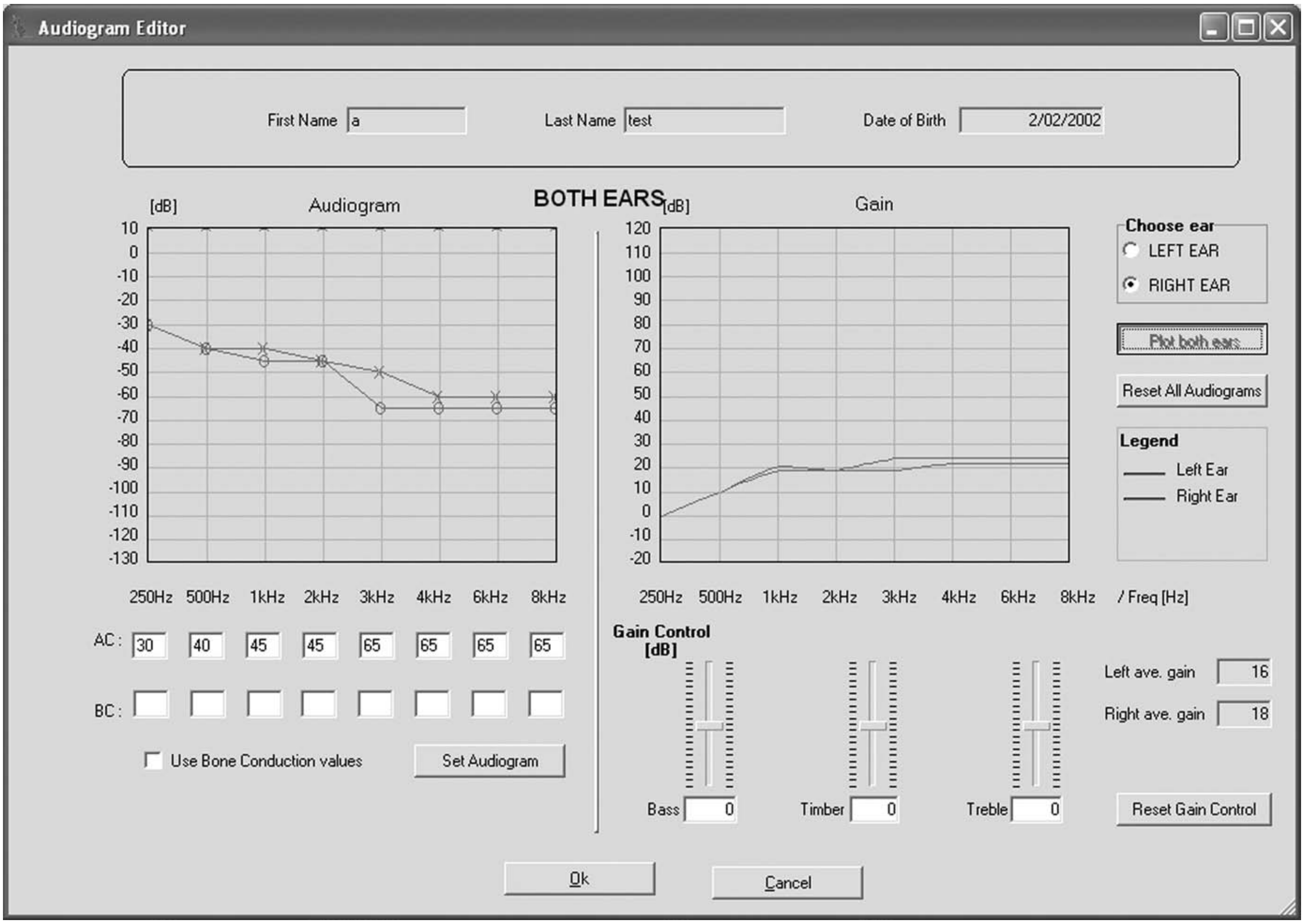
3. SSQ (Gatehouse & Noble 2004). Completion of the SSQ involved rating perceived listening difficulty in real-life situations on a scale from 0 to 10 for 53 questions. The questions are grouped into three categories; (a) speech (14 items)—which focuses on hearing speech in a wide range of situations; (b) spatial (17 items)—concerning the ability to perceive location, movement, and distance; and (c) quality (22 items)—including ease of listening and quality (Gatehouse & Noble 2004). The SSQ was designed for use with adults and has been used extensively in the literature with both aided and unaided participants. To compare subjective listening experiences in quiet and in noise for the purposes of the present study, the questions from each section were rearranged into two further subscales before the commencement of data collection: (d) listening in noise—concerning the ability to perceive a target signal in the presence of background noise; and (e) listening in quiet—concerning the ability to perceive a target signal in quiet. A list of the questions included in the two subscales can be found in Table 2. An example of an item categorized as listening in noise is "You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you're talking to says?" (speech item 1). Items such as "You are talking with one other person in a quiet, carpeted lounge-room. Can you follow what the other person says?" (speech item 2) were classified as listening-in-quiet questions. Six items from the SSQ qualities subscale were not administered as they are only relevant to aided participants and the research sample contained both aid users and nonaid users. The excluded items were 15, 16, 17, 20, 21, and 22.
4. LIFE (Anderson & Smaldino 1998). The LIFE is a self-report measure of difficulty in hearing in classroom settings. It was designed for use with a pediatric population. The questionnaire comprises 15 different items, each describing an educational situation. For example, item 4 asks "The teacher is talking. Other kids are making noise in the hall. Tell me how well you can hear the words the teacher is saying." The LIFE can be used with either a 3- or 5-point response scale. To ensure that task comprehension what not an issue for the younger children in the sample the 3-point response scale was used. The three response options were "easy" (score = 10), "medium" (score = 5), and "hard" (score = 0).

Procedure

Testing for each participant was completed in one session lasting 1.5 hr. Participants were paid a $20 gratuity to cover travel costs. Both air and bone conduction audiometric thresholds were measured at octave frequencies from 250 to 8000 Hz using a Hughson-Westlake procedure. Screening tympanometry was also undertaken to confirm the presence of type A tympanograms.

TABLE 2. Individual Speech Spatial and Qualities of Hearing scale items included in each subscale

Speech Spatial and Qualities of Hearing Subscale	Contributing Items
d) Listening in noise	Speech items: 1, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 14 Spatial item: 7 Qualities items: 1, 2, 3, and 19
e) Listening in quiet	Speech items: 2, 3, and 13 Spatial items: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, and 17 Qualities items: 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18



First Name a
Last Name test
Date of Birth 2/02/2002

Choose ear
○ LEFT EAR
● RIGHT EAR

AC : 30 40 45 45 65 65 65 65

BC :

☐ Use Bone Conduction values

Left ave. gain 16
Right ave. gain 18

Bass 0
Timber 0
Treble 0

Fig. 3. Screenshot of Listening in Spatialized Noise-Sentences prescribed gain amplifier user interface.

Real-ear insertion gain (REIG) was measured for all participants who reported being regular hearing aid users. REIG measurements were performed using an Aurical system with a modulated speech-weighted noise signal. Measurements were taken at 50, 65, and 80 dB SPL with hearing aids set to the participant's preferred setting. On the basis of the findings of Keidser et al. (2010) corrections were later applied to the auricle measurements as the Aurical speech-weighted noise differs from the international long-term average speech spectrum (Byrne et al. 1994) on which NAL fitting prescriptions were derived. REIG was undertaken to ensure that the hearing aids that participants reported wearing were working and providing appropriate amplification. Participants aged 18 years and above completed the COGNISTAT, which was administered by the researcher in an interview format.

