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Spatial Benefit of Bilateral Hearing Aids

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Abstract

Objectives—To assess the extent to which hearing aids improve spatial benefit by restoring the availability of interaural difference cues, the benefit attributable to spatial separation of speech and babble with and without bilateral hearing aids was measured as a function of low-pass cutoff frequency.

Design—Twenty-one older adults with sloping high-frequency hearing loss were provided commercially available bilateral hearing aids. After a 3 to 6 month acclimatization period, speech levels corresponding to 50% correct recognition of sentences from the Hearing in Noise Test (HINT) were measured in a 65-dB SPL babble, with speech and babble low-pass filtered at 1.8, 3.6, and 5.6 kHz. Sentences were always at 0° azimuth, and babble was at either 0° or 90°. Speech and babble spectra for all conditions were digitally recorded using a probe microphone placed in each ear canal of each subject. Spectra and levels of speech and babble and unaided thresholds for narrowband noises were used to calculate the aided audibility index and provide predictions of unaided and aided thresholds for HINT sentences, hearing aid benefit, and spatial benefit for each cutoff frequency. In addition, subjects' willingness to tolerate background noise with and without amplification was measured in the spatially coincident and spatially separated conditions using the Acceptable Noise Level (ANL) procedure.

Results—Thresholds for HINT sentences in babble and ANL improved significantly when aided and when speech and babble were spatially separated. Specifically, hearing aid benefit improved significantly as cutoff frequency increased from 1.8 to 3.6 kHz but only when speech and babble were spatially separated; likewise, spatial benefit improved significantly from 1.8 to 3.6 kHz but only in the aided condition. No further improvement in hearing aid or spatial benefit was observed when cutoff frequency was increased from 3.6 to 5.6 kHz, although improvement in hearing aid benefit was predicted.

Conclusions—Hearing aid benefit, although significant, was poorer than predicted, suggesting that these older adults with high-frequency hearing loss did not take full advantage of the increase in audible speech information provided by amplification. Hearing aid benefit was also limited because hearing aids for some subjects did not restore speech audibility across the full bandwidth of speech. Unaided and aided spatial benefit was significantly greater than predicted, and aided spatial benefit was greater than unaided. This suggests that these older adults were able to take advantage of interaural level and time difference cues to improve speech recognition in babble and that they benefited from these cues to a greater extent with than without bilateral hearing aids. Finally, in contrast to results of previous studies, ANL may vary for an individual depending on the listening condition.

INTRODUCTION

Relative to listeners with normal hearing, individuals with hearing loss have more difficulty understanding speech in noise (Eisenberg et al. 1995; Humes 1996; McArdle et al. 2005; van Rooij & Plomp 1990), have reduced ability to detect and localize signals in space (Drennan et al. 2005; Häusler et al. 1983; Lorenzi et al. 1999; Noble et al. 1994), and derive less benefit from spatial separation of speech and noise sources (Dubno et al. 2002; Duquesnoy 1983; Gelfand et al. 1988; Peissig & Kollmeier 1997). Improvements in speech recognition when speech and noise originate from spatially separated sources derive from two main binaural cues: (1) interaural level differences (head shadow at the far ear and “boost” at the near ear), which are largest between 2.0 and 5.0 kHz (Festen & Plomp 1986; Nordlund 1962; Tonning 1971) and (2) interaural time differences, which have their greatest contribution at lower frequencies (Wightman & Kistler 1992; Zurek 1993a,b).

The reduced advantage of spatial separation for individuals with hearing loss largely results from the frequency dependence of interaural level differences and high-frequency hearing loss. That is, speech information that could be made audible because of an improved signal-to-noise ratio (SNR) in the ear away from the noise remains inaudible as a result of high-frequency hearing loss. In a previous study (Dubno et al. 2002), the benefit attributable to spatial separation of speech and noise sources was measured as a function of low-pass cutoff frequency to vary the presence of interaural level difference cues. In general, as low-pass cutoff frequency and the availability of high-frequency level difference cues increased, speech-recognition thresholds for older adults with hearing loss improved significantly less than for younger and older adults with normal hearing. In another study, spatial benefit for older subjects with normal hearing was reduced relative to benefit for younger subjects and was significantly less than predicted by the Articulation Index (AI; Dubno et al. 2008). Because differences in audibility for younger and older subjects were accounted for, poorer-than-predicted performance by older subjects suggested an age-related deficit in the use of interaural difference cues to produce binaural advantages for speech recognition in noise. Other studies have also shown that these cues may be limited by age or hearing loss (Abel et al. 2000; Cranford et al. 1990; Strouse et al. 1998; Tremblay et al. 2003). Given that effective use of interaural difference cues provided by spatial separation improves the functional SNR, deficits in the use of these cues by older adults with hearing loss may contribute to their speech-recognition difficulties.

Bilateral amplification should benefit speech recognition in noise in at least four ways: (1) increase speech audibility; (2) improve directional hearing; (3) improve spatial benefit by restoring the availability of interaural level and timing cues; and (4) provide binaural redundancy, which refers to the relatively small advantage arising from listening to the same signal delivered to the two ears (Bronkhorst & Plomp 1988; Day et al. 1988). In addition, modern hearing aids that incorporate directional microphones can improve the SNR and contribute to better speech understanding. Indeed, several studies have assessed the potential of directional amplification to improve localization and speech recognition in noise (Drennan et al. 2005; Freyaldenhoven et al. 2005; Hornsby & Ricketts 2007; Musa-Shufani et al. 2006; Ricketts et al. 2005; Van den Bogaert et al. 2006). In general, these studies reported improved speech recognition in noise with directional amplification, although localization results were inconsistent. However, less is known about the extent to which hearing aids improve speech recognition by restoring binaural advantages when compared with unaided listening.

In contrast to improving performance, bilateral hearing aids could reduce spatial benefit by altering interaural difference cues, although results are equivocal (Drennan et al. 2005; Marrone et al. 2007; Musa-Shufani et al. 2006; Van den Bogaert et al. 2006). Bilateral

hearing aids that are programmed with different compression ratios and attack/release times and work independently may alter interaural time and intensity cues and have a negative effect on binaural cues (Dillon et al. 2003; Van den Bogaert et al. 2006). Additionally, the acoustic characteristics of the ear canal with a hearing aid in place may affect the phase response of the aided signals and thus have a negative effect on binaural cues (Drennan et al. 2005). Finally, although technological improvements have resulted in hearing aids with wider band frequency responses that make it possible to provide increased higher frequency gain, hearing aid benefit and aided spatial benefit may be less than expected if speech recognition does not improve with increased higher frequency speech audibility (Ching et al. 1998; Hogan & Turner 1998).

Previous studies have reported that individuals with sensorineural hearing loss require a more advantageous SNR to achieve speech recognition equivalent to that of listeners with normal hearing (Dirks et al. 1982; Plomp 1978, 1986). Although other factors may contribute to poorer speech recognition in older adults with hearing loss (e.g., peripheral temporal deficits and cognitive declines), reduced audibility, especially in the higher frequencies, has been shown to account for a substantial portion of the speech recognition or SNR deficit (Humes 2002; Lee & Humes 1993; van Rooij et al. 1992; van Rooij & Plomp 1990). Thus, hearing aid gain that restores speech audibility across the full bandwidth of speech should result in speech-recognition thresholds for listeners with hearing loss nearly equivalent to those of listeners with normal hearing. Indeed, results from several studies with younger subjects with normal hearing and younger and older subjects with hearing loss have shown that when speech audibility has been restored across the full bandwidth of speech, speech-recognition thresholds in steady-state noise are equivalent between the two groups (Lee & Humes 1993; Van Tasell & Yanz 1987). However, in more realistic environments, such as with modulated maskers, subjects with hearing loss did not perform as well as subjects with normal hearing, even when speech and noise were presented at levels that provided audible speech across most of the speech bandwidth (Eisenberg et al. 1995). This suggests that factors other than simple audibility may account for reduced speech recognition in noise by older adults with hearing loss.

