Speech Intelligibility Benefits of Hearing Aids at Various Input Levels

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Abstract

Background: Although the benefits of hearing aids are generally recognized for soft- and conversational-level sounds, most studies have reported negative benefits (i.e., poorer aided than unaided performance) at high noise inputs. Advances in digital signal processing such as compression, noise reduction, and directional microphone could improve speech perception at high input levels. This could alter our view on the efficacy of hearing aids in loud, noisy situations.

Purpose: The current study compared the aided versus the unaided speech intelligibility performance of hearing-impaired (HI) listeners at various input levels (from 50–100 dB SPL) and signal-to-noise ratios (SNRs; quiet, +6, +3, and −3 dB) in order to document the benefits of modern hearing aids. In addition, subjective preference between aided and unaided sounds (speech and music) at various input levels was also compared.

Research Design: The experiment used a factorial repeated-measures design.

Study Sample: A total of 10 HI adults with symmetrical moderate to severe hearing losses served as test participants. In addition, speech intelligibility scores of five normal-hearing (NH) listeners were also measured for comparison.

Intervention: Speech perception was studied at 50 and 65 dB SPL input levels in quiet and also in noise at levels of 65, 85, and 100 dB SPL with SNRs of +6, +3, and −3 dB. This was done for all participants (HI and NH). In addition, the HI participants compared subjective preference between the aided and unaided presentations of speech and music stimuli at 50, 65, 85, and 100 dB SPL in quiet.

Data Collection and Analysis: The data were analyzed with repeated-measures analysis of variance.

Results: The results showed a decrease in aided benefits as input levels increased. However, even at the two highest input levels (i.e., 85 and 100 dB SPL), aided speech scores were still higher than the unaided speech scores. Furthermore, NH listeners and HI listeners in the aided condition showed stable speech-in-noise performance between 65 and 100 dB SPL input levels, except that the absolute performance of the NH listeners was higher than that of the HI listeners. Subjective preference for the unaided sounds versus the aided sounds increased as input level increased, with a crossover intensity at approximately 75 dB SPL for speech and 80 dB SPL for music.

Conclusions: The results supported the hypothesis that the study hearing aid can provide aided speech-in-noise benefit at very high noise inputs in a controlled environment.

Key Words: speech-in-noise benefit, high input levels, hearing aid benefits

Abbreviations: ANOVA = analysis of variance; BTE = behind-the-ear; DSP = digital signal processing; HI = hearing-impaired; NAL- NL1/NL2 = National Acoustics Laboratories, nonlinear fitting formula versions 1 and 2; NH = normal-hearing; ORCA-NST = Office of Research in Clinical Amplification Nonsense Syllable Test; OSPL-90 = output sound pressure level at 90 dB SPL input; rau = rationalized arcsine unit; RMS = root mean square; SE = speech enhancer; SII = Speech Intelligibility Index
Hearing aids provide sustained quality-of-life benefits to people with a hearing impairment (Mulrow et al, 1992; Chisolm et al, 2007). The acoustic benefits have been documented extensively for the soft and conversational levels (e.g., Walden et al, 1984; Cox and Alexander, 1991). There were far fewer studies on the aided speech-in-noise benefit at a high input level. In those rare reports, the conclusion was that hearing aids provided no or negative benefit at high input levels (e.g., Duquesnoy and Plomp, 1983; Cox and Alexander, 1991). Because such studies were based on older analog hearing aid technology, it is possible that studies in digital signal processing (DSP) may alter some of the previous conclusions on hearing aid performance in high noise situations. However, this study was not aimed at comparing analog and digital hearing aids because almost all hearing aids sold today are digital. The findings would not benefit the dispensing clinicians. Rather, it would be more meaningful to evaluate if today's DSP hearing aids could provide aided speech benefits over a range of input levels and signal-to-noise ratios (SNRs).

In this study, we will define high noise situations as those with an overall level that exceeds 80–85 dB SPL. At these high levels, saturation of the physiological responses at the cochlear and/or neural levels has been documented. Wever and Bray (1938) reported nonlinearity in the cochlear microphonics above a presentation level of 74 dB SPL. Above 94 dB SPL, the magnitude of the cochlear microphonics decreased. Wong et al (1998) showed asynchronous firing of a cat's auditory nerves at levels between 80 and 100 dB SPL. These actions would suggest a loss of tuning to sounds presented at high input levels. The perceptual correlate may be a loss of speech intelligibility. Indeed, Studebaker et al (1999) showed a gradual decrease in monosyllabic word identification at a fixed SNR when the overall input level increased above 69 dB SPL. The rate of decrease was higher at the higher input level of 100 dB SPL. Most importantly, both NH and HI adults exhibited the same behaviors at the same high input levels. Subsequent studies by other researchers (e.g., Molis and Summers, 2003; Dubno et al, 2006; Summers and Cord, 2007) confirmed Studebaker et al's (1999) findings. These studies suggest that the ability to understand speech at very high input levels, in quiet and in noise, in NH and HI listeners may often be compromised. This decrease in speech recognition ability at high input levels is to be distinguished from the term rollover, which also describes a decrease in speech understanding with increasing input.

However, rollover has a neural origin (Bess et al, 1979), whereas those noted in the hearing aid literature may not.

If a decrease in speech intelligibility occurs in both NH and HI listeners (unaided) at similarly high input levels, it stands to reason that linear hearing aid wearers may be at risk of encountering such a decrease at a lower or more moderate input level. This is because the output of a linear hearing aid (which forms the input to the hearing aid wearer, or effective input) is dependent on the input to, and gain setting of, the hearing aid. As an example, if the decrease occurs above 100 dB SPL and the hearing aid gain is set at 50 dB, then a decrease in speech intelligibility can be expected at an input level of 50 dB SPL. If that is indeed the case, one would understand why hearing aid wearers report limited or no benefit from linear hearing aids above a moderate input level. One may even expect decreases in aided speech understanding ability at high input levels.

There is support for limited hearing aid benefit at high input levels in linear hearing aids. Plomp (1978) and Duquesnoy and Plomp (1983) argued that hearing aid benefits could only be realized in people with hearing losses between 35 and 60 dB HL. Furthermore, negligible benefit can be expected when the background noise exceeds 50 dB SPL. Cox and Alexander (1991) measured the Connected Sentence Test scores (aided and unaided) in three simulated environments representing normal casual conversational level (A: speech at $L_{eq} = 55$ dB and babble at $L_{eq} = 48$ dB), low noise and reduced speech cues from reverberation (B: speech at $L_{eq} = 63$ dB and noise at $L_{eq} = 55$ dB), and high speech level with visual cues (C: speech at $L_{eq} = 64$ dB and noise at $L_{eq} = 62$ dB). Listeners wore analog, linear omnidirectional hearing aids. The authors reported most aided benefit at the conversational level in Environment A and no benefit at the high level in Environment C. Indeed, the authors reported negative benefit with some participants in Environment C. The authors hinted that the distortion products produced by the hearing aids at the high input levels might be responsible.