The participants' audiometric results were then entered into the prescribed gain amplifier of the LiSN-S (Fig. 3). After a short period of practice, the participant's SRT was determined by varying the target sentence level adaptively and then averaging the signal-to-noise ratios (SNRs) for all sentences presented after practice concluded. The SNR was decreased by 2 dB if the participant scored more than 50% of the words in each sentence correct, and increased by 2 dB if he or she scored less than 50% correct. If exactly 50% of the words were repeated correctly the SNR remained unchanged. All words in the target sentences were scored, including definite and indefinite articles. For example, if the sentence "The cat stretched out on the couch," was repeated word for word then a score of 7 out of 7 was recorded. Testing in each condition continued until the entire 30 sentences were completed or at least 17 scored sentences had been completed and the participant's SE was less than 1 dB.

After completion of the LiSN-S all participants completed a questionnaire, which asked them to rate listening difficulty in everyday situations. This was included to allow for investigation into how spatial-processing ability related to the participants' subjective real-world listening experience. Adult participants (n = 65) completed the SSQ in an interview format. A laminated copy of the SSQ was placed in front of the participant and then each question was read aloud by the researcher. The participant indicated their response either verbally or by pointing to the corresponding position on the scoring scale. Participants were not restricted to integer responses. The participant's response was then recorded by the researcher. Participants less than 18 years of age (n = 15) completed the LIFE, which was also administered in an interview format. One at a time, standardized pictures of each educational situation were placed in front of the participant along with a response sheet with three cartoon faces. The researcher would read each item allowed and then the participant was required to respond by pointing to the picture corresponding to their response.

Data Analysis

The data was analyzed using Statistica version 7.1 and R version 2.12.0 (with the additional R packages rms and ggplot2) to perform multiple regression analysis. Multiple regression involves investigation of the effect of each predictor variable on a dependent variable while simultaneously considering the effects of the other predictor variables, thus allowing the effects of correlated predictor variables (such as age and hearing level) to be estimated separately. Although the basic ideas of multiple regression are well known, some of the specific techniques used here are less well known, so a brief explanation is given.

In some of the regression models presented in the Results section, age and hearing level are represented as "splines" (Durrleman & Simon 1989). Splines are a type of nonlinear function, and the usage of splines to represent predictor variables in regression has the advantages that (1) we avoid the restrictive assumption that the associations between dependent and predictor variables are linear, and (2) compared with the most common way of including nonlinearity (that is, including a squared predictor term) for the same number of additional parameters a spline allows a wider range of shapes of curve.

Splines are defined piecewise, that is, a spline is defined differently for different ranges of values of the predictor variable, but there are constraints to ensure that the pieces join together in a smooth way. The points at which the pieces join are called "knots," and the number of knots is chosen in advance. There are different types of splines; the ones used here are called "restricted cubic splines" because between adjacent knots the function is a cubic polynomial, and in the tails (to the left of the first knot and to the right of the last knot) the function is restricted to being linear. The splines used here have three knots, located at the 10th, 50th, and 90th percentiles of the sample values of the relevant predictor. When a predictor variable is represented by a spline with three knots, the predictor has two terms in the regression function, and the significance of the predictor is tested using an F test to test the two terms simultaneously.

Three different types of r^2 values are reported in the Results. Simple r^2 refers to the proportion of variance in the dependent variable that could be attributed to the predictor variable if the other predictor variables were not included in the model. Partial r^2 is the amount of variance each predictor variable accounts for, after the other predictors have been allowed for, as a proportion of the variance unexplained by the other predictors. Multiple r^2 refers to the proportion of variance explained by the predictor variables in combination. Associated with each type of r^2 is a corresponding p value.

RESULTS

Data from all 80 participants were included in the following analyses except where explicitly stated otherwise.

Before undertaking statistical analyses to assess the effect of hearing impairment, multiple regression analyses were conducted to determine which measure of hearing impairment would serve as the best predictor of LiSN-S performance. The five LiSN-S measures (low-cue SRT, high-cue SRT, talker advantage, spatial advantage, and total advantage), were included as dependent variables and average low-frequency hearing loss, mid-frequency hearing loss, and high-frequency hearing loss as the predictor variables. Average low-frequency hearing loss was calculated as the average of 250 and 500 Hz in the worse ear. Average mid-frequency hearing loss was calculated as the average of 1000 and 2000 Hz in the worse ear and average high-frequency hearing loss as the average of 4000 and 8000 Hz in the worse ear. An apriori decision was taken to compare performance with the worse ear rather than the better ear as binaural processing relies on the hearing properties of both ears and, therefore, is likely to be influenced by the worse ear.

Results from the multiple regression are shown in Table 3. Each of the LiSN-S measures that involve the use of spatial cues (i.e., high-cue SRT, spatial advantage, and total advantage) was most highly correlated with mid-frequency hearing loss ($p < 0.001$). These measures were also significantly correlated to high-frequency hearing loss ($p < 0.001$, $p = 0.031$, $p = 0.010$). High-cue SRT and spatial advantage were also significantly correlated to low-frequency hearing loss ($p < 0.001$, $p = 0.009$). However, low-cue SRT was significantly correlated with both low-frequency hearing loss ($p = 0.007$) and high-frequency hearing loss ($p = 0.012$). Talker advantage, which is a measure of the benefit gained from access to pitch cues, was significantly correlated with high-frequency hearing loss ($p = 0.003$). Therefore it was deemed inappropriate to use any one of these measures of hearing impairment in isolation in the subsequent regression analysis as it would result in hearing impairment seeming to have a weaker influence on some LiSN-S measures than if a different measure of hearing impairment had been chosen. Thus, four-frequency average hearing loss (4FAHL) in the worse ear (worse 4FAHL), which includes frequencies from all the three measures discussed earlier, was used as the sole measure of hearing loss for all subsequent analyses.

Effect of Hearing Impairment and Aging

Figure 4 shows the raw scores for each LiSN-S condition versus hearing impairment. For all four conditions a strong relationship with 4FAHL is evident, in the direction of worsening hearing thresholds leading to poorer performance on the LiSN-S. However, as a wide age range is included in the data set shown, more detailed analysis is necessary to interpret these findings. Age and hearing loss are weakly correlated within the sample ($r = 0.33$) and moderately correlated ($r = 0.71$) if only the adult participants are considered.

A multiple regression with nonlinear terms was conducted, incorporating hearing loss as a spline with three knots and age as a spline with three knots, for each of the five LiSN-S measures. Results of the regression are shown in Table 4 as simple, partial, and multiple r^2 values. Though the focus of this article is spatial processing we will also report the findings associated with the talker advantage measure of the LiSN-S as it provides a useful comparison point.

On the basis of the simple r^2 results it seems that, when considered in isolation, both age and hearing loss explain a significant amount of the variance on each of the five LiSN-S measures ($p < 0.001$). The partial r^2 demonstrates that when both predictor variables, age and hearing loss, are considered together hearing loss remains a significant predictor for all five LiSN-S measures ($p < 0.001$), and age is a significant predictor only for high-cue SRT ($p = 0.001$). Once hearing loss is allowed for, age accounts for a small and insignificant proportion of variance in the remaining four measures.