In experiments designed to establish if amplification improves speech recognition, it is helpful to determine the amount of benefit expected from well-fit hearing aids. For example, the National Acoustics Laboratory Non-Linear (NAL-NL1) hearing aid fitting algorithm (Byrne et al. 2001) prescribes limited gain for many individuals with moderate to severe high-frequency hearing loss. That is, less gain is prescribed at frequencies where hearing loss is greatest to allow for more gain at frequencies that may be more beneficial for speech audibility and speech recognition (Ching et al. 2001). If limited hearing aid gain and inadequate audibility is provided in the higher frequencies, improvements in speech recognition in noise may be relatively small. On the other hand, speech recognition that does not improve, even when high-frequency audibility is restored with amplification, suggests that factors other than increased thresholds contribute to reduced aided speech recognition. Predictions of speech recognition from an aided importance-weighted speech-audibility metric (Aided Audibility Index [AAI]) can differentiate between these two explanations. That is, comparisons of observed and predicted speech recognition can determine the extent to which (1) amplification improves audibility and (2) subjects benefit from additional cues (such as binaural cues) made available by improved audibility. This approach was taken in the current experiment.

The primary goal of this experiment was to assess benefit of bilateral hearing aids and benefit of spatial separation for speech recognition in noise. Subjects were older adults with sloping high-frequency hearing loss who were provided with commercially available bilateral hearing aids. Because one goal of providing bilateral amplification is to enable

individuals with hearing loss to benefit from binaural hearing in real-world listening situations, several additional measures were obtained in this experiment. The Acceptable Noise Level (ANL), a speech-in-noise measure developed by Nabelek et al. (1991), was designed to quantify subjects' willingness to accept background noise. In their study, full-time users of hearing aids were able to tolerate higher levels of background noise compared with part-time and unsuccessful hearing aid users. Results of other studies showed that ANLs were not related to age (Freyaldenhoven & Smiley 2006; Nabelek et al. 2006), hearing sensitivity (Nabelek et al. 2006), or speech recognition in aided or unaided conditions (Nabelek et al. 2004). Thus, it has been suggested that the ANL is intrinsic to an individual and is a predictor of hearing aid success (Nabelek et al. 2006); however, more recent data suggest the ANL alone may not be sufficient to differentiate between successful and unsuccessful hearing aid users (Freyaldenhoven et al. 2008). It was of interest to determine if ANL predicted hearing aid use in the current experiment and if ANL was associated with speech-recognition measures.

Additionally, to assess each listener's perspective on the success of their hearing aids, self-report questionnaires were administered, including the Glasgow Hearing Aid Benefit Profile (GHABP) (Gatehouse 1999), Satisfaction with Amplification in Daily Life (SADL) (Cox & Alexander 1999), Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse & Noble 2004), and Attitudes Toward Loss of Hearing Questionnaire (ALHQ) (Cienkowski & Saunders 2000). To assess the role of cognitive abilities in hearing aid and spatial benefit, a visual letter-monitoring task (Gatehouse et al. 2003) was administered. This task has been shown to influence the outcome of speech-recognition measures, particularly in noise (Gatehouse et al. 2003). Approximately 3 to 6 months after the initial hearing aid fitting, subjects returned to the laboratory for measures of speech recognition in noise, ANL, and to complete self-report questionnaires (see Table 1 for an overview of the experimental design).

MATERIALS AND METHODS

Participants

Twenty-one* older adults (mean age, 75.3 yr; range, 69–83 yr) with adult-onset sensorineural hearing loss and normal immittance measures participated in the study. Mean pure-tone thresholds in quiet (± 1 SD) for each ear measured under headphones (ANSI 2004) are shown in Figure 1. For all subjects, interaural differences, averaged across frequency from 0.25 to 6.0 kHz, were ≤ 11 dB; for 13 subjects, differences were ≤ 5 dB. Seven of the 21 subjects were experienced hearing aid users, that is, they used hearing aids with various types of compression circuits for at least 1 yr. In addition to being compensated on an hourly basis for their participation, subjects were offered the opportunity to keep their hearing aids (provided by Starkey Laboratories at no cost) at the end of the study.

Subjects had no previous experience with the speech materials used in the experiment or with the listening tasks. During training, the examiner provided extensive feedback to the subject until the subject understood the task and provided consistent results. For the simple task of measuring detection thresholds with narrowband noise, this was accomplished after four to five measurements for most participants. Practice sentences provided with the speech materials were used to train participants. The narrowest and widest of three low-pass-filter cutoffs were included during this practice period in both unaided and aided conditions. After

*Twenty-five subjects were fit with bilateral hearing aids. Of those, one subject was recruited for pilot testing only, two subjects dropped from the study because of illness, and one subject was lost to follow-up before all testing was completed.

approximately 1 hr of practice with the various tasks, data collection was completed in two or three 2 hr sessions (see Table 1).

Apparatus and Stimuli

Thresholds for pure tones—Pure-tone thresholds for frequencies from 0.25 to 8.0 kHz were measured in quiet with a Madsen Orbiter 922 audiometer and TDH-39 headphones using a clinical adaptive psychophysical procedure (ASHA 2005). As described later, these monaural thresholds determined the noise-source location for the babble masker used for sound field speech measures.

Thresholds for narrowband noises—Thresholds for narrowband noises were measured in the sound field and were used in AAI predictions. Signals were digitally generated (TDT DD1) narrowband noises, 350 msec in duration (including 10 msec rise/fall ramps) with nominal filter slopes of 96 dB/oct or steeper. Narrowband noises were centered at 0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, and 6.0 kHz; bandwidths were 0.072, 0.120, 0.170, 0.195, 0.220, 0.270, 0.320, and 0.480 kHz, respectively. These bandwidths were selected as a compromise between sound field uniformity (obtained with wider bandwidths) and frequency specificity for characterizing thresholds (obtained with relatively narrow bandwidths) (ASHA 1991). Thresholds in the sound field were measured for each ear with the nontest ear plugged with an E-A-R[®] roll-down foam earplug (Aearo Company). After inspecting the ear canal with an otoscope, an appropriate earplug size was selected (small, medium, or large) and inserted deeply into the ear canal. Placement was verified by visual inspection and, after adjustment, attenuation was confirmed by the subject. Actual attenuation provided by the earplug was not directly measured; however, earplugs were only used for measuring thresholds, and interaural differences for each subject were small. Additionally, Royster et al. (1996) suggested that experimenter-fit earplugs provide amounts of attenuation similar to those claimed by the manufacturer. Narrowband noises were low-pass filtered at 5.6 kHz (Stanford Research Dual Channel Filter Model 650 and TDT PF1), passed through an amplifier (Crown D-75A) and 8-ohm attenuator (Audioplex Technology[™]), and delivered through a loudspeaker (RCA Pro ×4AV) 1 m from the listener's head (see Dubno et al. 2008 for additional details regarding sound field calibration).

Thresholds for speech in babble—Speech levels corresponding to 50% correct recognition of sentences in babble were measured in the sound field using 250 sentences from a CD recording of the Hearing in Noise Test (HINT) (Nilsson et al. 1994).[†] The HINT consists of 25 lists of 10 sentences each. Sentences are approximately equal in length, and lists have been equated for difficulty (Hanks & Johnson 1998). The masker was the multitalker babble from the Speech Perception in Noise test (SPIN; Kalikow et al. 1977) and was fixed at 65 dB SPL. Overall levels of the speech and babble were controlled individually using programmable and manual attenuators (TDT PA4). Speech and babble were low-pass filtered (Stanford Research Dual Channel Filter Model 650 and TDT PF1) at 1.8, 3.6, and 5.6 kHz (3 dB down points), passed through one or two amplifiers (Crown D-75A) and 8-ohm attenuators (Audioplex Technology[™]), and delivered through one or two loudspeakers (RCA Pro × 4AV), depending on the babble condition. Sentences were always presented at 0°. Babble location was either 0° (spatially coincident) or 90° (spatially separated). For the 90° condition, the masker was presented from the loudspeaker nearest each subject's ear with higher unaided thresholds, which was determined from average pure-tone thresholds measured in quiet under headphones. Thus, with the signal source at 0°, the

[†]A DAT recording of the HINT materials was obtained from the House Ear Institute, Los Angeles, CA and copied onto a CD for playback.

poorer hearing ear was closer to the noise source, under the assumption that listeners would likely position themselves in a similar manner in real-world listening.