Shanks et al (2002) compared aided and unaided performances on the Connected Sentence Test using linear, compression limiting (CL) and wide dynamic range compression (WDRC) hearing aids at inputs of 52, 62, and 74 dB SPL at an SNR of $-3$, 0, and $+3$ dB. The authors reported aided benefits of 27 rationalized arcsine units (rau; Studebaker, 1985) in the 52 dB SPL condition, 17 rau in the 62 dB SPL condition, and 6 rau in the 74 dB SPL condition. Interestingly, no difference was noted among hearing aid processing strategies. Participants with the least hearing loss (<40 dB HL PTA and <10 dB HL PTA) showed the greatest benefit.
dB/oct slope) showed decreases in aided benefit as input level increased (from 16 rau at 52 dB SPL to ~5 rau for the 74 dB SPL). Participants with more severe hearing loss showed consistent aided benefit at all input levels. The authors reported that only 35% of the performance-intensity functions measured in the aided condition showed an increase in performance as the input level increased.

More recently, Davies-Venn et al. (2009) compared the benefits between fast-acting WDRC and compression limiting (CL) in a 16-channel hearing aid using participants with a mild to moderate hearing loss and participants with a severe hearing loss. Speech test was presented at 50, 65, and 80 dB SPL in quiet. Whereas performance improved from the 50 dB SPL condition to the 65 dB SPL condition in both groups of participants, performance decreased slightly (~5 rau) as input increased from 65 to 80 dB SPL. Both groups performed more poorly with the fast-acting WDRC than with the CL circuit above an input level of 65 dB SPL. Unfortunately, no unaided data were available for a measurement of aided benefit.

The previous studies were limited in the input levels that were evaluated. Notwithstanding, they all reported limited hearing aid benefits at or above a level as low as 70 dB SPL. These studies suggest the need for better hearing aid design for high-input level sounds. Ideally, hearing aids should improve speech intelligibility in noise even at high input levels. Minimally, aided speech understanding should only be limited by the physiology of the auditory system at such high input levels and not be poorer than unaided speech understanding. Although approximately 20% of everyday sounds exceed 70 dB SPL and only 1% exceeds 90 dBA, these loud sounds are frequently associated with socializing, entertaining, and transportation. These activities account for a significant portion of the leisure time of adults (Neitzel et al., 2004). As suggested by Kochkin (2010), consumer satisfaction with hearing aids increases when the number of situations in which the hearing aids perform well increases. Improvements in aided performance at high input levels could further enhance a wearer’s satisfaction with hearing aids. Because the reported studies on aided hearing aid benefits at high noise levels were conducted more than 10–20 yr ago, it is necessary to examine if current hearing aids can provide aided speech recognition benefit at the higher input levels that were once deemed impossible.

There are reasons to expect that current hearing aids may provide some aided benefits at high input levels. The main reason can be attributed to changes in technology in the last two decades. The introduction of DSP in the late 1980s and early 1990s marked the beginning of seismic changes to this profession. DSP hearing aids by themselves do not improve performance; on the contrary, they could reduce performance at extreme input levels (very low and/or very high) even when careful designs are made. The use of DSP enables the realization of sophisticated processing algorithms at a much lower current drain. This enables the practical development of algorithms such as auditory scene analysis for proper input classification and handling, amplitude compression to automatically regulate gain based on the input levels, noise reduction to automatically reduce the gain for high-level “noise” signals, adaptive directional microphone for spatial enhancement of sounds leading to an improved SNR, and active feedback cancellation to allow more usable gain in a vented earmold. These advances, especially those of the noise reduction and directional microphone algorithms, have demonstrated improvement in listening comfort and better SNR at high-input, noisy backgrounds (e.g., Peeters et al., 2009). This could change the conclusion that hearing aids do not provide benefit when the noise level is greater than 70 dB SPL.

The use of DSP could potentially affect speech understanding (and sound quality) at very high and very low input levels. This is because the majority of today’s DSP hearing aids use a 16-bit analog-to-digital converter. This effectively limits the range of sounds that can be digitized to a theoretical maximum of 96 dB (in reality, it is less than this value because of associated circuit noise from electronic components). One may choose an input range from 0–96 dB SPL, or a range from 20–116 dB SPL to digitize. Although conversational speech and most input sounds would be covered by the 96 dB range, the limitation of choosing the 0–96 dB SPL range is that input sounds higher than 96 dB SPL would be severely limited before they are digitized. The excessive input may be clipped to result in significant distortions in the input, or it may be managed using compression limiting. In the latter case, temporal smearing of the input occurs. Although the very high-input sounds would be spared, the limitation of choosing the 20–116 dB SPL input range would limit the audibility of the softer sounds and increase the noisiness of the circuit. Today’s commercial DSP hearing aids have input limits ranging from 96–113 dB SPL, whereas the analog microphones used in commercial hearing aids have a maximum input limit of 115 dB SPL. This suggests that it is possible for DSP hearing aids (although not every digital hearing aid) to fully use the dynamic range available in an analog microphone.

The importance of a high input limit can be appreciated from the study reported by Kuk et al. (2014). In the study, speech understanding at high noise background was compared between a hearing aid with an input limit of 103 dB SPL (typical) and one with an input limit of 113 dB SPL. The hearing aid was evaluated in the omnidirectional mode with and without noise reduction, and also in the directional microphone mode. Continuous speech-shaped background noise was presented at 85 and 100 dB SPL with NU-6 words at SNRs of −3, +3, and +6 dB. Speech was presented from the front, and the uncorrelated noise was presented from 90°, 180°, and 270°. The output from the hearing aids was recorded through the Knowles Electronic Manikin for Acoustic Research and
was presented to participants through insert earphones at a “loud, but not uncomfortable” level as determined by the participants. The results of the study showed no difference in performance between the two hearing aids when the stimuli were presented at 85 dB SPL. However, more than 20% difference in speech recognition scores in favor of the hearing aid with the higher input limit was noted at the 100 dB SPL input level across SNRs. Although this study supported the use (and necessity) of a hearing aid with a high input limit, it did not measure the unaided performance under identical test conditions to allow an estimation of aided benefit at high input levels.