The regression coefficients were used to show graphically the separate effect of each predictor. The graphs in Figure 5 show each LiSN-S measure versus hearing threshold, with each data point adjusted vertically to allow for the effect on the LiSN-S measure of the participant's age relative to the mean age

TABLE 3. Coefficient estimates, 95% CI, and *p* values for different measures of hearing level versus Listening in Spatialized Noise-Sentences measure

	Low-Cue SRT		High-Cue SRT		Spatial Advantage		Talker Advantage		Total Advantage	
Predictor	Estimate (CI)	*p*	Estimate (CI)	*p*	Estimate (CI)	*p*	Estimate (CI)	*p*	Estimate (CI)	*p*
Low-frequency HL	0.048 (0.013, 0.083)	0.01*	0.093 (0.044, 0.141)	<0.001*	−0.071 (−0.123, −0.019)	0.01*	−0.011 (−0.060, 0.037)	0.64	−0.044 (−0.092, 0.004)	0.07
Mid-frequency HL	0.008 (−0.024, 0.039)	0.63	0.120 (0.076, 0.163)	<0.001*	−0.089 (−0.137, −0.042)	<0.001*	−0.039 (−0.083, 0.005)	0.08	−0.112 (−0.156, −0.069)	<0.001*
High-frequency HL	0.026 (0.006, 0.047)	0.01*	0.063 (0.035, 0.091)	<0.001*	−0.034 (−0.065, −0.003)	0.03*	−0.043 (−0.072, −0.015)	0.003*	−0.037 (−0.065, −0.009)	0.01*

** Indicates significant correlations.*
CI, confidence interval; SRT, speech-reception threshold.

of all participants. That is, the effects of age, as calculated from the regression analysis, have been removed from the data. The line on each plot shows the predicted value of the dependent variable (SRT or advantage measure) versus hearing threshold, were all participants to have an age equal to the mean age of the participants. In the same way, Figure 6 shows the effect of age, after removing the systematic effects of hearing thresholds.

In the plots of each LiSN-S measure versus hearing loss, the band shows the 95% confidence interval for the mean for the dependent variable when the age variable is held fixed at its mean. The individual points on each plot can be thought of as the values of the dependent variable after being adjusted for the effects of the other variable.

There was a significant relationship between low-cue SRT and hearing loss ($p < 0.001$, partial $r^2 = 0.40$). As hearing loss increases, performance on the low-cue SRT measure worsens. However, a stronger relationship was found to exist between high-cue SRT and hearing loss ($p < 0.001$, partial $r^2 = 0.82$). This indicates that hearing loss explains 82% of the variance seen on the high-cue SRT measure, which is not explained by age.

Spatial-processing ability is most clearly captured by the spatial advantage measure of the LiSN-S. The relationship between spatial advantage and hearing loss was also significant ($p < 0.001$, partial $r^2 = 0.66$), with increased hearing loss associated with poorer spatial-processing ability. Variation in hearing thresholds in the minimal-to-mild range seem to cause smaller variations in spatial advantage than do variations in hearing thresholds in the severe range (Fig. 5C). Although the effect of hearing thresholds on spatial advantage was highly significant, the nonlinearity term, and hence the variation in slope shown in Figure 5C, just failed to reach significance ($p = 0.06$).

The relationship between talker advantage and hearing loss is also significantly correlated ($p < 0.001$, partial $r^2 = 0.39$). It is evident from the plot that the spread of performance on this measure is greater. Subsequently, less of the variance in talker advantage can be explained by hearing loss.

Total advantage, which is a measure of the benefit gained from access to both pitch and spatial cues, was also significantly correlated with hearing loss ($p < 0.001$, partial $r^2 = 0.71$). As was the case with spatial advantage and talker advantage, the graph shows that worsening hearing loss results in reduced total advantage score.

The effect of age on LiSN-S performance, although hearing is accounted for, is shown in Figure 6. The plot in Figure

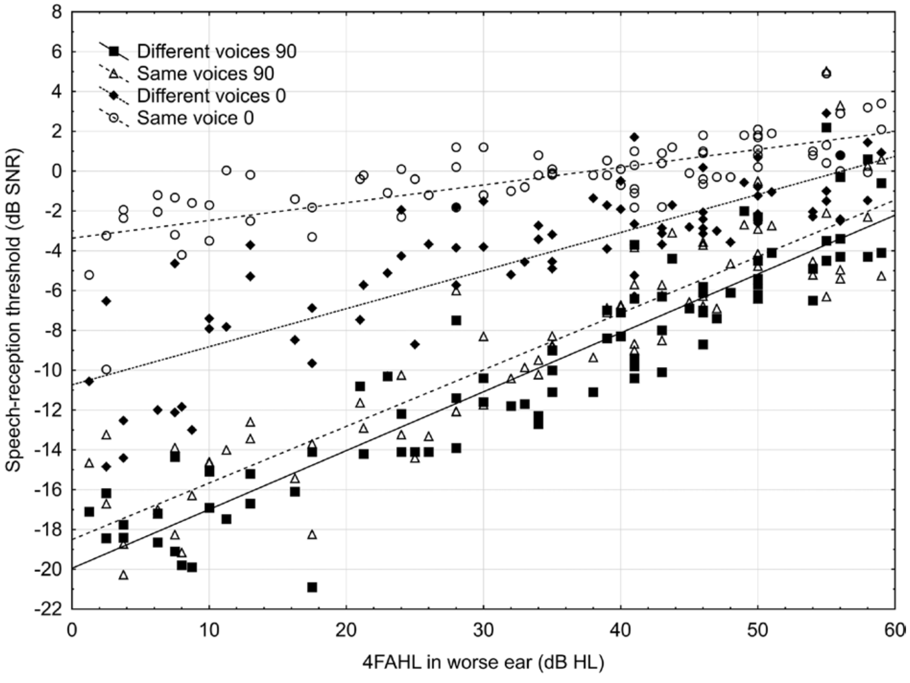


Fig. 4. Plot of Listening in Spatialized Noise-Sentences SRT raw scores versus 4FAHL in worse ear. 4FAHL, four-frequency average hearing loss, SNR, signal-to-noise ratio; SRT, speech-reception threshold.

TABLE 4. Multiple regression with nonlinear terms for hearing loss and age (n = 80)

		Simple		Partial		Multiple	
Measure	Predictor	r^2	p	r^2	p	r^2	p
Low-cue speech-reception threshold	4FAHL	0.56	<0.001*	0.40	<0.001*	0.59	<0.001*
	Age	0.32	<0.001*	0.07	0.08		
High-cue speech-reception threshold	4FAHL	0.87	<0.001*	0.82	<0.001*	0.89	<0.001*
	Age	0.41	<0.001*	0.17	0.001*		
Spatial advantage	4FAHL	0.74	<0.001*	0.66	<0.001*	0.76	<0.001*
	Age	0.30	<0.001*	0.06	0.10		
Talker advantage	4FAHL	0.51	<0.001*	0.39	<0.001*	0.51	<0.001*
	Age	0.21	<0.001*	0.02	0.52		
Total advantage	4FAHL	0.80	<0.001*	0.71	<0.001*	0.81	<0.001*
	Age	0.34	<0.001*	0.07	0.06		

**Significant correlations.*
4FAHL, four-frequency average hearing loss.

6A shows a slight but not significant deterioration in low-cue score in older adults ($p = 0.08$, partial $r^2 = 0.07$). However, this decline in performance equates to less than 2 dB change in SRT. Figure 6B displays the relationship between high-cue SRT and age, which reached significance ($p = 0.001$, partial $r^2 = 0.17$). A sharp deterioration in high-cue SRT can be seen with increasing age from approximately 60 years. The cause of this deterioration cannot be identified based on this analysis. Similarly, high-cue SRT score seems to improve with increasing age until early adulthood. Once the effects of hearing loss on high-cue SRT have been accounted for, age only explains 2% of the total variance or 17% of the remaining variance.