Acceptable Noise Level—For the measurement of ANL, connected discourse with a male talker (CD recording of Arizona Travelogue)[‡] was presented at 0°, and the SPIN babble was presented at 0° or 90°. ANL was measured only for broadband speech and babble (low-pass cutoff at 5.6 kHz). Routing of the speech and babble through the equipment and loudspeakers was the same as previously described for the speech thresholds. Characteristics of all signals were verified with a precision sound level meter (Brüel & Kjær) and a signal analyzer (Stanford Research SR780).

Hearing aids—All subjects were fit with bilateral digital in-the-ear Starkey Axent II hearing aids with four-channel wide-dynamic-range compression (WDRC). For each subject, compression ratios and compression thresholds for speech stimuli were based on the NAL-NL1 fitting strategy (Byrne et al. 2001). The between-channel crossover frequencies, determined by the Starkey software, were 0.75, 1.75, and 3.75 kHz for all subjects. Noise management, expansion, and directionality features were not engaged. Signal phase and digital processing delay introduced by each hearing aid were measured using the Fonix 7000 Hearing Aid Test System (i.e., verifying that the receivers in the bilateral pair were acting as a matched system).

Each hearing aid was programmed to match NAL-NL1 2 cc coupler targets using the International Collegium of Rehabilitative Audiology (Dreschler et al. 2001)–weighted composite steady-state noise provided by the Fonix system. The hearing aid gain was adjusted across frequency until values were generally within ± 5 dB of target values for input levels of 50, 65, and 80 dB SPL; no further adjustments were made to match targets. Because the hearing aids were determined to have very slow time constants, it was assumed that after the circuit was engaged and stabilized, the gain of the hearing aid did not change (i.e., as in a linear hearing aid). Thus, all gain measurements were recorded after the hearing aid's compression circuit stabilized (~ 10 – 20 sec). Probe measures were also obtained using the Fonix real ear system and were also generally within ± 5 dB of the targets except at 5.0 kHz. Table 2 shows mean absolute differences between measured and target gain at 0.5 to 5.0 kHz for both the 2 cc coupler and real ear measures. Figure 2 shows the mean and range of 2 cc coupler gain across frequency for both hearing aids of all subjects.

Procedures

Thresholds for narrowband noises—Thresholds for narrowband noises in the sound field were measured using a single-interval (yes/no) maximum-likelihood psychophysical procedure (Green 1993; Leek et al. 2000). The slope factor (k) was 0.5 according to Green (1993). Each threshold was determined from 24 trials, including four catch trials. Signal level was varied adaptively with a minimum step size of 0.5 dB. Threshold was defined as the sweet point (Green 1993), which was calculated based on the estimated m (the midpoint of the psychometric function) and α (the false alarm rate) after 24 trials. Narrowband-noise threshold was the average of two measurements. “Listen” and “Vote” periods were displayed on a computer monitor placed above and behind the 0° loudspeaker. Participants responded by clicking one of two mouse buttons corresponding to the responses “yes, I heard the noise” and “no, I did not hear the noise.”

Thresholds for speech in babble—With the babble fixed at 65 dB SPL, sentence level was varied adaptively using a one-down, one-up tracking paradigm (Levitt 1971)

[‡]The CD recording of the Arizona Travelogue was obtained from the University of Tennessee, Knoxville, TN.

converging on 50% correct sentence recognition. Subjects were instructed to repeat the entire sentence and guess when required. Responses were recorded as correct when the entire sentence was repeated accurately. The step size was 3 dB for the first four reversals and 2 dB for the remaining eight reversals. Threshold was defined as the average speech level (in dB SPL) of the last six reversals. Each threshold required approximately 15 to 17 sentences. Noise-source location and filter cutoff were randomized. Odd-numbered subjects completed all testing without hearing aids before testing with hearing aids; even-numbered subjects were tested first with hearing aids. In the aided conditions, the babble was played through the 0° or 90° loudspeaker for approximately 20 sec before playing the first HINT sentence to allow the hearing aids' compression circuits to engage and stabilize and then was on continuously.

Acceptable Noise Level—For measurement of ANL, a procedure similar to Nabelek et al. (1991) was used. Written and verbal instructions were provided to the subjects before testing. First, the most comfortable level (MCL) was established with a sample of the connected discourse (Arizona Travelogue) presented at 0°. This level was defined as the level the subject would set when listening to a radio. The connected discourse was initially presented at an inaudible level and then gradually increased by the experimenter until the subject reported that it was too loud. The level was decreased until the subject reported that it was too soft to understand the connected discourse. Using an up-down procedure, the level was adjusted in 2 dB steps to determine the MCL and then was fixed at that level. With the speech remaining at 0°, babble was presented at a low level at 0° or 90°, depending on the test condition. The babble was then adjusted in 2 dB steps using an up-down procedure to determine the maximum acceptable background noise level (BNL) that could be tolerated while following the connected discourse without fatigue. The BNL was measured three times and averaged. ANL was defined as the difference between MCL and the average BNL ($ANL = MCL - BNL$).

Hearing aids—The hearing aids were initially fit by a clinical audiologist. After the hearing aid fitting, an orientation was provided that included training on use and care of the instruments, a review of communication strategies, and instructions for obtaining replacement batteries. A mark was made on the volume control wheel of each hearing aid to ensure that it could be accurately returned to the identical setting for all aided laboratory testing. Further counseling and orientation were provided if required. Subjects were initially instructed to wear the hearing aids as many hours during the day as they found comfortable, but after a period of 2 wk, they were strongly encouraged to wear the hearing aids between 8 and 12 hr per day. No adjustments in hearing aid gain settings were made at follow-up visits; however, any problems with the physical fit of the hearing aids were addressed.

Aided Audibility Index—Predicted thresholds for HINT sentences in babble were determined from AAI values (Souza & Turner 1999; Stelmachowicz et al. 1994; Stelmachowicz et al. 2002), computed using procedures similar to ANSI (1969) including (1) each subject's thresholds for narrowband noises measured in quiet at 0°; (2) the spectra and levels of the HINT sentences (at 0°) and babble (at 0° and 90°); (3) the frequency-importance function developed by Pavlovic (1989) for "average everyday speech;" and (4) the AI-recognition transfer function reported for HINT sentences by Eisenberg et al. (1998). It is important to note that the AAI predictive model includes frequency-dependent level differences between ears (i.e., head shadow and boost resulting from the change in noise-source location from 0° to 90°) but does not include effects of other interaural difference cues that may influence speech-recognition thresholds (e.g., interaural delay).

Specifically, to quantify each subject's quiet thresholds to be used in AAI calculations, recall that narrowband-noise thresholds were measured at 0° in the sound field for each ear

individually with the nontest ear plugged. To transform these thresholds into individual *in situ* dB SPL values, the narrowband noises were presented from the 0° loudspeaker at 80 dB SPL (a level chosen to be well above the noise floor of the probe microphone system). Using a probe microphone (Etymotic Model ER-7C), the output from each ear canal was measured independently, and the ear-canal resonance at each narrowband frequency was determined by subtracting the input from the measured output. This level, added to the measured quiet threshold, resulted in a threshold defined in terms of SPL generated in each individual ear canal (Erber 1973; Saunders & Morgan 2003).