Chasin (2014) used the hearing aids reported in the Kuk et al (2014) study to examine subjective preferences of HI musicians for speech and music stimuli processed at a conversational level and at a high level (103 dB SPL). At the high presentation level, more than 80% of the preferences were toward the hearing aid with a higher input limit for both the speech and music stimuli. At the conversational level of presentation, there was no difference in preference between the two hearing aids when speech was used as the stimulus. However, a significant preference for the hearing aid with the higher input limit was seen when music was used as the stimulus.

A sufficiently high output sound pressure level at 90 dB SPL input (OSPL-90) is also necessary to ensure the integrity of the output. Kuk et al (2011) compared the reception threshold for speech of listeners with a severe hearing loss wearing the same hearing aid at a default OSPL-90 (according to a National Acoustics Laboratories, nonlinear fitting formula version 1 [NAL-NL1] prescription) and one that was 20 dB less than the default value. An identical frequency gain response was used for both conditions. The results showed an SNR advantage of 1.5–2 dB associated with the higher OSPL-90 condition. The authors suggested that a sufficiently high OSPL-90 was important to ensure the integrity of the output signal and optimal performance of the hearing aid. Thus, one must use a hearing aid that has a high input limit and a sufficiently high OSPL-90 to eliminate the possibility of distortion at the input and the output stages of the hearing aid before one can evaluate and safely conclude on the benefit of a hearing aid in loud, noisy situations.

If minimal aided benefit at high input levels is the result of excessive SPL at the eardrum, hearing aids that use minimal, or even negative, gain at high input levels should show a lower risk for decreases in speech recognition (and thus positive aided benefits) than hearing aids that do not reduce gain as input level increases (i.e., linear hearing aids). Hearing aids that use compression and noise reduction algorithms reduce gain as input level increases. Thus, these hearing aids will likely have a lower output above a conversational input level than linear hearing aids reported in previous studies. If the output of the hearing aid does not exceed the “trigger point” when the decrease occurs, one could expect aided benefits even at a high input level. In addition, the common use of directional microphones in today’s hearing aids also suggests that the effective input level and SNR to the analog-to-digital converter of the hearing aid would be lower (or better) than the nominal input levels to an omnidirectional microphone. This could also provide significant aided benefits at high input levels and reduce the potential for a decrease in speech understanding.

The purpose of the current study was to examine the aided benefit of one current hearing aid across a wide range of input levels and SNRs. Special attention was paid to speech intelligibility above 65 dB SPL, although speech intelligibility at lower input levels was also examined. The hearing aid with the highest input limit and the widest bandwidth was used in the study to document what can be achieved with the latest in hearing aid technology. Specifically, we wanted to document the speech intelligibility (in quiet and in noise) benefits at various input levels and SNRs. In addition, we wanted to estimate the input level at which subjective preference changed in favor of the unaided sounds over the aided sounds. The current study did not focus on determining the contribution of specific features (or algorithms) to the overall performance; rather, it focused on how these combined features affected the overall hearing aid benefit.

**METHODS**

**Participants**

A total of 10 participants (2 male, 8 female) with an adult-onset, symmetrical (≤15 dB at any frequency), moderate to severe sensorineural hearing loss (45–75 dB HL) participated in the study. The mean hearing thresholds for the left and right ears of all participants are displayed in Figure 1. The participants ranged in age from 28–84 yr (mean age = 70.4 yr, SD = 17.5 yr). Eight were experienced hearing aid wearers with an average of 12.4 yr hearing aid experience (SD = 7.6 yr). All were native speakers of American English. None of the participants expressed any loudness tolerance issues or hypersensitivity to sounds before or after the study. The individuals’ demographic information is shown in Table 1. In addition, five NH participants (<20 dB HL at any frequency, three females and two males) between 21 and 34 yr old (mean age = 24.6 yr, SD = 5.3 yr) were also included to provide a reference. All of the participants were explained the risks and benefits of the study before providing consent. They were financially compensated for their participation.

**Hearing Aids and Fitting**

Bilateral Widex Dream Fashion 440 behind-the-ear (BTE) hearing aids were used. This hearing aid has
15 channels, is digitally wireless, and uses primarily slow-acting WDRC. The hearing aid provides several features that supported its choice for this study. First, it allows input as high as 113 dB SPL to be digitized without distortion or a loss of audibility for soft sounds and/or a higher noise floor (equivalent input noise level <25 dB SPL). This setup allows undistorted processing at the later stages of the hearing aid. The peak OSPL-90 is 132 dB SPL. Furthermore, a broadband and a 15-channel narrow-band output compression limiter (10:1) was used at the output stage to minimize frequency-specific saturation distortion occurring at the output. The default OSPL-90 on the hearing aid was adjusted to that recommended by the NAL-NL2 (version 2) target.

There are additional features that are relevant to the conduct and potential outcome of this study. There is a microphone pinna compensation algorithm (also known as “digital pinna”) to compensate for the loss of pinna cue in a BTE. This microphone algorithm remains in an omnidirectional mode below 2000 Hz and maintains a fixed hypercardioid polar pattern with a directivity index between 2 and 4 dB above 2000 Hz. This pinna compensation algorithm operates in parallel with the 15-channel, fully adaptive directional microphone. The hearing aid switches into the appropriate polar pattern in each of the 15 channels, depending on the azimuth of the noise and the nature of the input signal. The directivity index of the system is 6 dB across frequencies.

The hearing aid uses two noise reduction algorithms: a classic noise reduction and a speech enhancer (SE) noise reduction. Both algorithms examine the level distributions of the input signals to estimate the nature of the input (i.e., speech or noise, Kuk et al., 2002). In the classic noise reduction, gain for “speech” signals is left at the prescribed level whereas gain for nonspeech signals or “noise” is reduced. The amount of gain reduction depends on the level and the SNR of the input signal, with more gain reduction as the input level increases. The “normal” noise reduction reduces a maximum of 12 dB gain. However, maximum levels of 6 and 18 dB gain reduction are also available. In the SE noise reduction, the amount of gain reduction is modulated by the “optimal” Speech Intelligibility Index (SII) calculated for the specific wearer and the specific sound environment. That is, the SE only reduces gain when the result of gain reduction will not compromise the SII. It considers not just the level of the “noise” spectrum, but also the speech spectrum at the specific noise level and the hearing loss of the wearer. Thus, different degrees of gain reduction will be provided under the same acoustic environment for people with different degrees of hearing losses. People with more severe hearing losses receive less gain reduction than those with a milder hearing loss (Kuk and Paludan-Müller, 2006). The maximum amount of gain reduction is 12 dB across any frequency channels. In addition, the SE allows a gain increase of up to 4 dB in the mid- to high-frequency channels if (1) gain is available and (2) such gain increase could further improve the calculated SII. Peeters et al. (2009) reported on the efficacy of the SE, classic noise reduction, and the adaptive directional