None of the LiSN-S advantage measures was found to be significantly correlated with age once the effect of hearing loss was allowed for. Spatial advantage showed minimal variation across age ($p = 0.10$, partial $r^2 = 0.06$) as did talker advantage ($p = 0.52$, partial $r^2 = 0.02$). The relationship between total advantage and age approached but did not reach significance ($p = 0.06$, partial $r^2 = 0.07$). This result can be attributed to the fact that total advantage is a difference score, and one of the measures it is derived from, high-cue SRT, is significantly affected by age.

Effect of Cognition

The following analyses included data from the 65 participants aged 18 years and above. A multiple regression with nonlinear terms was conducted with COGNISTAT overall score represented as a linear term, hearing loss as a spline with three knots, and age as a spline with three knots as the predictor variables, and the five LiSN-S measures as dependent variables (Table 5). When considered in isolation (i.e., without examining the effects of hearing loss and age) COGNISTAT overall score seems to be significantly correlated with low-cue SRT ($p = 0.004$), high-cue SRT ($p = 0.002$), spatial advantage ($p = 0.009$), and total advantage ($p = 0.006$). Once the effects of hearing loss and age have been accounted for, COGNISTAT overall score is no longer significantly correlated with any of the five LiSN-S measures (p ranging from 0.27–0.95).

Self-Report Measures of Listening Difficulty

Separate analyses were conducted on the LIFE data collected from the 15 participants aged 7 to 17 years and the SSQ data collected from the 65 participants aged 18 to 89 years. The self-report measures were included to examine whether a relationship exists between spatial-processing ability (as measured by the LiSN-S spatial advantage measure) and self-reported listening difficulty. As such, the spatial advantage measure of the LiSN-S was used as the predictor variable in the following analyses.

A linear regression found no significant correlation between LIFE score and performance on the spatial advantage measure ($p = 0.226$, $r^2 = 0.089$). Conversely, a regression with SSQ listening-in-noise score and SSQ listening-in-quiet score as dependent variables revealed a significant relationship between listening difficulty in noise and spatial advantage performance ($p < 0.001$, $r^2 = 0.282$). The direction of the relationship indicates that as spatial-processing ability worsened adult participants reported greater difficulty hearing in situations in which background noise was present.

As spatial advantage was previously shown to be significantly related to hearing loss it is possible that the relationship between listening difficulty, as measured by the SSQ, and spatial advantage was actually attributable to both variables being associated with hearing loss. The multiple regression analysis for SSQ listening-in-noise score was therefore reanalyzed, this time including both spatial advantage and 4FAHL as predictor variables. When considered together 4FAHL was shown to be significantly correlated to SSQ listening-in-noise score ($p = 0.002$, partial $r^2 = 0.144$), and spatial advantage was no longer a significant predictor ($p = 0.937$, partial $r^2 = 0.000$) once the effect of 4FAHL had been accounted for.

DISCUSSION

Effect of Hearing Impairment on Spatial Processing

The present study set out to examine the effects of hearing impairment on spatial-processing ability. It was hypothesized that, given the physiological changes associated with sensorineural hearing loss, spatial-processing ability would be reduced in hearing-impaired people. This hypothesis was previously supported by the findings of Gelfand et al. (1988), Dubno et al. (2002), and Arbogast et al. (2005) who reported reduced spatial-processing ability in hearing-impaired listeners compared with normal-hearing listeners. The results of the present study provide further validation of this hypothesis, showing a strong relationship between spatial processing, as quantified by the spatial advantage measure of the LiSN-S, and hearing impairment.

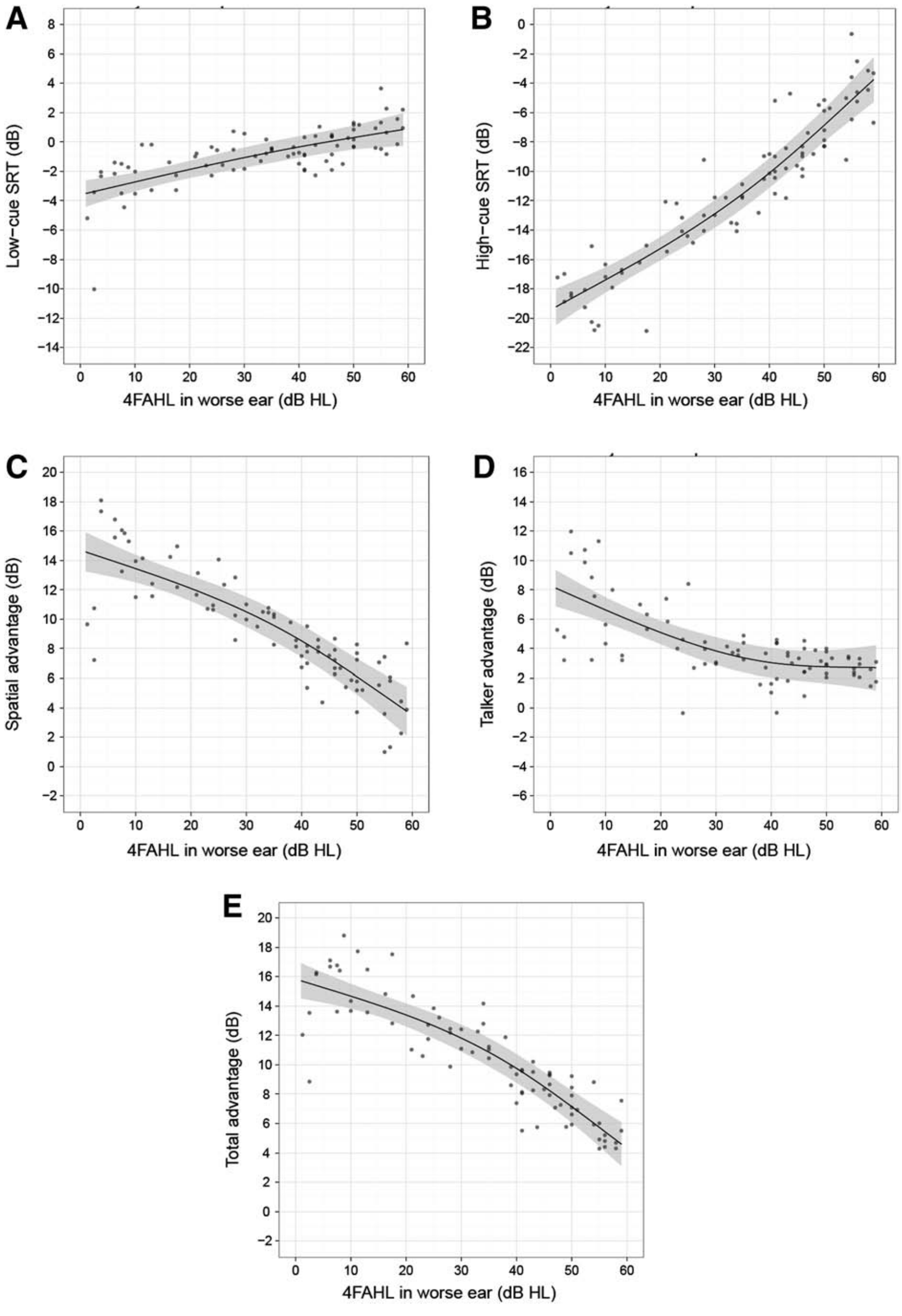


Fig. 5. Plot of Listening in Spatialized Noise-Sentences SRT or advantage measure versus 4FAHL in worse ear, adjusted for age. A, low-cue SRT; B, high-cue SRT; C, spatial advantage; D, talker advantage; E, total advantage. 4FAHL, four-frequency average hearing loss; SRT, speech-reception threshold.