Additionally, to use the frequency-importance function provided by Pavlovic (1989), all AAI parameters were adjusted to correspond to eight frequency bands of variable width centered at audiometric frequencies (Pavlovic 1989). Speech and babble levels for the eight frequency bands were based on individual subjects' probe microphone (ER-7C) recordings of a broadband noise, which had been spectrally shaped in 1/3 octave intervals to match the long-term spectrum of either the speech or babble (Cool Edit Pro™ Version 1.2). Ear-canal recordings for each ear separately were made with the speech-shaped noise presented at 0° and the babble-shaped noise at either 0° or 90° in both unaided and aided conditions. The probe tube was placed in the ear canal at a depth of 27 mm past the intratragal notch, resulting in a location within ~5 to 7 mm of the eardrum of the average ear (Dirks et al. 1996). It was verified that this placement also was at least 5 mm beyond the sound bore of each hearing aid. The level of the speech-shaped and babble-shaped noises was fixed at 65 dB SPL during the recordings. Similar to aided speech testing, during recordings in the aided conditions, the noise was turned on for approximately 20 sec before recording a sample of noise to allow the hearing aids' compression circuits to engage and stabilize. The waveform recordings were analyzed using Adobe Audition (Version 1.5).

An AAI value was calculated for each ear of each subject, unaided and aided, and for each low-pass filter and noise-source condition (0° and 90°). Speech level was each subject's measured threshold for HINT sentences in the appropriate condition; babble level was fixed at 65 dB SPL. A 30 dB dynamic range (+12 dB speech peaks and -18 dB speech minima) was assumed, given the slow time constants of the hearing aid and compression ratios less than 3:1 (Woods et al. 2006). Similar to Stelmachowicz et al. (2002), a binaural AAI was then calculated based on the better sensation level for each frequency band regardless of ear; no increase in audibility was assumed when the ears were symmetrical. This procedure takes into account differences in simple audibility due to the frequency-gain response of the hearing aid, and changes in audibility resulting from level differences associated with head shadow or boost. Other spatial and binaural listening benefits for recognition of speech attributable to binaural processing were not accounted for by the AAI model.

Subjective and cognitive measures—The GHABP, SADL, SSQ, and ALHQ were administered to the subjects in an interview format after 3 to 6 mo of hearing aid use. The GHABP provides scales that cover Initial Disability, Handicap, Hearing-aid Use, Satisfaction and Residual Disability. Four prespecified and one or two subject-specified listening situations were assessed. The SADL is a 25-item satisfaction questionnaire, which yields a Global Satisfaction Score and subscale scores, including Positive Effects, Service and Cost, Negative Features, and Personal Image. The SSQ is a questionnaire developed to measure a range of hearing disabilities across several domains. It is composed of 50 questions divided into three sections: Speech, Spatial, and other Qualities, which characterizes hearing using the concept of the auditory scene and focuses on hearing functions related to binaural listening. Finally, the ALHQ (v2.1) is a 25-item questionnaire with five scales that address Denial of Hearing Loss, Negative Associations, Negative Coping Strategies, Manual Dexterity and Vision, and Hearing-related Esteem. Results have indicated that this questionnaire can be used as a valid measure of a subject's attitude

towards hearing loss and hearing aids, which then can be related to satisfaction and hearing aid use.

In the cognitive visual-monitoring task, a stream of vowels and consonants was presented on a computer screen positioned in front of the subject. The subject's task was to monitor the letters and press the keyboard space bar as quickly as possible each time the combination of letters formed a valid three-letter word. The subject was instructed to ignore all letters not forming a word. Letters were first presented every 2 sec for a "slow" trial and then every 1 sec for a "fast" trial. A single score was calculated from both trials.

Data Analyses

Outcome measures included the following values: (1) observed thresholds for HINT sentences, hearing aid benefit (defined as unaided threshold minus aided threshold), and spatial benefit (defined as threshold with babble at 0° minus threshold with babble at 90°); (2) AAI-predicted thresholds for HINT sentences, hearing aid benefit, and spatial benefit; (3) observed ANL, hearing aid benefit for ANL (defined as unaided ANL minus aided ANL), and spatial benefit for ANL (defined as ANL with babble at 0° minus ANL with babble at 90°); and (4) questionnaire responses and cognitive measures. Differences in threshold and benefit measures were assessed by repeated-measures analysis of variance. Associations among subjective and cognitive measures and objective speech-recognition measures were assessed by Pearson product moment correlations. For all analyses, effects were significant with $p < 0.05$.

RESULTS

Thresholds for Speech in Babble

Hearing aid benefit—Figure 3 shows mean unaided and aided thresholds for HINT sentences as a function of low-pass cutoff frequency for babble at 0° (top) and babble at 90° (middle). HINT sentences were always at 0°. Observed thresholds for HINT sentences in babble improved significantly with hearing aids [$F(1,20) = 5.21$; $p = 0.034$], as seen in both panels where aided thresholds (filled triangles) were lower (better) than unaided thresholds (filled circles). Thresholds predicted by the AAI (open symbols) also show thresholds significantly lower than unaided [$F(1,20) = 24.14$; $p = 0.0001$]. Both observed and predicted thresholds varied significantly with cutoff frequency [$F(2,40) = 216.81$; $p < 0.0001$; $F(2,40) = 363.41$; $p < 0.0001$, respectively]. There were also significant interactions between aid and cutoff frequency [observed: $F(2,40) = 4.26$; $p = 0.021$; predicted: $F(2,40) = 15.34$; $p < 0.0001$], such that differences between unaided and aided thresholds were larger at the two higher cutoff frequencies. *Predicted* thresholds for HINT sentences were better than *observed* thresholds in the spatially coincident conditions (top panel), especially with hearing aids (open triangles). In contrast, *observed* thresholds for HINT sentences were generally better than *predicted* thresholds in the spatially separated conditions (middle panel) (see Discussion section for additional details).

The bottom panel of Figure 3 shows mean hearing aid benefit (unaided thresholds minus aided thresholds) as a function of low-pass cutoff frequency. Mean observed hearing aid benefit ranged from -0.7 to 1.6 dB, depending on cutoff frequency and noise-source location, whereas mean predicted benefit ranged from 1.4 to 2.8 dB. Observed hearing aid benefit significantly improved as cutoff frequency increased from 1.8 to 3.6 kHz [$F(1,20) = 17.38$; $p = 0.0005$] but only in the spatially separated condition. No further improvement was observed when cutoff frequency was increased from 3.6 to 5.6 kHz. Predicted hearing aid benefit improved significantly as cutoff frequency was increased from 1.8 to 3.6 kHz [$F(1,20) = 10.40$; $p = 0.004$]. In contrast to observed benefit, predicted hearing aid benefit

continued to improve significantly as cutoff frequency increased to 5.6 kHz [$F(1,20) = 17.58$; $p = 0.0004$]. Taken together, these results revealed that, on average, bilateral amplification improved speech thresholds in babble. However, the significantly poorer-than-predicted hearing aid benefit suggested that listeners did not take full advantage of the increase in audible speech information provided by amplification.

To help clarify individual listeners' ability to benefit from amplification, correlations between aided HINT thresholds (0°) and average high-frequency thresholds at 2.0, 3.0, and 4.0 kHz measured in quiet were examined and are shown in Figure 4. For observed thresholds (top panel), significant positive correlations were seen for speech and babble filtered at 3.6 and 5.6 kHz ($r = 0.646$ and $r = 0.552$, respectively). That is, listeners with more high-frequency hearing loss had higher HINT thresholds (i.e., required more favorable SNRs) with amplification. Significant positive correlations were also found (middle panel) between predicted aided HINT thresholds for speech and babble filtered at 3.6 and 5.6 kHz and high-frequency thresholds ($r = 0.462$ and $r = 0.501$, respectively). Thus, listeners with more high-frequency loss were also predicted to require more favorable SNRs. The bottom panel of Figure 4 shows differences between observed HINT thresholds and predicted HINT thresholds plotted against high-frequency thresholds. Nearly all observed thresholds were poorer than AAI-predicted thresholds (generally positive values in the bottom panel). Although more modest than the correlation with observed thresholds, a significant positive correlation remained between observed–predicted HINT thresholds and high-frequency thresholds at the 3.6 kHz cutoff. With an increase in cutoff frequency to 5.6 kHz, a trend for increases in observed–predicted differences with increases in high-frequency hearing loss remained, but the correlation was no longer statistically significant ($r = 0.384$; $p = 0.173$).