Table 1. Demographic Information of the 10 Hearing-Impaired Participants

<table>
<thead>
<tr>
<th>Participant ID#</th>
<th>Age (yr)</th>
<th>Gender</th>
<th>Make</th>
<th>Model</th>
<th>Style</th>
<th>Experience (yr)</th>
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<tr>
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<td>80</td>
<td>F</td>
<td>Phonak</td>
<td>Audeo IX</td>
<td>Open Fit BTE</td>
<td>10</td>
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<tr>
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<td>75</td>
<td>F</td>
<td>Phonak</td>
<td>Quest V</td>
<td>CIC</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>66</td>
<td>F</td>
<td>Phonak</td>
<td>VT</td>
<td>ITC</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>82</td>
<td>F</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>73</td>
<td>M</td>
<td>Miracle Ear</td>
<td>Unknown</td>
<td>ITC</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>54</td>
<td>F</td>
<td>ReSound</td>
<td>Dot</td>
<td>RIC</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>F</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>8</td>
<td>84</td>
<td>F</td>
<td>Widex</td>
<td>Mind</td>
<td>BTE Open Fit with Custom Shells</td>
<td>11</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>F</td>
<td>Rexton</td>
<td>Targa Plus HP</td>
<td>BTE</td>
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<tr>
<td>10</td>
<td>79</td>
<td>M</td>
<td>Widex</td>
<td>Mind m 220</td>
<td>BTE with Open Molds</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: N/A = not available.
microphones. During the study, the fully adaptive directional microphone with pinna compensation and SE noise reduction was activated.

The test hearing aids were coupled to the individual’s ears using EAR foam tips with #13 tubes. In situ thresholds (or sensograms) were measured at frequencies from 250–8000 Hz at octave intervals using an up-down procedure. Adjustment on the hearing aid was made using the Compass GPS fitting software so that the frequency-output matched the NAL-NL2 targets (Dillon, 2006). The default OSPL-90, which was based on the NAL recommendation, was also used. Real-ear verification using the AudioScan with international speech test signals presented at 55 and 65 dB SPL was conducted to verify that the output of the hearing aid matched the NAL-NL2 targets to within 5 dB between 250 and 4000 Hz.

**General Description**

The overall objective of the study was to examine speech understanding and subjective preference for speech and music stimuli at multiple input levels and SNRs in both the unaided (in NH and HI participants) and aided conditions (for the HI participants only). To facilitate paired comparison of stimuli between the unaided and aided conditions (for the HI participants), and to control the output level during the study, we presented all stimuli to a manikin head (Neumann KU-100) placed inside a sound booth. The stereo output from the manikin head was delivered to the participants via ER-3A insert earphones. Speech identification was evaluated at an input level of 50 and 65 dB SPL in quiet, and at noise levels of 65, 85, and 100 dB SPL at a SNR of +6, +3, and –3 dB in a counterbalanced manner. Preference for aided versus unaided processing of music and speech stimuli was also evaluated at input levels of 50, 65, 85, and 100 dB SPL in quiet. To minimize the potential of loudness discomfort, the output from the manikin (with and without the hearing aids) to the 100 dB SPL input condition was adjusted by each participant so that the output from the insert earphones was “Loud, but OK” for both the aided and unaided testing. This is similar to lowering the volume control of the hearing aid in response to loud sounds in real life. Each participant spent two 2-hr sessions completing the data collection. Each trial took approximately 5–7 min to complete. Rest periods were interspersed during the data collection periods to avoid fatigue and prolonged exposure to loud sounds.

**Test Materials**

**Speech Recognition Test**

The 32-item version of the Widex Nonsense Syllable Test (Office of Research in Clinical Amplification Nonsense Syllable Test [ORCA-NST], Kuk et al, 2010) was used. This test was chosen because of the availability of normative data and its allowance for error analysis. This nonsense syllables test has a consonant-vowel-consonant-vowel-consonant (CVCCVC) format. The 25 consonants (p, t, k, b, d, g, m, n, η, f, v, ð, s, z, j, 3, l, w, w, x, j, h, tʃ, dʒ) and 5 vowels found in American English (i, æ, a, u) were used to create the nonsense syllables. The test consists of 32 nonsense syllables, each preceded by the carrier phrase (“Please say the word…”). The source materials were spoken by a female speaker. All speech items were saved in wave files and were equalized in peak RMS (root mean square) level in a 50 msec sliding window. A custom computer program was used to present the 32 syllables in a random manner. Scoring of the test was based on the identification of target phonemes in all test items. Overall consonant scores were computed and were reported in subsequent sections.

Speech identification performance was measured at 50 and 65 dB SPL in quiet, and also at noise levels of 65, 85, and 100 dB SPL at an SNR of –3, +3, and +6 dB. The input levels of 85 and 100 dB SPL were included to directly evaluate if hearing aids provide benefits at high and very high input levels. A high input level of 99 dB SPL was also used by Studebaker et al (1999) to examine the effect of input levels on monosyllabic word identification. Kuk et al (2014) demonstrated that testing at high input levels may differentiate among digital hearing aids that have identical feature sets but different input limits.

Because talkers in a noisy environment reflexively increase their vocal efforts leading to changes in the spectra of their voice, the ORCA-NST test materials for the 85 and 100 dB SPL presentation levels were spectrally shaped according to the American National Standards Institute ANSI 3.5 recommendations (ANSI 3.5-1997) such that the 85 dB SPL condition was shaped for “loud” speech and 100 dB SPL input was shaped for “shouted” speech. The averaged spectra of the speech materials at 65, 85, and 100 dB SPL are shown in Figure 2.

**Noise Stimuli**

An 8-talker babble noise was generated for the study to approximate the type of noise in real-life loud, noisy situations. The passages used in the generation were obtained from audio books in public domains. The source materials were spoken by two male and two female talkers. The original recordings were digitized using 44.1 kHz audio-sampling frequency. Each of the passages was 30 sec long, and they were equalized for a peak RMS level in a 50 msec sliding window. They were then overlapped to form a 30 sec noise segment and looped for continuous presentation. In all testing, the noise stimulus was presented at least 30 sec before the presentation of any speech materials in order to ensure activation of the noise reduction algorithm and directional microphone on the test hearing aids. As indicated, noise levels of 65, 85,
Music and Speech Stimuli for Paired Comparison

Five music and five speech samples were used for preference judgment between the unaided and aided conditions. The speech stimuli consisted of sentences spoken by three male and two female speakers (not the same speaker used in the ORCA-NST). The music stimuli included samples of a musical, a recorder, a piano, a symphony, and a cell phone ringtone. Each stimulus lasted approximately 10 sec. All stimuli were equalized at the same peak RMS level.