The design of this study allows for further description of the relationship between spatial processing and hearing impairment than was possible with previous studies. For example, Gelfand et al. (1988) used a group design in which each group was either designated as “normal hearers” or “presbycusic.” This approach does not allow for differentiation between degrees of hearing loss. By including hearing-impaired participants with a wide range of degrees of loss in the present study it was possible to demonstrate how spatial-processing ability changes as hearing impairment increases. It was demonstrated that as hearing loss increases spatial-processing ability decreases. Therefore, the spatial-processing ability of a person with a mild sensorineural hearing loss is not, on average, going to be equivalent to that of a person with a moderate sensorineural hearing loss.

Although the nonlinearity between spatial advantage and hearing loss was not statistically significant (p = 0.06), some degree of nonlinearity was observed (Fig. 5C). Changes to hearing thresholds in the minimal-to-mild range seem to have a less detrimental effect on spatial-processing ability than changes in the severe range.

It is also worth noting that plotting the relationship between degree of hearing loss and LiSN-S high-cue SRT score revealed that even between 0 and 20 dB 4FAHL, which is routinely considered within the normal-hearing range, there is evidence of performance beginning to deteriorate with increasing hearing thresholds. High-cue SRT, for example, is estimated to vary by 2 dB over this range of hearing levels. This indicates that even minimal shifts in hearing thresholds, which would normally not be considered clinically significant, may be detrimental to

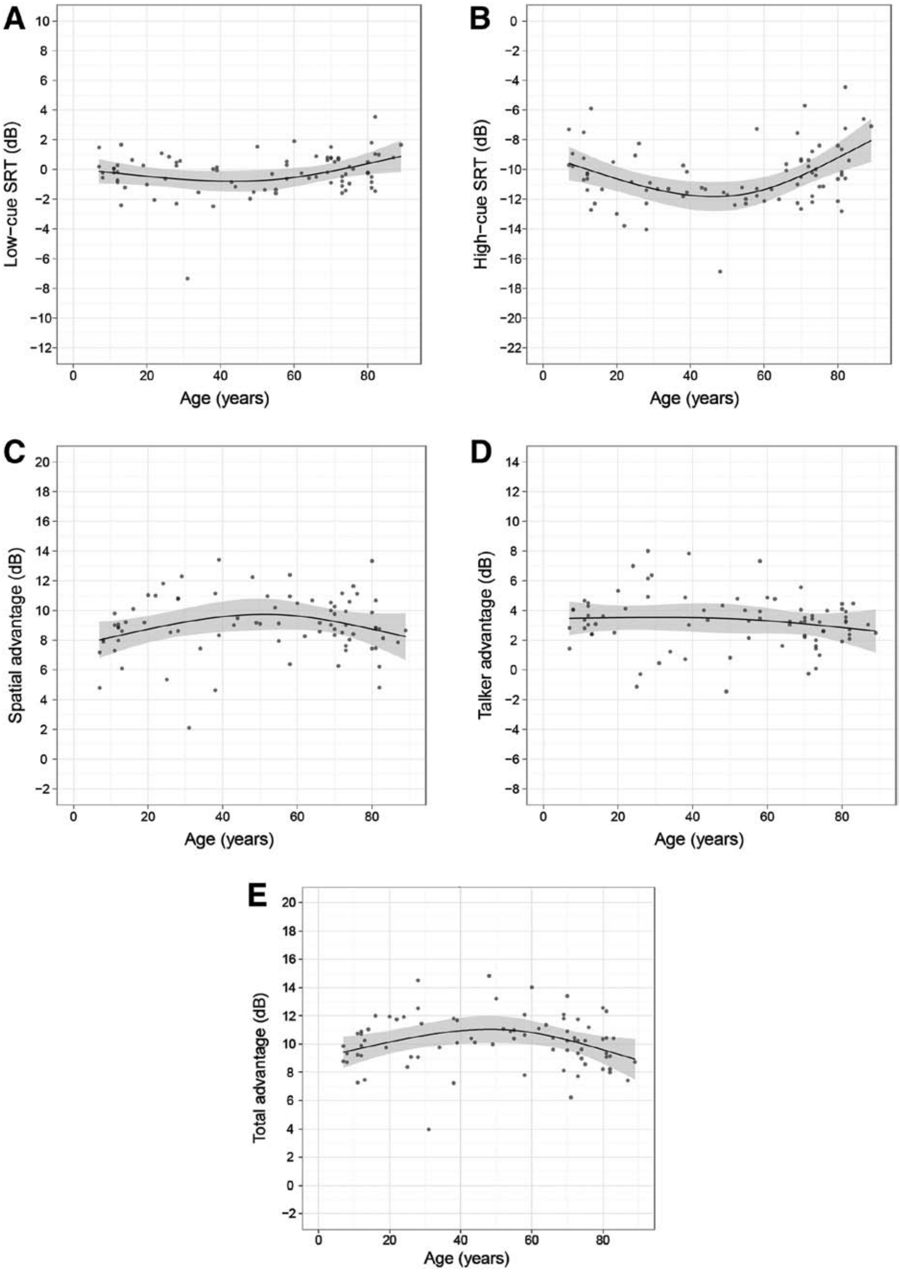


Fig. 6. Plot of Listening in Spatialized Noise-Sentences SRT or advantage measure versus age, adjusted for hearing loss. A, low-cue SRT; B, high-cue SRT; C, spatial advantage; D, talker advantage; E, total advantage. SRT, speech-reception threshold.

a person's ability to use spatial cues to aid in auditory stream segregation.

Further, an examination of Figure 5C shows that a small number of hearing-impaired and normal-hearing participants performed more poorly on the spatial advantage measure of the LiSN-S than would be expected given their hearing loss. These results cannot be explained by above-average performance in the low-cue condition of the LiSN-S or age, and the cause of this poorer performance cannot be clearly identified. It is possible that these participants may have a central component to their spatial-processing deficit, in addition to the component that seems to be an inevitable result of sensorineural hearing loss. However, it is also possible that this poorer performance represents normal variation within the population.