Spatial benefit—Figure 5 (data recast from Fig. 3) shows mean thresholds for HINT sentences with the babble at 0° and 90° as a function of low-pass cutoff frequency without hearing aids (top) and with hearing aids (middle). Observed thresholds for HINT sentences improved significantly when speech and babble were spatially separated [$F(1,20) = 72.41$; $p < .0001$], as seen in both panels where thresholds were lower with the babble at 90° (filled triangles) than at 0° (filled circles). In contrast, predicted thresholds for HINT sentences improved somewhat when speech and babble were separated for both unaided and aided conditions; however, this improvement was not statistically significant.

As seen in the bottom panel of Figure 5, mean observed spatial benefit (thresholds with babble at 0° minus thresholds with babble at 90°) ranged from 2.7 to 5.0 dB, depending on cutoff frequency and noise-source location; predicted values ranged from 0.1 to 0.8 dB. Observed spatial benefit improved significantly as cutoff frequency was increased from 1.8 to 3.6 kHz but only with hearing aids [$F(1,20) = 9.29$; $p = 0.006$]. No further improvement in spatial benefit was observed as cutoff was increased from 3.6 to 5.6 kHz. Although somewhat unexpected, little spatial benefit was predicted in either the unaided or aided condition. Recall that the AAI calculation used here did not account for low-frequency interaural timing cues that contribute to spatial benefit. Taken together, with effectively no predicted spatial benefit, observed spatial benefit suggests that older individuals with hearing loss were able to use binaural cues to improve speech recognition in babble and that this improvement increased with amplification.

To summarize, speech-recognition results suggest that, on average, bilateral amplification improved speech recognition in babble and increased the availability of some interaural difference cues. No further improvement in hearing aid or spatial benefit was observed when bandwidth was increased from 3.6 to 5.6 kHz, although further improvement in hearing aid benefit was predicted. That is, although mean speech audibility was improved with amplification, on average, listeners did not benefit from this increased audibility. In

addition, significant spatial benefit suggested that older individuals with hearing loss were able to take advantage of interaural difference cues. Spatial benefit that was greater when aided than unaided further suggests that these bilateral hearing aids with slow time constants and low compression ratios did not disrupt interaural difference cues but, instead, enhanced perception of these cues when mid-to-high-frequency amplification was available.

Acceptable Noise Level

Figure 6 shows mean ANL values; lower ANLs indicate that subjects were willing to tolerate more noise (babble). ANL decreased significantly [$F(1,20) = 9.70$; $p = 0.006$] with hearing aids (i.e., subjects tolerated less favorable SNRs), as seen by comparing solid and striped bars for both the 0° and 90° conditions. In addition, ANL decreased significantly when speech and babble were spatially separated [$F(1,20) = 8.79$; $p = 0.008$], as seen by comparing the 0° and 90° bars for both the unaided and aided conditions. Thus, in this group of listeners, ANL was not a characteristic of the individual listener but varied with amplification and noise-source location. No significant interaction was found between ANL and hearing aid condition or noise-source location, although there was a trend for more benefit for ANL in the aided, spatially separated condition.

Significant positive correlations were found between unaided thresholds for HINT sentences and unaided ANL with babble at 0°, as shown in Figure 7. To simplify comparisons, thresholds for HINT sentences were converted to SNR values (HINT threshold minus the 65 dB babble level). As with ANL, lower SNRs signify better performance. Thus, listeners who tolerated less favorable SNRs at threshold for unaided speech also tolerated less favorable SNRs for the unaided ANL. In addition, although the two measures were significantly correlated, the range of SNRs for thresholds for HINT sentences was narrower (−0.3 to 6.0 dB) than for ANL (−1.0 to 14.0 dB), indicating larger individual differences for ANL than for thresholds for speech. Large individual differences in the ANL were reported by Rogers et al. (2003), although speech recognition was not measured in that study.

Significant positive correlations were also found between aided spatial benefit for HINT sentences and aided spatial benefit for ANL, as shown in Figure 8. That is, listeners who achieved more spatial benefit with their hearing aids for speech recognition tolerated less favorable SNRs with their hearing aids when speech and babble were spatially separated. Significant positive correlations between ANL and speech recognition supports an association between the two measures, which is not consistent with previous results (Nabelek et al. 2004, 2006).

Subjective and Cognitive Measures

We hypothesized that self-report and cognitive measures would relate to the various objective measures of speech recognition. For example, because the SSQ was designed to assess binaural listening situations, subjects with more spatial benefit measured objectively were expected to have higher SSQ scores, reflecting a better outcome. In addition, subjects with more hearing aid benefit were expected to have higher satisfaction ratings on both the GHABP and the SADL. However, few correlations between objective and subjective measures reached statistical significance. One example of a significant correlation is shown in Figure 9. A significant positive correlation was found between aided benefit for ANL and hearing aid use. Here, hearing aid use was determined from the GHABP, where listeners reported the proportion of time they wore their hearing aids in several situations. Those individuals who had more hearing aid benefit, as determined by the ANL (i.e., tolerated more babble aided than unaided), also reported more hearing aid use. Interestingly, there was also a significant positive correlation ($r = 0.456$, not shown) between the unaided ANL and hearing aid use; that is, listeners with higher ANL values without hearing aids (i.e.,

tolerated less babble) also reported more hearing aid use. This is inconsistent with earlier findings of Nabelek et al. (2004, 2006) who reported that listeners who tolerated more noise without hearing aids reported more hearing aid use.

Significant positive correlations were also found between the aided Speech-in-Noise factor (a subscale of the speech section) from the SSQ and spatial benefit of hearing aids for speech at 1.8 kHz ($r = 0.433$) and 3.6 kHz ($r = 0.482$). Two questions that are components of this factor are, “You are in a group of about five people in a busy restaurant. You cannot see everyone else in the group. Can you follow the conversation?” and “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?” Significant positive correlations revealed that as aided SSQ score increased, spatial benefit of hearing aids (i.e., aided spatial benefit minus unaided spatial benefit) increased, reflecting a greater ability when listening in noise while wearing hearing aids. This finding is consistent with that reported by Gatehouse and Akeroyd (2006), who observed a significant correlation between the Speech-in-Noise subscale and a dynamic psychoacoustic measure of masking level difference in which the interaural correlation of the masking noise varied as a function of time.

DISCUSSION

Hearing Aid Benefit

The current study examined the benefit attributable to bilateral hearing aids with and without spatial separation as a function of low-pass cutoff frequency of speech and babble. In addition, thresholds for HINT sentences, hearing aid benefit, and spatial benefit predicted by the AAI provided a means to determine the extent to which hearing aids improved speech audibility and listeners benefited from improved speech audibility. Although mean speech thresholds were significantly lower aided than unaided, hearing aid benefit was relatively small. As discussed earlier, this may be attributed to (1) less-than-optimal improvements in speech audibility provided by amplification or (2) subjects’ inability to benefit from improved speech audibility. Three approaches were taken to differentiate these two explanations for individual subjects (analyses of aided spectra, predicted speech thresholds, and observed–predicted differences in speech thresholds).