Equipment and Setup

All testing was conducted inside and outside of a double-walled sound-treated booth (Industrial Acoustics Company) with internal dimensions of $3 \times 3 \times 2 \text{ m}$ ($W \times L \times H$). Stimuli were presented from four KRK-ST6 two-way passive loudspeakers (external dimension = $330 \times 220 \times 245 \text{ mm}$) that were placed inside the booth at 1 m height from the floor. The loudspeakers were distributed evenly (90° spacing) on a horizontal plane around the center of the room. These loudspeakers had a flat frequency response with a deviation of less than ±2 dB between 62 Hz and 20 kHz. The tweeter (1" diameter) and the woofer (6.5" diameter) were 15 cm apart (center-to-center) vertically. The loudspeakers were individually calibrated using a sound level meter (Quest model 1800) placed 1 m in front of the loudspeaker. A speech-shaped noise was presented from each loudspeaker at an intended target output level of 68 dB (A-weighted, slow response). Loudspeakers with an output deviation from the target level were electrically compensated to within ±1 dB. In addition, the frequency response of each loudspeaker was measured at one-third octave intervals using a white-noise stimulus. Linearity of the loudspeakers was measured up to 110 dB SPL at 0.4 m from the loudspeaker. Daily calibration checks were conducted during the course of the study.

All stimuli were presented to a manikin head that is designed for high-fidelity stereo recording of sounds presented in a diffuse field (Neumann KU100 Binaural Head Microphone). The manikin head was placed in the center of the Industrial Acoustics Company sound booth with the ears at 118 cm above the floor and 0.4 m away from the front-facing loudspeaker. Stimuli were acoustically modified by the “head and pinna” of the manikin head and were transduced by the stereo microphones in the unaided condition. During the aided testing, the individually adjusted hearing aids (with the foam-tip earmolds) were placed on the manikin’s ears. Putty was applied around the earmold and canal entrance to create a tight seal. All signals (unaided and aided) that were picked up by the embedded left and right microphones in the manikin head were routed through a GSI 61 audiometer to the mixer (Mackie 1202-VELZ PRO). The outputs from the mixer were then directed through an external attenuator (Tucker Davis PA5 programmable attenuator) before being finally delivered to the participants via ER-3A insert earphones. The attenuator enabled participants to adjust the output from the manikin at the 100 dB SPL input to a “Loud, but OK” level for testing. The participants were seated (and tested) outside the sound booth within an enclosed test suite where the measured ambient noise level was below 43 dBA during the course of the study.

For the quiet conditions, the test stimuli were presented from the front loudspeaker. For the speech-in-noise conditions, speech was presented from the front loudspeaker and uncorrelated babble noise was delivered through loudspeakers placed at 90°, 180°, and 270° azimuths 1 m from the manikin. A custom computer program was written for the personal computer (HP Compaq DC 5800 Intel Core2 Duo CPU, Windows XP) to control the delivery of the speech and noise stimuli. An external sound card (Echo Gina 24/96) and an external amplifier (Rotel RMB-1048) were used to deliver the stimuli to the loudspeakers.

Special Setup for Paired Comparison between Unaided and Aided Listening

A paired-comparison paradigm was used to evaluate subjective preference for unaided and aided listening of music and speech stimuli. To evaluate both conditions with minimal delay between presentations, the test stimuli were presented only in the aided condition, whereas prerecorded stimuli through the manikin head were used for the unaided condition. This method allowed rapid presentations of the aided and unaided stimuli without the need for participants to take off (for the unaided) and put on (for the aided) their hearing aids during paired comparison. The recorded .wav files of the unaided stimuli
were stored in a stereo mode and were presented directly to the ER-3A insert earphones during the unaided condition, whereas the test stimuli were processed by the hearing aids and delivered through the recording setup and ER-3A earphones in the aided condition. All timing and synchronization were controlled via a custom PC program. The order of presentation of the stimulus levels was counterbalanced across participants. The order of presentation of the individual stimulus, along with the order of presenting the aided and unaided conditions, was randomly selected to avoid bias (i.e., double-blind). A total of 80 comparisons (4 levels by 2 conditions by 10 stimuli) were made.

**Procedures**

Each participant underwent two 2 hr visits. During the first visit, bilateral hearing aids were fit and proper attenuator settings for the 100 dB SPL input level were determined. The individual attenuator settings ranged from –4 to –14 dB, with an average attenuation of –10 dB for the HI participants and –9.6 dB for the NH participants. This adjustment was only applied to the output of the 100 dB SPL input condition. The ORCA-NST speech test was then conducted in the various listening conditions in a counterbalanced manner. Evaluation in the aided and unaided conditions was also counterbalanced among all participants. The order of noise conditions was randomly selected by the computer program for each participant. Because of time limitation, only one test condition of speech recognition (aided or unaided) could be completed at the first visit.

The participants completed the unfinished speech test conditions during the second visit. In addition, participants also completed the paired comparison tasks that measured the preference for unaided and aided presentations of the music and speech stimuli. The participants selected their preference based on a judgment of sound clarity (“which interval has the clearer sound?”). Both the participants and the study audiologist were blinded to the test conditions.

In addition, an Audioscan Verifit real-ear measurement system was used in the “speech live” mode to measure the real-ear SPL in the participants’ ears after the attenuator was adjusted for the 100 dB SPL noise input. The overall level of the aided real-ear output was calculated based on the one-third octave output reading from the real-ear measurement system. The output varied from 88 dB SPL to 106 dB SPL with an average of 98 dB SPL. The unattenuated output would have varied from 101–115 dB SPL with a mean output of 108 dB SPL. In addition, the output waveform of the speech-in-noise signal recorded at an input level of 100 dB SPL at an SNR of +6 dB (or 106 dB SPL) was visually examined (after the insert earphone) to ensure that no clipping of the output occurred.

**RESULTS**

**Nonsense Syllable Scores across Input Levels**

Separate scores for consonant and vowel were available. Because the vowel scores reached ceiling performance in several conditions, only the consonant scores were reported in this paper. The overall consonant scores were first transformed into rau before any display and statistical analysis. Figure 3 summarizes the consonant scores (in rau) for the NH (unaided only, n = 5) and the HI participants (unaided and aided, n = 10) across the different input levels and SNRs. It should be noted that performance at the 100 dB SPL input level was obtained at a reduced output level to minimize discomfort.