The effect of reduced spatial-processing ability on difficulty in understanding speech in noise is emphasized by comparing the relationship between low-cue SRT and 4FAHL with the relationship between high-cue SRT and 4FAHL. When no spatial cues are present, as is the case with the low-cue condition of the LiSN-S, on average, each 10 dB of 4FAHL hearing loss results in a need for an approximately 0.7 dB increase in SNR, though the rate changes with degree of hearing loss, decreasing from 0.9 to 0.6 dB per 10 dB of loss around the transition from moderate to severe hearing loss. By comparison, each 10 dB of 4FAHL hearing loss results in a need for an approximately 2.8 dB increase in SNR in the high-cue condition (in which spatial cues are present), though the rate changes with degree of hearing loss, increasing from 2.1 to 3.4 dB per 10 dB of loss around the transition from moderate to severe loss. This raises a number of questions about the use of traditional speech-in-noise tests, in which there is no spatial separation of speech from maskers, as a measure of hearing aid fitting success. If the

TABLE 5. Multiple regression including hearing loss, age, and cognition for adult participants only (n = 65)

		Simple		Partial		Multiple	
Measure	Predictor	r^2	p	r^2	p	r^2	p
Low-cue speech-reception threshold	4FAHL	0.57	<0.001*	0.27	<0.001*		
	Age	0.45	<0.001*	0.06	0.15	0.61	<0.001*
	Cognition	0.13	0.004*	0.01	0.35		
High-cue speech-reception threshold	4FAHL	0.89	<0.001*	0.80	<0.001*		
	Age	0.53	<0.001*	0.12	0.02*	0.91	<0.001*
	Cognition	0.15	0.002*	0.02	0.27		
Spatial advantage	4FAHL	0.74	<0.001*	0.58	<0.001*		
	Age	0.39	<0.001*	0.02	0.59	0.75	<0.001*
	Cognition	0.10	0.009*	0.00	0.70		
Talker advantage	4FAHL	0.50	<0.001*	0.22	<0.001*		
	Age	0.38	<0.001*	0.03	0.44	0.52	<0.001*
	Cognition	0.05*	0.07	0.00	0.95		
Total advantage	4FAHL	0.81	<0.001*	0.68	<0.001*		
	Age	0.42	<0.001*	0.04	0.29	0.82	<0.001*
	Cognition	0.11	0.006*	0.00	0.70		

**Significant correlations.*
4FAHL, four-frequency average hearing loss.

goal of a speech-in-noise test performed clinically is to demonstrate how well the client will perform in background noise then it would be advantageous to incorporate spatial separation of the test stimuli in the test design. Without spatial separation the difficulties experienced by the client will be underestimated.

The 13.5 dB benefit from access to spatial cues gained by individuals with a 10 dB HL 4FAHL was almost identical to the value of 12.8 dB reported in the study by Cameron et al. (2011) for adult normal hearers aged from 18 to 60 years. This is much larger than the 5 to 6 dB of benefit that Gelfand et al. (1988) found their normal hearers experienced. This difference may be a result of the differences in type of masking noise used in the two studies. In the present article, as in the study by Cameron et al., two talkers at different azimuths were used as the competition whereas Gelfand and colleagues used 12-speaker babble. The difference in amount of benefit from spatial cues may be attributable to the fact that there is greater amount of informational masking present when individual talkers are used as maskers, and therefore spatial-processing ability becomes far more important. This theory is supported by the work of Arbogast et al. (2005) that showed that the masker type affects amount of benefit from spatial cues, with individual speech maskers allowing for greater spatial release from masking. It can be argued that the use of speech maskers also provides the most realistic estimate of people's spatial-processing ability as speech maskers most closely mimic real-life conditions (Arbogast et al. 2005).

Effect of Aging on Spatial Processing

The results of this study indicate that the effect of age on spatial-processing ability is far smaller than the effect of hearing loss, so small in fact that it could not be detected on the spatial advantage measure of the LiSN-S once hearing loss had been allowed for. Figure 6 shows that each of low-cue SRT, spatial advantage, and talker advantage has a small and statistically insignificant deterioration as age increases from 60 to 90 years. It is only in the high-cue condition, in which performance is simultaneously affected by all the factors affecting the other measures, that the decline with age becomes significant. The lack of a detectable effect on spatial advantage is in contrast to the findings reported in many earlier studies such as those by Divenyi and Haupt (1997), Dubno et al. (2002), Divenyi et al. (2005), and Murphy et al. (2006). There are a number of reasons why this may have occurred. It is possible that the lack of an age effect in this study is a result of the built-in LiSN-S prescribed gain amplifier providing better audibility than was available to participants of past studies in which methods such as flat amplification or testing with hearing aids in situ were used. Furthermore, hearing impairment was controlled for in the statistical analyses of the present study, allowing the effects of hearing impairment and aging to be separated.

Alternatively it could be argued that the absence of an age effect in this study is because of the different materials and maskers used in the study design. The LiSN-S target sentences were designed to be easily understood by a 4-year-old hearing-impaired child (Cameron & Dillon 2007). Had the speech materials been more cognitively taxing it is possible an age effect may have become evident given the cognitive declines frequently associated with aging.

It is worth noting that the results of Gelfand et al. (1988) and Cameron et al. (2011), in relation to spatial-processing ability and aging, support our current findings. Consequently, it is suggested that any link between spatial-processing ability and aging found in other studies is a result of the poorer hearing thresholds of older participants than those of their younger counterparts. The findings here indicate that when older adults are provided with adequate amplification they are able to use spatial cues to aid in speech understanding as well as younger adults with equivalent hearing thresholds are.

The argument that age explains as little variance in LiSN-S performance as demonstrated here, is strengthened when we consider the total amount of variance for each LiSN-S measure that has been explained by a model incorporating both hearing loss and age. If age had a greater effect than we had managed to measure it would be expected that a large amount of unexplained variance would remain. Table 4 shows that between 51 and 89% of variance in each LiSN-S measure has been accounted for, with talker advantage having the least explained variance and high-cue SRT the most. However, every test includes a certain degree of measurement error, which also explains an amount of the variance in scores. It is possible to estimate the amount of variance that could be attributable to measurement error based on the test–retest reliability data provided in the study by Cameron et al. (2011). Squaring the reported test–retest standard deviation of the mean values and then dividing by two gives the estimated error variance for a single test for each LiSN-S condition. This indicates that measurement error accounts for approximately 35% of the variance of low-cue SRT, 4% of the variance of high-cue SRT, 23% of the variance for spatial advantage, 49% of the variance for talker advantage, and 13% of the variance for total advantage. It should be stressed that given these values are based on a different sample population the actual error variance in our sample may be slightly larger or slightly smaller. However, based on these estimations the least amount of variance accounted for by hearing loss, age, and measurement error in any LiSN-S measure would be 93%.

Where Cameron et al. (2011) demonstrated stable spatial-processing ability in adults up to 60 years of age, our current findings expand on this result further showing stable spatial-processing ability continuing up to 89 years of age. However, aging was found to be correlated with reduced scores on the high-cue measure of the LiSN-S. This suggests that some factors related to aging, other than, or in addition to, spatial-processing ability or audibility, do affect the ability of older adults to understand speech in spatially separated background noise. As mentioned previously, successful auditory stream segregation involves the use of multiple cues including, but not limited to, location of the sound source, contextual information, and spectral information (Alain 2007). It is possible that deficits in spectral discrimination or poorer ability to use context contributed to the poorer performance of older adults on the high-cue SRT measure. It is interesting to note that the reduced performance on the high-cue SRT in older adults was also observed by Cameron et al. (2011). Further investigation into the cause of this increased difficulty would certainly be warranted, and one area that will need to be considered as part of that investigation is the role of cognition.