First, calculations made using ear-canal recordings of unaided and aided speech and babble spectra showed that, for many subjects, quiet thresholds in the higher frequencies rendered portions of the babble spectrum inaudible, even with amplification. Specifically, the level of the aided babble spectrum in the 0° condition at the highest cutoff frequency (5.6 kHz) was lower than quiet thresholds for 9 of 21 subjects at 3.0 kHz and for 15 of 21 subjects at 4.0 kHz. As a consequence, speech audibility for these subjects was not restored with hearing aids across the full bandwidth of speech (i.e., amplification did not fully compensate for their increased thresholds). Limited high-frequency speech audibility likely resulted in higher thresholds for speech (more favorable SNRs) compared with normal subjects (Lee & Humes 1993; Van Tasell & Yanz 1987). This finding is consistent with the significant positive correlation found between observed aided HINT thresholds and high-frequency hearing loss (Fig. 4, top panel) and is also in agreement with many studies (described earlier) that report reduced aided speech recognition in noise for individuals with high-frequency hearing loss. Thus, these results support the conclusion that less-than-optimal speech audibility provided by amplification contributed to higher aided thresholds for speech and limited hearing aid benefit. This lack of audible speech across bandwidth may have been a consequence of the relationship between NAL-NL1–prescribed hearing aid gain and magnitude of high-frequency hearing loss. That is, as hearing loss increased, the amount of prescribed gain did not increase accordingly. Although improving high-frequency audibility is a main goal of amplification, there is generally a tradeoff between optimization

of speech audibility and subjective quality judgments of the hearing aid user (Byrne 1986; Byrne & Tonisson 1976).

Second, aided thresholds for speech predicted from AAI values can also help determine if individual subjects were provided with adequate speech audibility by their hearing aids and were unable to use the newly provided information or if amplification was inadequate. Mean predicted thresholds in Figure 3 (top panel) showing significantly lower speech thresholds when aided than unaided demonstrate that, on average, hearing aids provided at least some increase in audible speech. For individual subjects, if hearing aids provided audibility across the full bandwidth of speech, no significant correlation between predicted HINT thresholds and high-frequency thresholds would be observed. However, a significant positive correlation was found between predicted aided HINT thresholds and high-frequency hearing loss (Fig. 4, middle panel), consistent with the finding (described above) that amplification did not fully compensate for increased thresholds for all subjects.

Third, comparing observed and predicted aided thresholds for speech reflects the extent to which aided HINT thresholds were a result of limited speech audibility. That is, if poor speech thresholds were entirely attributed to reduced audibility resulting from increased thresholds and less-than-optimal amplification, observed speech thresholds would be equivalent to predicted thresholds. However, mean results in Figure 3 showing aided speech thresholds that were poorer than predicted (top panel) and smaller-than-predicted hearing aid benefit (bottom panel) suggest that, on average, these subjects with hearing loss did not fully benefit from the increased audibility provided by their hearing aids. These results are consistent with the positive correlations found between aided observed–predicted differences and high-frequency thresholds (Fig. 4, bottom panel). That is, subjects with more high-frequency hearing loss required more favorable SNRs than needed to compensate for their increased thresholds. Taken together, these results suggest that: (1) hearing aids did not provide optimal audibility across the full speech bandwidth for all subjects, (2) factors beyond inadequate aided speech audibility resulted in higher speech thresholds, and (3) improvement in speech information provided by amplification declined with increasing high-frequency hearing loss.

Several factors may have contributed to smaller-than-predicted hearing aid benefit. First, listeners with hearing loss may have higher masked thresholds in background noise compared with listeners with normal hearing (Dubno & Ahlstrom 1995a,b; Hornsby & Ricketts 2003). Indeed, in these previous studies, AI predictions were more accurate when actual masked thresholds were used to determine speech audibility, rather than relying solely on expected masked thresholds. Higher-than-normal masked thresholds of older listeners with hearing loss may reduce the amount of audible speech and account for poorer-than-normal speech thresholds. Here, because of the nature of the experimental design, masked thresholds were not measured and, therefore, AAI predictions were based on quiet thresholds. From data obtained in a recent study conducted in our laboratory (Horwitz et al. 2008), excess masking was estimated for 10 of the subjects in the current study who listened to speech and noise that had been shaped with a gain-frequency response similar to NAL-NL1. Excess masking was defined as the difference between thresholds measured in the NAL-NL1 speech-shaped noise and thresholds predicted in that same noise using normal critical ratios. A significant positive correlation ($r = 0.644$) was found in that listeners with higher-than-predicted masked thresholds had poorer-than-predicted aided HINT thresholds. Furthermore, as part of the protocol for an ongoing study of age-related hearing loss conducted at the Medical University of South Carolina, masked thresholds were measured in the presence of a high-level noise low-pass filtered at 0.5 kHz. For the listeners in the current study, masked thresholds at 1.5 kHz were significantly ($r = 0.565$) correlated with aided HINT thresholds for speech and babble filtered at 5.6 kHz. That is, subjects with more

upward spread of masking tended to have poorer aided speech thresholds in babble. A partial correlation between quiet thresholds at 1.5 kHz and HINT threshold was not statistically significant, suggesting that quiet thresholds did not affect this result. Because no correction was made for spread of masking in the AAI calculations, aided audibility may have been overestimated, resulting in lower predicted speech thresholds and poorer-than-predicted speech thresholds and aided benefit.

Second, signal distortion in the hearing aids, in the form of circuit noise and nonlinear distortion, could reduce the positive effects of amplification and reduce speech recognition (Kates & Arehart 2005). Coherence measurements are becoming important in evaluating hearing aids and measurement procedures have been standardized (ANSI 1992). Several recent studies have attempted to quantify effects of noise and various types of nonlinear hearing aid distortions on speech recognition and sound quality (Arehart et al. 2007; Kates & Arehart 2005). Modifications to the Speech Intelligibility Index (ANSI 1997) to include a measure of the signal-to-distortion ratio calculated from coherence measures may provide a useful method for estimating the effects of distortion and noise on speech recognition (Kates & Arehart 2005). Nevertheless, additional measures suggested that the hearing aids in the current study did not add an appreciable amount of distortion, so that this factor may have had a negligible effect.

Finally, those subjects whose performance was poorer than predicted by the AAI may have additional peripheral and central impairments that may not be corrected with amplification and may result in more limited benefit of hearing aids. For instance, the consequences of high-frequency hearing loss may not be limited to a loss of high-frequency speech audibility, given the importance of the base of the cochlea to the encoding of lower frequency information (Horwitz et al. 2002; Joris et al. 1994; Kiang & Moxon 1974). Accordingly, providing amplified high-frequency speech would not necessarily restore the contribution of the base of the cochlea for lower-frequency cues. Although no significant correlations were observed between a cognitive measure and speech thresholds or hearing aid benefit, several studies of speech recognition in older adults in which background noise or reverberation were used have shown age-related declines in auditory behavior that may result from cognitive deficits. For example, Humes (2007) reported that differences in hearing aid benefit among older adults may result from aging, cognitive, or central factors once audibility is restored through amplification.

Although improvements in speech recognition with hearing aids were small, it should be noted that scores for HINT sentences increase rapidly with level, with slopes of psychometric functions ranging from 8.9%/dB (Nilsson et al. 1997) to 11.8%/dB (Eisenberg et al. 1998). Taking the average of these two slopes as an estimate, even a seemingly small increase in hearing aid benefit of 1.0 dB corresponds to ~10% change in sentence recognition score.

Spatial Benefit

There is an extensive body of research demonstrating the benefit to speech recognition of spatially separating speech and noise sources (Bronkhorst & Plomp 1988; Levitt & Rabiner 1967; Plomp 1976; Zurek 1993a). Although the issue remains unresolved, several studies have shown objective and subjective benefit of providing bilateral amplification (Byrne 1981; Holmes 2003; Noble & Gatehouse 2006; Silman et al. 1984; Simon 2005). Recent research has begun to focus on quantifying and predicting an individual listener's ability to make use of spatial cues provided by bilateral hearing aids, in part because of the increased use of directional microphones (Dhar et al. 2004; Hornsby & Ricketts 2007; Ricketts et al. 2005). In the current experiment, unaided spatial benefit predicted by the AAI was expected to be very small, assuming that subjects' high-frequency hearing loss would reduce the

potential benefit of an improved SNR at higher frequencies because of head shadow. That is, simple estimates of audibility (AAI) would not take into account interaural difference cues that can provide a sizable spatial benefit, especially at low frequencies.