**Normal-Hearing Listeners (n = 5)**

The left-hand column of Figure 3 summarizes the overall consonant scores of the NH participants. As expected, their performance was close to perfect even at the 50 dB SPL input level (85 rau). An increase in performance was noted at the 65 dB SPL condition (95 rau). This increase was significant \( t(4) = 10.16, p = 0.0005 \). Performance decreased in noise to approximately 70 rau at an SNR = +6 dB and 40–50 rau at the SNR = –3 dB. At a fixed SNR, little change in performance was noted between 65 and 85 dB SPL input levels. However, performance decreased between 85 and 100 dB SPL input levels. On the other hand, at a fixed input level, approximately 3–5 rau changes in performance were noted when the SNR changed from +3 to +6 dB, but almost 15 rau change was noted when the SNR changed from +3 to –3 dB.

A two-way repeated-measures analysis of variance (ANOVA) was conducted to examine the effect of input
level (65, 85, 100) and SNR (–3, +3, +6) on consonant performance. The results showed that the effect of input level \( F_{(2,8)} = 6.30, p = 0.022, \eta^2 = 0.61, \text{power} = 0.7 \) and the effect of SNR \( F_{(2,8)} = 158.25, p < 0.001, \eta^2 = 0.97, \text{power} = 1.0 \) were significant. The interaction between input level and SNR was not significant \( F_{(4,16)} = 1.52, p > 0.05, \eta^2 = 0.27, \text{power} = 0.3 \). A post hoc analysis with Bonferroni adjustment for multiple comparisons (36 comparisons) showed no significant difference in consonant performance between any two input levels for all SNRs \( p > 0.0014; 0.05/36 \).

### Hearing Impaired–Unaided (n = 10)

The middle column of Figure 3 summarizes the overall consonant scores of the HI participants in the unaided condition. On the basis of the degree of hearing loss of the participants, it is expected that their unaided scores at the 50 dB SPL input level to be poor (–5 rau). Their performance improved rapidly to 30 rau at the 65 dB SPL input level. This change in consonant score was significant \( t_{(9)} = 5.15, p = 0.0005 \). The performance in noise was mixed when compared with that in quiet at the 65 dB SPL condition, depending on the stimulus level and SNR. At the SNR = +6 dB, performance improved from 39 rau from 65 dB SPL input to 51 rau at 85 dB SPL input, and remained at 50 rau at the 100 dB SPL input. The performance at the SNR = +3 dB showed a similar trend other than an overall decrease of 3–5 rau. On the other hand, at the SNR = –3 dB, performance improved from –5 to 30 rau when the input was increased from 65–85 dB SPL but remained at 28 rau when the input increased to 100 dB SPL. An increase in performance was noted when the input increased from 65–85 dB SPL. However, little or no change was observed at the 100 dB SPL input noise level.

The results of a two-way repeated-measures ANOVA showed that the effects of input level \( F_{(2,18)} = 30.92, p < 0.001, \eta^2 = 0.77, \text{power} = 0.9 \) and SNR \( F_{(2,18)} = 182.56, p < 0.001, \eta^2 = 0.95, \text{power} = 1.0 \) were significant on consonant scores. The interaction between the input level and SNR was significant \( F_{(4,36)} = 11.56, p < 0.001, \eta^2 = 0.56, \text{power} = 0.9 \). A post hoc analysis showed that the performance at 65 dB SPL input level was significantly poorer than the performance at 85 dB SPL input level for the three SNRs tested. In addition, performance at the 65 dB input level was also poorer than the performance at the 100 dB input level for SNR = –3 dB \( p < 0.0014 \). The decrease in performance observed at the higher input levels was significant only at the SNR = +3 dB condition with a difference of 5.8 rau \( p < 0.0014 \).

### Hearing Impaired–Aided (n = 10)

The right-hand column of Figure 3 summarizes the overall consonant scores of the HI participants in the aided condition. An immediate impression of the aided performance is that it was somewhat similar to that of the NH listeners, except that the absolute score was 20–30 rau poorer in quiet and 10–15 rau poorer in noise than in the NH listeners. For example, aided consonant scores ranged from 57–70 rau as input increased from 50–65 dB SPL in quiet. Performance decreased in noise to approximately 60 rau at a SNR = +6 dB and 45 rau at the SNR = –3 dB. At a fixed SNR of +6 and +3 dB, slight change in performance (2–3 rau) was noted between 65 and 100 dB SPL input levels.

The results of a two-way repeated-measures ANOVA showed that the effects of input level \( F_{(2,18)} = 8.78, p = 0.002, \eta^2 = 0.49, \text{power} = 0.9 \) and SNR on consonant score \( F_{(2,18)} = 112.48, p < 0.001, \eta^2 = 0.92, \text{power} = 1.0 \) were significant. The interaction between the input level and SNR \( F_{(4,36)} = 5.43, p = 0.001, \eta^2 = 0.37, \text{power} = 0.9 \) was significant. A post hoc analysis showed that the performance at 65 dB input level was significantly poorer than the performance at 85 dB input level at the SNR = –3 dB condition \( p < 0.0014 \). The decrease in performance at the 100 dB SPL input level was significant only at SNR = –3 dB with a difference of 7.0 rau \( p < 0.0014 \).

#### Comparison between Normal-Hearing and Hearing-Impaired Listeners in the Unaided Mode

Figure 4 summarizes the difference in consonant scores between the NH and HI participants in the unaided mode. As expected, large differences were noted at the lower input level (e.g., 50 and 65 dB SPL) and poorer SNR (e.g., –3 dB) conditions. Less than 20 rau difference was noted at input levels of 85 and 100 dB SPL.

A one-way repeated-measures ANOVA was conducted to examine the effect of test condition (two quiet and nine noise) on consonant scores while holding participant group (NH, HI) as a between-participant factor. The results showed that both the test condition \( F_{(10,130)} = 23.94, p < 0.001, \eta^2 = 0.64, \text{power} = 1.0 \) and participant group were significant \( F_{(1,130)} = 65.58, p < 0.001, \eta^2 = 0.83, \text{power} = 0.9 \). A post hoc analysis with multiple-comparison adjustment indicated that consonant performance of NH participants was significantly better than the performance of the HI participants in all test conditions \( p < 0.0045 \). These significant comparisons are marked with an asterisk in Figure 4.