Cognition

The effects of cognition on spatial-processing ability have not previously been investigated. What is widely accepted in the literature is that aging results in reduced cognitive ability, manifesting in a number of ways including reduced working memory, slower processing speed, and poorer attention (Lunner 2003). With this in mind, it was deemed that a cognitive screening tool that covered a large number of skills would provide the best opportunity of identifying any cognitive effects on spatial-processing ability.

The present study did not find a significant correlation between performance on the COGNISTAT and any of the LiSN-S measures including spatial advantage, once age and hearing loss had been allowed for. Given this is the only research that directly considers the relationship between spatial-processing ability and cognition, it is difficult to determine whether the lack of correlation is true in general or is because of some factor specific to the design of the study. Daneman and Merickle (1996) point out that some measures of cognition may not be sensitive enough to small cognitive changes to reveal relationships between cognition and other factors.

The COGNISTAT has been widely validated and shown to be a sensitive screening measure to general cognitive decline in geriatric populations (Ruchinskas & Curyto 2003). Therefore, it seems unlikely that a lack of sensitivity in the chosen measure could explain the lack of effect. What is possible is that, by choosing a general measure we could not observe relationships between specific cognitive functions and spatial-processing ability. Lunner (2003) was able to identify a link between speech understanding in noise and cognition by using a visual working memory task and a processing speed task as the measures of cognition. It is thus suggested that future research using alternative and, perhaps, more specific measures of cognition, such as those described in Hafter (2010), would be needed before it could be conclusively stated that cognition is not related to spatial-processing ability. It is also possible that the COGNISTAT may not be sensitive enough to detect minor cognitive decline that is not significant enough to be clinically relevant.

Another factor that may have affected the findings relating to spatial-processing ability and cognition relates to the participant sample. Close examination of data showed very little spread of cognitive abilities, with only one of the 65 participants who completed the COGNISTAT assessment scoring less than 60 out of a possible 74 points. This small range of cognitive abilities occurred despite no specific inclusion criterion for cognition, and may simply reflect the type of people who are likely to volunteer as research participants. If a sample with a wider range of cognitive abilities had been tested it seems possible that a link between cognition and spatial-processing ability may have emerged.

It is also possible that a relationship between spatial-processing ability and cognitive ability may have emerged had a more cognitively demanding test of spatial-processing ability been used. As previously discussed, the LiSN-S was designed to place minimum cognitive demands on the listener (Cameron & Dillon 2007). If one considers the degradation hypothesis described by Lindenberger and Baltes (1994) the presence of a cochlear hearing loss and background noise makes listening more effortful. Consequently, resources have to be diverted away from other functions to effortful listening instead. As the LiSN-S requires minimal cognitive resources to begin with, it is possible that it was not affected by the reduced amount of cognitive resources available whereas a test that required more than simple sentence repetition may well have been.

Self-Report

Last, the present research set out to determine whether spatial-processing ability is related to real-life listening difficulty. Given the wide age range covered in this study it was deemed most appropriate to make use of two different measures of listening difficulty; the LIFE for participants aged under 18 years of age and the SSQ for participants aged 18 years and above. The results of the questionnaires were then considered and analyzed separately. No relationship was found between the LIFE and spatial-processing ability for the pediatric participants. This was contrary to our hypothesis that spatial-processing ability would be related to reported listening difficulty.

Before discounting the link between spatial processing and listening difficulty in children it is important to note the relatively small number of child participants and to consider whether the LIFE was actually measuring the desired factors. A number of items on the LIFE do not include any background noise components and one would not expect them to be related to spatial-processing ability. It is important to note that a number of additional factors such as attention may be captured in the items of the LIFE and we would not expect these to be related to spatial processing. Furthermore, there are limitations to using self-report questionnaires in the pediatric population and it is not clear whether the reports of the younger participants were in fact accurate representations of their experiences. It would be advantageous if one could instead compare LiSN-S results with data gathered from professional observations of real-life performance or, perhaps even better, a listening-difficulty test that seeks to mimic real-life listening conditions as closely as possible. Unfortunately, as yet such a test does not exist and until it does it will be difficult to reach any concrete conclusions regarding the link between spatial-processing ability and real-life listening difficulty in a pediatric population.

The SSQ listening difficulty in noise subscale initially seemed to be strongly correlated to the LiSN-S spatial advantage score, which would provide support for the hypothesis that spatial-processing ability affects real-life listening difficulty. This is despite the fact that the participant group included aided and unaided adults, which could have obscured the effect because of the different levels of audibility causing variation in responses. The relationship between spatial advantage score and SSQ listening difficulty in noise was no longer significant once hearing impairment was included in the analyses. However, one cannot discount the possibility that had a different measure of self-reported listening difficulty been used, a different conclusion may have been reached.

Study Limitations

In this experiment spatial-processing ability was assessed using the LiSN-S with a built-in prescribed gain amplifier providing frequency-specific gain based on the NAL-RP prescription described in the work by Dillon (2001). NAL-RP recommends less high-frequency gain than that recommended by other prescription methods such as desired sensation level, raising questions regarding whether high frequencies were amplified adequately to provide access to IIDs that are prominent in the high frequencies (Dillon 2001). However, subjective reports from participants indicated that the speech was very clear and, in the case of most aided participants, far clearer than they were used to with their hearing aids. The high-frequency gain provided by NAL-RP is based on experiments showing that, once hearing thresholds exceed 60 dB, speech information in the high-frequency region becomes decreasingly useful despite increased amplification (Byrne et al. 1990). Therefore it seems unlikely that a different prescription method would have provided participants better access to IID or that the strong relationship between hearing impairment and spatial processing could be explained by poor high-frequency audibility alone.

The head-related transfer functions used to create the spatialized stimuli in the LiSN-S were recorded in an anechoic environment. The extent to which the benefit of spatial cues in reverberant environment varies from the benefit in anechoic environments is unknown.

CONCLUSIONS

This study has demonstrated that spatial-processing ability is closely related to degree of hearing impairment. On the basis of the data presented here it is likely that every person with a sensorineural hearing loss will also have a reduction in spatial-processing ability of some degree. Therefore audiologists working clinically should consider this when counseling their patients in regard to realistic expectations of amplification. This research has demonstrated that, despite appropriate amplification, patients should expect to continue to have greater difficulty understanding speech in noise than normal hearers have, and this needs to be made clear to patients before hearing aid fitting. The LiSN-S may prove to be a useful clinical tool for demonstrating this to clients in the future. Further, a small number of hearing-impaired participants may have an additional central component to their spatial-processing deficit, resulting in more aberrant performance than their hearing levels may predict, and testing on the LiSN-S may help clinicians to identify these clients.

No significant relationship was found between spatial-processing ability and aging. This indicates that once people learn to use spatial cues to aid in speech segregation they retain this skill unless a hearing loss develops. However, even a mild hearing loss degrades spatial processing. Age was shown to account for a small, but, significant, amount of the variance seen on the high-cue measure of the LiSN-S. This suggests that even though spatial processing remains intact, age does affect speech understanding in noise through some other unknown mechanism.

The relationship between cognition and spatial-processing ability and spatial-processing ability and real-life listening difficulty require further investigation.