To the extent that amplification increased the audibility of high-frequency speech and babble, observed and predicted aided spatial benefit was expected to be larger than unaided spatial benefit. That is, it was anticipated that the increase in speech and babble level because of amplification and the reduction in the level of the babble in the far ear would result in an overall improvement in audibility of high-frequency speech. This was not the case. As noted in the discussion of hearing aid benefit, high-frequency amplification was limited for some subjects. In those cases, the measured improvement in audibility because of head shadow would be negligible, resulting in similar unaided and aided mean predicted spatial benefit.

Observed spatial benefit was significantly greater than predicted, suggesting that listeners were able to take advantage of interaural level and time difference cues to improve speech recognition in babble. This improvement increased when amplification was provided, especially for the two higher cutoff frequencies. Although interaural time cues are carried more efficiently by low frequencies, these cues are present in the envelope of speech and therefore may be conveyed across the entire frequency range (Henning 1974). Given the absence of predicted spatial benefit, the observed improvement in thresholds with spatial separation was likely related to the use of binaural difference cues, rather than simply an improvement in SNR because of head shadow.

The amount of unaided spatial benefit observed in this study was similar to that reported by Dubno et al. (2002) for a group of older listeners with hearing loss, although background noise and cutoff frequencies were somewhat different between the studies. Relative to younger subjects, less spatial benefit was observed for older subjects with hearing loss. For unfiltered speech and noise, unaided spatial benefit obtained by subjects with hearing loss in the current study (3.8 dB) was less than obtained by subjects with normal hearing in the previous study (5.3 dB). With amplification, spatial benefit increased to 4.7 dB, more similar to results for listeners with normal hearing.

Interestingly, for the lowest cutoff frequency (1.8 kHz), more spatial benefit was seen unaided than aided. This resulted from better unaided than aided HINT thresholds at 1.8 kHz in the spatially separated condition. This finding is consistent with previous results (Dubno et al. 2002), which demonstrated that listeners with hearing loss rely more on low-frequency timing cues than high-frequency level cues, most likely related to the configuration of their hearing loss. Some studies have shown that immediately after hearing aid fitting, bilateral hearing aids have a negative effect on the use of binaural cues (Drennan et al. 2005; Van den Bogaert et al. 2006). Furthermore, Noble and Byrne (1990, 1991) reported that listeners performed better on a localization task with their own hearing aids compared with novel hearing aids. Therefore, more unaided than aided spatial benefit for low-pass filtered speech and babble may suggest that subjects are more efficient at using low-frequency binaural cues to which they have become accustomed in frequency regions for which their hearing is best.

Acceptable Noise Level

It has been reported that the ANL is a feature inherent to an individual listener and is a predictor of hearing aid use (Nabelek et al. 2004, 2006). In previous studies using SPIN sentences, no correlation was found between speech-recognition scores and ANL (Crowley & Nabelek 1996; Nabelek et al. 2004, 2006). Additionally, ANL did not change significantly with amplification, although SPIN scores were better aided than unaided. These findings led to the conclusion that acceptance of background noise and speech-recognition

scores obtained in background noise were different measures of hearing aid improvement and outcome (Nabelek et al. 2006). In contrast to those results, significant correlations between ANL and speech recognition in babble were observed in the current study, which suggests an association between the two measures.

In contrast to previous studies, ANL improved significantly with hearing aids, similar to the aided improvement in ANL reported by Mueller et al. (2006) for hearing aids with digital noise reduction. In the current study, ANL improved significantly when aided speech and babble were spatially separated. That is, more babble was tolerated with the babble at the side than in front of the listener. Similarly, in a study designed to assess the benefit of directional hearing aids, Freyaldenhoven et al. (2005) reported that ANL spatial benefit (defined as omni-directional ANL minus directional ANL at 180° azimuth) was observed and was of similar magnitude to more traditional measures of hearing aid directional benefit, such as masked speech-recognition thresholds and front-to-back ratios. These authors concluded that ANL was a valid measure for assessing directional benefit in hearing aids. Although differences in speech materials and hearing aid parameters may account for some differences among the studies, additional research is required to determine the role of noise tolerance in predicting hearing aid outcomes.

Subjective Measures

Few significant correlations were observed between self-report measures and objective measures of speech recognition. This was not entirely unexpected given the complexities associated with hearing aid outcomes and the multiple factors that influence hearing aid benefit (Saunders & Cienkowski 2002). Several studies have examined self-report outcome measures for individuals using one hearing aid compared with two (see Noble 2006 for a review). In many of these studies, the self-report measures assessed only a limited range of listening conditions, which may have underestimated the benefit of bilateral amplification (Gatehouse & Akeroyd 2006; Noble & Gatehouse 2006). It has been suggested that the lack of significant correlations between objective psychoacoustic measures and subjective self-report measures reflects the inherent differences between traditional “static” laboratory measures in which reverberation and head movement are controlled and more dynamic real-world listening environments (Gatehouse & Akeroyd 2006; Mencher & Davis 2006). Here, the significant positive correlations found between aided spatial benefit and a subscale of the SSQ supported an association between objective and subjective binaural performance. This is consistent with positive correlations observed by Mendel (2007) between aided HINT thresholds in spatially separated conditions and several categories of the Hearing Aid Performance Inventory (Walden et al. 1984).

Furthermore, the lack of association between cognitive ability and objective speech measures may also relate to the laboratory environment, as well as the hearing aid time constants used in this study. Gatehouse et al. (2003) observed an interaction between cognitive ability, temporal characteristics of background noise, and hearing aid time constants. Those listeners with hearing loss with greater cognitive ability derived more benefit in a temporally modulated background noise when fast time constants were used. In the current study, the background noise was a 12-talker babble and the hearing aids had very slow time constants. Additionally, using a working-memory test and a test of verbal information-processing speed to categorize cognitive function, Lunner (2003) observed a correlation between cognitive function and a speech-recognition-in-noise measure with and without hearing aids. Similar to the present findings, however, no significant correlation was found between the cognitive variables and hearing aid benefit.

With the role of subjective outcome measures of hearing aid benefit receiving increased attention in recent years, especially with regard to user benefit claims (Humes et al. 2001;

Humes 2002; Saunders et al. 2005), further research is warranted. More complex laboratory tasks that involve dynamic listening environments, and high stimulus uncertainty, and demand focused attention may better correlate with self-reported benefit of amplified speech in adverse listening conditions often found in everyday communication.

Study Limitations

In this experiment, observed thresholds for HINT sentences, hearing aid benefit, and spatial benefit were compared with predicted measures using the AAI. Although the AAI has been used in other studies with hearing aids and with laboratory simulations of amplification with headphones (Souza & Turner 1999; Stelmachowicz et al. 1994; Stelmachowicz et al. 2002), certain assumptions and measurement techniques were unique to the current study, which may have influenced the predictions.

For example, although the hearing aids provided to our subjects were WDRC instruments, it was assumed that the very slow time constants allowed the hearing aid to perform like a linear hearing aid during speech-in-babble testing and probe microphone recordings. In an attempt to verify this assumption, several subjects returned to the laboratory after the completion of the study. Their hearing aids were reprogrammed to provide the same amount of gain regardless of input level (i.e., linear gain). Thresholds for speech in babble were measured for the 0° low-pass-filter conditions in both the linear and the original WDRC gain settings. Average HINT thresholds for the two hearing aid settings were within 1 dB and did not differ significantly. This supports the assumption that hearing aid gain in the presence of fixed-level babble did not change once the compression circuit was engaged and stabilized.