#### Comparison between Normal-Hearing and Hearing-Impaired Listeners in the Aided Mode

Figure 5 compares the difference in consonant scores between the NH and HI listeners in the aided mode. In contrast to the comparison in the unaided mode, much smaller differences were noted in the aided comparison.
Nonetheless, there was still a 20–30 rau difference between normal performance and the aided performance at the 50 and 65 dB SPL in quiet conditions. The difference decreased to less than 10 rau when stimuli were presented in noise. Indeed, less than 2 rau difference was noted at the 85 and 100 dB SPL at the SNR = 6 dB condition.

A one-way repeated-measures ANOVA showed that test conditions \[ F(10,130) = 125.68, p < 0.001, \eta^2 = 0.90, \text{power} = 1.0 \] and participant groups \[ F(1,13) = 9.96, p = 0.007, \eta^2 = 0.43, \text{power} = 0.8 \] were significant. A post hoc analysis with multiple-comparison adjustment indicated that consonant performance of NH listeners was significantly better than that of the HI listeners only at the two quiet conditions (i.e., 50 and 65 dB levels) and at the 85 dB input level with an SNR = 6 dB condition.

Comparison between Aided and Unaided Performance in Hearing-Impaired Participants

Figure 6 summarizes the difference in performance between the aided and unaided conditions of the HI participants, reflecting the benefits provided by the hearing aids. As expected, aided benefit decreased as input level increased. It is of interest to note that aided benefit also decreased as SNR increased from –3 to +6 dB. For example, at the 65 dB SPL noise condition, aided benefit decreased from 48 rau in the SNR = –3 dB condition to 25 and 20 rau in the SNR = +3 and +6 dB conditions, respectively. The benefits offered by the hearing aids remained at 5–10 rau at the 85 and 100 dB SPL input levels.

A two-way repeated-measures ANOVA showed that the listening mode (aided, unaided) was significant \[ F(1,9) = 170.34, p < 0.001, \eta^2 = 0.94, \text{power} = 1.0 \]. The test condition (two quiet, nine noise) was also significant \[ F(10,90) = 41.55, p < 0.001, \eta^2 = 0.82, \text{power} = 1.0 \]. A post hoc analysis with multiple-comparison adjustment indicated that the aided consonant scores were significantly higher than the unaided scores in all test conditions \((p < 0.0045)\), except at the 85 dB input level at an SNR = +3 dB and the 100 dB SPL input level at an SNR = +6 dB. That is, hearing aid benefit was seen at most (9/11) of the test conditions. The significant comparisons are marked with an asterisk in Figure 6.

Paired Comparison between Unaided and Aided Conditions

Mean results (frequency of preference) from the paired comparison test are displayed in Figure 7: the left side for the music stimuli and the right side for the speech stimuli. The percentage of times each stimulus was preferred in the unaided or aided mode was displayed for each of the four input levels. The input level at which unaided and aided preference intersected reflects equal preference for the two test modes (50% preference for each condition). For music stimuli, the 50% input level occurred at approximately 80 dB SPL. For speech stimuli, the level was estimated at approximately 75 dB SPL. Above these levels, the unaided stimuli were more preferred than the aided stimuli when sound clarity was used as the criterion.

DISCUSSION

The current study examined aided and unaided speech intelligibility at various input levels and SNRs in a controlled laboratory environment. The results showed that aided speech intelligibility was higher than the unaided condition at most input levels (50, 65, 86, and 100 dB SPL) and SNRs (quiet, –3, +3, and +6 dB).
Whereas the unaided speech scores improved with input levels, the aided speech scores remained relatively stable across input levels between 65 and 100 dB SPL for the same SNRs. This pattern was similar to that of NH listeners, although the absolute performance was poorer in the HI participants. These observations suggest that hearing aids can provide aided benefits over a wide range of input levels and SNRs. At high input levels, aided performance could parallel that of NH listeners. Preference for the unaided sounds (speech and music) increased as input level increased above 75–80 dB SPL.

It is generally accepted that hearing aids provide speech intelligibility benefits to soft and conversational level sounds, especially when they are presented in quiet (e.g., Walden et al, 1984; Cox and Alexander, 1991; Shanks et al, 2002). The current study confirms such benefits by showing that the aided speech scores at the 50 and 65 dB SPL presentation levels in quiet improved by 60 and 40 rau, respectively, over the unaided condition. The aided scores were 20–30 rau poorer than those of the NH listeners. It is unclear if this performance difference can be narrowed further through adjustments of the frequency-output characteristics of the hearing aids without affecting performance in other aspects (e.g., speech-in-noise performance at higher levels).

For higher input levels (85 and 100 dB SPL), aided speech performance was also better than unaided performance. These observations are different from previous reports on the benefits of hearing aids at high input levels. For example, it was indicated in the Introduction that Cox and Alexander (1991) reported negative hearing aid benefits in their Environment “C” (speech level of 64 dBA and noise level of 62 dBA). Differences between studies may originate from changes in technology and fitting targets. The previous studies used analog, single-channel, linear hearing aids with omnidirectional microphones fit using linear prescriptive targets. A characteristic of linear hearing aids is that the same gain value is applied to all input levels. This means that the output of the linear hearing aid would reach the maximum power output or saturate at a much lower input level than a WDRC hearing aid. Temporal and/or spectral distortions occur when saturation occurs. The likelihood of saturation is affected by the gain on the hearing aid. Prescriptive formulae that prescribe more gain, and especially linear gain, would reach the saturation point at a lower input level than a nonlinear prescription that recommends less gain.

The current study used a multichannel WDRC hearing aid with noise reduction and an adaptive directional microphone. A characteristic of a WDRC hearing aid is the reduction of gain as input level increases. In some instances, negative gain may be prescribed. In effect, the range of input levels to reach saturation is increased in a WDRC (depending on the gain, compression ratio, and threshold) over a linear hearing aid. Figure 8 shows the simulated in situ input-output function of the current hearing aid programmed for the average hearing loss of the HI participants at various input levels at the four main frequencies (500, 1000, 2000, and 4000 Hz). Even at the input level of 100 dB SPL, an in situ output of approximately 85 dB SPL was noted at 500 and 1000 Hz, and <100 dB SPL was noted at 2000 Hz.
and 4000 Hz. This output level is comparable to the input level and was achieved with zero or negative gain in some instances. Indeed, when we measured the overall output of the hearing aid, we measured an output of 108 dB SPL (unattenuated; attenuated was 98 dB SPL), 102 and 96 dB SPL for the 100, 85, and 65 dB SPL noise inputs, respectively. In essence, the overall output of the hearing aid at the very high input level was not much higher than the input in this study.

In addition to the compression circuit, the SE noise reduction algorithm and the adaptive directional microphone on the hearing aid also reduce gain (and output) at high noise levels. These actions would have resulted in a lower output (and a lower risk for saturation) from the current hearing aid than in an analog linear hearing aid fit for the same hearing loss. The reduced output at high input levels may be one reason why participants in the current hearing aid study still experienced hearing aid benefits at the very high input levels.