In addition, a number of questions have arisen from this investigation. Given the fact that all hearing-impaired people have reduced spatial-processing ability, attention should be directed to what can be done to address this deficit. Deficit-specific remediation for spatial-processing disorder has been shown to be effective in normal-hearing children (Cameron & Dillon 2011), so this should be investigated as an option for hearing-impaired people. If, however, the cause of spatial-processing deficits is different in adults with a sensorineural hearing loss than for children with normal-hearing sensitivity (as seems likely), we should have no expectation that the same type of remediation will be possible for the hearing-impaired adults. Given the size of the SNR deficit revealed when scores are spatially separated, there is a strong need for devices that improve SNR by a greater degree than is possible with current hearing aids.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the HEARing Cooperative Research Centre, established and supported under the Australian Government's Cooperative Research Centres Program. The authors also acknowledge the assistance of Dinh Trinh, Jorge Mejia, and Nicky Chong-White from the National Acoustic Laboratories for their work in developing the prescribed gain amplifier.

Findings from this research were presented at the 2011 American Academy of Audiology Conference, Chicago, Illinois, April 7, 2011.

The Listening in Spatialized Noise-Sentences test described in this article is distributed under license by Phonak Communications AG. Financial returns from the sale of this product will benefit Dr. Cameron and the National Acoustic Laboratories. This has in no way influenced the research reported in the present article.

The authors have no conflicts of interest to disclose.

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Received August 3, 2011; accepted May 23, 2012.

REFERENCES

Arbogast, T. L., Mason, C. R., Kidd, G. Jr. (2005). The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am*, *117*(4 Pt 1), 2169–2180.

Ahlstrom, J. B., Horwitz, A. R., Dubno, J. R. (2009). Spatial benefit of bilateral hearing AIDS. *Ear Hear*, *30*, 203–218.

Alain, C. (2007). Breaking the wave: Effects of attention and learning on concurrent sound perception. *Hear Res*, *229*, 225–236.

Anderson, K. L., & Smaldino, J. J. (1998). The Listening Inventory For Education: An efficacy tool. Student appraisal of listening difficulty. Educational Audiology Association.

Bamiou, D. E. (2007). Measures of binaural interaction. In F. E. Musiek & G. D. Chermak (Eds). *Handbook of (Central) Auditory Processing Disorder. Volume 1. Auditory Neuroscience and Diagnosis* (pp. 257–286). San Diego, CA: Plural Publishing.

Bregman, A. S. (1990). *Auditory Scene Analysis*. Cambridge, MA: MIT Press.

Byrne, D., Dillon, H., Tran, K., et al. (1994). An international comparison of long-term average speech spectra. *J Acoust Soc Am*, 96, 2108–2120.

Byrne, D., Parkinson, A., Newall, P. (1990). Hearing aid gain and frequency response requirements for the severely/profoundly hearing impaired. *Ear Hear*, *11*, 40–49.

Cameron, S., Brown, D., Keith, R., et al. (2009). Development of the North American Listening in Spatialized Noise-Sentences test (NA LiSN-S): Sentence equivalence, normative data, and test-retest reliability studies. *J Am Acad Audiol*, *20*, 128–146.

Cameron, S., & Dillon, H. (2007). Development of the Listening in Spatialized Noise-Sentences Test (LISN-S). *Ear Hear*, *28*, 196–211.

Cameron, S., & Dillon, H. (2008). The listening in spatialized noise-sentences test (LISN-S): Comparison to the prototype LISN and results from children with either a suspected (central) auditory processing disorder or a confirmed language disorder. *J Am Acad Audiol*, *19*, 377–391.

Cameron, S., & Dillon, H. (2009). *Listening in Spatialized Noise-Sentences test (LiSN-S) (Version 1.014) [Computer software]*. Murten, Switzerland: Phonak Communications AG.

Cameron, S., & Dillon, H. (2011). Development and evaluation of the LiSN & learn auditory training software for deficit-specific remediation of binaural processing deficits in children: Preliminary findings. *J Am Acad Audiol*, *22*, 678–696.

Cameron, S., Glyde, H., Dillon, H. (2011). Listening in Spatialized Noise-Sentences Test (LiSN-S): Normative and retest reliability data for adolescents and adults up to 60 years of age. *J Am Acad Audiol*, *22*, 697–709.

Ching, T. Y., van Wanrooy, E., Dillon, H., et al. (2011). Spatial release from masking in normal-hearing children and children who use hearing aids. *J Acoust Soc Am*, *129*, 368–375.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychon Bull & Review*, *3*, 422–433.

Dillon, H. (2001). *Hearing Aids*. Sydney, Australia: Boomerang Press.

Divenyi, P. L., & Haupt, K. M. (1997). Audiological correlates of speech understanding deficits in elderly listeners with mild-to-moderate hearing loss. III. Factor representation. *Ear Hear*, *18*, 189–201.

Divenyi, P. L., Stark, P. B., Haupt, K. M. (2005). Decline of speech understanding and auditory thresholds in the elderly. *J Acoust Soc Am*, *118*, 1089–1100.

Dubno, J. R., Ahistrom, J. B., Horwitz, A. R. (2002). Spectral contributions to the benefit from spatial separation of speech and noise. *J Speech Lang Hear Res*, *45*, 1297–1310.

Durrleman, S., & Simon, R. (1989). Flexible regression models with cubic splines. *Stat Med*, *8*, 551–561.

Gatehouse, S., & Noble, W. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *Int J Audiol*, *43*, 85–99.

Gates, G. A., & Mills, J. H. (2005). Presbycusis. *Lancet*, *366*, 1111–1120.

Gelfand, S. A., Ross, L., Miller, S. (1988). Sentence reception in noise from one versus two sources: Effects of aging and hearing loss. *J Acoust Soc Am*, *83*, 248–256.

Glyde, H., Hickson, L., Cameron, S., et al. (2011). Problems hearing in noise in older adults: A review of spatial processing disorder. *Trends Amplif*, *15*, 116–126.

Hafter, E. R. (2010). Is there a hearing aid for the thinking person? *J Am Acad Audiol*, *21*, 594–600.

Keidser, G., Dillon, H., Convery, E., et al. (2010). Differences between speech-shaped test stimuli in analyzing systems and the effect on measured hearing aid gain. *Ear Hear*, *31*, 437–440.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychol Aging*, *9*, 339–355.

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *Int J Audiol*, *42*(Suppl 1), S49–S58.

Marrone, N., Mason, C. R., Kidd, G. Jr. (2008). Evaluating the benefit of hearing aids in solving the cocktail party problem. *Trends Amplif*, *12*, 300–315.

Mueller, J., Kiernan, R., Langston, J. W. (2001). *Cognistat: The neurobehavioral Cognitive Status Examination.* Fairfax, VA: The Northern Californian Neurobehavioral Group.

Mueller, J., Kiernan, R., Langston, J. W. (2009). *Cognistat Manual (The neurobehavioral Cognitive Status Examination.* Fairfax, VA: The Northern Californian Neurobehavioral Group.

Murphy, D. R., Daneman, M., Schneider, B. A. (2006). Why do older adults have difficulty following conversations? *Psychol Aging*, *21*, 49–61.

Ruchinskas, R. A., & Curyto, K. J. (2003). Cognitive screening in geriatric rehabilitation. *Rehabil Psychol*, *48*, 14–22.

Schmiedt, R. A. (2010). The physiology of cochlear presbycusic. In S. Gordon-Salant, R. D. Frisina, A. N. Popper, R. R. Fay (Eds). *The Aging Auditory System* (pp. 9–38). New York, NY: Springer.

Warren, L. R., Wagener, J. W., Herman, G. E. (1978). Binaural analysis in the aging auditory system. *J Gerontol*, *33*, 731–736.