Assumptions about the hearing aid compression parameters and changes in gain could also have affected AAI values for the spatially separated conditions. With the babble at 90°, the reduced level of the babble in the far ear because of head shadow may have resulted in an increase in gain in the hearing aid in the far ear. Similarly, the increased level of the babble in the near ear because of boost may have resulted in a decrease in gain in the hearing aid in the near ear. These gain changes would have been captured in the probe recordings of the babble. However, probe recordings of the speech would not have reflected a change in gain because these recordings were obtained separately. Thus, if the gain in the far-ear or near-ear hearing aid changed with noise-source location, AAI calculations of speech audibility could have been inaccurate. To explore this possibility, the amount of head shadow and boost were estimated by comparing probe-microphone measures between the far and near ear both unaided and aided (i.e., spectra near ear–spectra far ear, with babble at 90°). It was hypothesized that a smaller difference in spectra aided than unaided would suggest that the gain in the far ear had increased the gain in the near ear had decreased. AAIs were recalculated incorporating these estimated gain changes. The results did not show systematic changes in predicted HINT thresholds.

Finally, AAI calculations may have been affected by various probe microphone measurement errors. First, although the difference between a single measure and the average of many measures is small, with a standard deviation of approximately 3 dB (Dillon 2001), 12 separate recordings [(unaided and aided HINT spectra × two ears) plus (unaided and aided babble spectra × two speaker locations × two ears)] were obtained for each subject for AAI calculations. Procedures were used to minimize error, such as marking individual probe tubes to ensure consistent placement of the probe and marking hearing aid volume controls. Second, according to Dillon (2001), probe microphone measures obtained at 45° azimuth allow for the greatest amount of head movement without adversely affecting measurement accuracy. However, probe measures in the current study were obtained at 0° and 90° azimuths. To reduce error, subjects were instructed to keep their heads in a fixed position

during speech testing and probe-microphone recordings. Although monitored by the experimenter, some head movement may have occurred.

CONCLUSIONS

1. For HINT sentences in babble, benefit of bilateral hearing aids improved significantly as cutoff frequency increased from 1.8 to 3.6 kHz but only when speech and babble were spatially separated; likewise, spatial benefit improved significantly but only with bilateral hearing aids. Thus, bilateral amplification improved speech recognition in noise and increased the availability of some mid-to-high-frequency interaural difference cues. No further improvement in hearing aid or spatial benefit was observed when bandwidth was increased from 3.6 to 5.6 kHz.
2. Although thresholds for speech in babble were significantly better aided than unaided, hearing aid benefit was significantly poorer than predicted, suggesting that listeners did not take full advantage of the increase in audible speech information provided by amplification. In addition, ear-canal recordings revealed that speech audibility for some subjects was not restored with hearing aids across the full bandwidth of speech. Thus, less-than-optimal speech audibility also contributed to higher aided thresholds for speech and limited hearing aid benefit.
3. Observed spatial benefit was significantly greater than predicted, suggesting that listeners were able to take advantage of interaural level and time difference cues to improve speech recognition in babble. This improvement increased with amplification, which further suggested that these cues were enhanced more than disrupted by bilateral hearing aids.
4. In contrast to previous studies, a significant improvement in ANL was observed with hearing aids and when speech and babble were spatially separated. Thus, in this group of listeners, ANL was not a characteristic of the individual but varied with amplification and noise-source location. In addition, significant positive correlations between ANL and speech recognition in babble supported an association between the two measures.
5. Few significant correlations were found between objective and subjective measures of hearing aid or spatial benefit. This was not entirely unexpected given the multiple factors that influence measures of hearing aid benefit, including differences between laboratory settings and real-world listening environments.
6. Although experimental factors may affect the accuracy of aided audibility measures, predictions of thresholds for speech, hearing aid benefit, and spatial benefit provided a means to separate simple audibility effects from other effects that may influence improvement in speech recognition for older adults using bilateral amplification.

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Fig. 1. Mean audiometric thresholds (± 1 SD) for frequencies from 0.25 to 8.0 kHz for 21 subjects who received bilateral hearing aids. Filled circles are for the right ear and open circles are for the left ear.

Fig. 2. Mean (solid line) and range (shaded area) of 2 cc coupler gain (in dB) across frequency for both hearing aids of all subjects. Input was the ICRA composite noise at 65 dB SPL. Arrows denote low-pass cutoff frequencies.

Fig. 3.

Observed (filled symbols) and predicted (open symbols) thresholds for HINT sentences (± 1 SE) without hearing aids (circles) and with hearing aids (triangles) as a function of low-pass cutoff frequency, with babble at 0° (top panel) and 90° (middle panel). HINT sentences were always at 0°. The bottom panel shows observed and predicted hearing aid benefit (± 1 SE) as a function of low-pass cutoff frequency for babble at 0° and 90°. Hearing aid benefit is defined as unaided HINT thresholds minus aided HINT thresholds.

Fig. 4.

Top: Aided thresholds for HINT sentences plotted against average high-frequency thresholds (2.0, 3.0, and 4.0 kHz) measured in quiet. Filled and open symbols correspond to thresholds for HINT sentences measured for speech and babble low-pass filtered at 3.6 and 5.6 kHz, respectively. Middle: Same as top panel, but for predicted aided thresholds for HINT sentences. Bottom: Same as top panel, but for differences between observed and predicted aided thresholds for HINT sentences. Pearson correlation coefficients and linear regression functions are included in each panel.

Fig. 5.

Data recast from Fig. 3. Observed (filled symbols) and predicted (open symbols) thresholds for HINT sentences (± 1 SE) with babble at 0° and babble at 90° as a function of low-pass cutoff frequency, without hearing aids (top panel) and with hearing aids (middle panel). The bottom panel shows observed and predicted spatial benefit (± 1 SE) as a function of low-pass cutoff frequency for unaided and aided conditions. Spatial benefit is defined as HINT thresholds with the babble at 0° minus HINT thresholds with the babble at 90°.

Fig. 6. Unaided (solid bars) and aided (striped bars) Acceptable Noise Levels (ANL [± 1 SE]) are plotted for two noise-source locations at the low-pass cutoff frequency of 5.6 kHz.

Fig. 7.

ANLs plotted against signal-to-noise ratios (SNR) at threshold for HINT sentences (5.6 kHz cutoff). Results are for unaided listening with the babble at 0°. The Pearson correlation coefficient and linear regression function are also included.

Fig. 8. Spatial benefit for ANL plotted against spatial benefit for HINT sentences (5.6 kHz cutoff). Results are for aided listening. The Pearson correlation coefficient and linear regression function are also included.

Fig. 9.

Aided benefit for ANL (0°) plotted against hearing aid use as determined by the Glasgow Hearing Aid Benefit Profile (GHABP). The Pearson correlation coefficient and linear regression function are also included.

TABLE 1

Overview of experimental design

TABLE 2

Average ($\pm$ 1 SD) absolute differences between measured and target gain at six frequencies (kHz) for input levels of 50, 65, and 80 dB SPL for 2 cc coupler gain and real ear gain

Frequency (kHz)	2 cc Coupler Gain			Real Ear Gain		
	50 dB	65 dB	80 dB	50 dB	65 dB	80 dB
0.5	2.6 (1.9)	2.1 (2.1)	3.4 (2.6)	3.7 (2.9)	2.6 (2.1)	2.1 (1.6)
1.0	2.2 (1.7)	1.9 (1.4)	2.1 (1.6)	2.6 (2.4)	2.3 (1.7)	2.8 (2.0)
2.0	2.5 (1.7)	1.4 (1.1)	2.1 (2.0)	4.3 (3.2)	4.2 (3.5)	3.6 (2.5)
3.0	1.4 (1.2)	3.1 (1.7)	3.0 (2.1)	2.5 (2.0)	3.5 (2.7)	3.0 (2.0)
4.0 *	1.5 (1.2)	2.3 (1.6)	2.5 (1.7)	3.4 (2.7)	4.8 (3.1)	2.9 (2.3)
5.0 *	3.7 (2.5)	2.2 (2.1)	3.2 (2.4)	5.5 (4.0)	6.7 (4.4)	6.8 (4.0)

* Target gain values were not prescribed for all subjects.