It is of interest to note higher benefit for the poorer SNR condition. For example, Figure 6 shows that for the three noise levels, the SNR = −3 dB condition reported greater aided benefit than the SNR = +3 and +6 dB conditions, where the benefit seemed similar. Greater aided benefit for the SNR = −3 dB condition could suggest greater difficulty (poorer performance) in the unaided condition. That was indeed the case for the 65 dB SPL input level (Fig. 3). Another possible reason for the greater benefit at the poorer SNR condition may be related to the use of a directional microphone in the study hearing aid. Valente et al (1999) tested a fixed directional microphone at SNRs of +7, 0, and −7 dB using the Speech Perception in Noise test. A mean difference of 10.5% was noted at a SNR = +7 dB, 19.7% at the SNR = 0 dB, and 33.6% at the SNR = −7 dB condition. Kuk et al (1999) reported similar findings using HI children as the test participants. These studies suggest that the magnitude of speech improvement provided by a directional microphone is affected by the SNR of the test environment. An environment with a negative SNR is likely to benefit more from a directional microphone than an environment where the SNR is positive. If a directional microphone had not been used in the current study, the benefit seen at the SNR = −3 dB may be similar to those observed at the SNR = +3 and +6 dB conditions. This further supports the use of hearing aids with a directional microphone in daily lives, including loud and very loud, noisy situations.

Although hearing aids cannot replace normal hearing, aided performance of the HI participants seen in the current study paralleled that of the NH listeners. Indeed, examination of Figure 3 shows similar performance-intensity functions between the NH and the HI listeners in the aided condition. Figure 5 shows that performance difference between NH and HI listeners (aided) in quiet was less than 20–30 rau. The difference decreased to 3–5 rau at high noise levels. Most of the test conditions showed a difference of less than 10 rau between the NH and HI listeners in the aided mode. Although this was a laboratory study under controlled conditions, the closeness in performance between NH listeners and the aided HI listeners is encouraging. It is especially noteworthy because the NH listeners were much younger than the HI listeners (average age = 24.6 yr versus 70.4 yr). Such age differences may be associated with differences in cognitive ability between the two participant groups and may have exaggerated the differences in speech recognition scores between the two groups of participants. An older group of NH participants may perform more poorly than the younger normal ones, leading to a smaller difference in performance between the NH control and the aided performance of the HI participants. Although such a possibility needs further deliberation, the results of the current study confirm the possibility for hearing aids (with the features such as those on this hearing aid) to narrow the speech intelligibility gap (at least under certain test conditions) between NH listeners and HI listeners.

Viewed from a different perspective, the closeness in performance between NH listeners and the aided performance in HI listeners would suggest that the difficulties reported by hearing aid wearers in noise may not be unique to HI listeners. The evidence presented here suggests that NH listeners have similar difficulties at loud and noisy situations. Clinically, this suggests that hearing aid wearers should be properly counseled of their expectations and taught strategies to enhance their communication ability. In addition, rehabilitation training may be necessary to train the hearing aid wearers to fully use the features within the hearing aid and/or improve their overall speech-in-noise performance such as the use of a Listening and Communication Enhancement program (Sweetow and Sabes, 2006).
Figure 7 shows that participants preferred the unaided sound quality when speech was presented above 75 dB SPL and music was presented above 80 dB SPL. This finding suggests that the contribution of the aided sound to the overall perception diminishes above this input. Despite speech-in-noise benefit even at the 100 dB SPL input level, subtle differences in sound quality remain to result in a higher preference for the unaided sound as input level increases above 80 dB SPL. Additional studies are needed to understand the reasons for such a preference.

There are several caveats that are important to remember. First and foremost is that the conclusion is necessarily based on the study hearing aid and its features and fitting. Other hearing aids may yield different outcomes. Nevertheless, the results with the study hearing aids support the contention that it is possible for hearing aids to provide aided benefit at high noise levels so that performance of the HI listeners can be comparable to that of NH listeners at the same levels.

The output from the insert earphone for the 100 dB SPL input level was individually adjusted so that the output was “Loud, but OK.” Dirks et al (1982) commented that a decrease in speech scores with increasing level was more likely to occur when sounds are “uncomfortably loud.” This suggests that our action could have reduced the magnitude of any decrease in speech scores seen in this study, although our intention was to ensure comfort during the evaluation. Despite such a limitation (of not fully examining the effect), our objective of demonstrating aided hearing aid benefits at a high input level was accomplished—aided benefit was seen at input levels as high as 100 dB SPL.

The current study was conducted with the individually fit hearing aids on a manikin head with its output transduced through ER-3A earphones. Minor differences in frequency-output may be expected between the hearing aids worn in situ and output through the insert earphones. It is possible that such differences may result in performance deviations at the lower input levels where the frequency-gain/output characteristics may be more critical because of audibility issues. At a high input level, minor deviations in frequency-output may not contribute to differences in speech intelligibility. In that regard, it is possible that performance at the 50 and 65 dB SPL levels may be different from what was reported here when the hearing aids were worn in situ. The performance at the three noise levels should remain relatively stable.

The foam earmold that was coupled to the hearing aid was sealed on the outside so that only the output of the hearing aids reached the recording microphones that were embedded in the manikin’s head. This was done for two reasons. First, an occluding or minimally vented earmold would be appropriate for listeners with this degree and configuration of hearing loss (Kuk et al, 2009). Second, an occluded earmold would minimize (if not completely prevent) entry of the direct sounds into the recording microphones. This would ensure that it was the hearing aid–processed sounds that were being evaluated and not the unamplified, direct sounds. On the other hand, some hearing aid wearers have milder hearing losses that necessitate the use of open or vented earmolds. Depending on the amount of venting and input level, different amounts of direct sounds could enter through the vent. At a very high input level and with a large vent, the direct sound dominates the SPL at the ear drum and could reduce the benefit provided by any hearing aid processing such as noise reduction (Bentler et al, 2006) and directional microphones (Mueller and Ricketts, 2000). In those situations, the aided performance that was observed in this study would likely decrease to the unaided level (i.e., no benefits). However, it should not be poorer than the unaided performance. Consequently, the aided benefit observed in this study should be viewed as the optimal, and not the typical, benefit for all hearing aid wearers. HI wearers with different degrees of hearing loss and/or cognitive capacity may exhibit different degrees of benefit.

CONCLUSIONS

The current study demonstrated that in a controlled environment, the study hearing aids with noise reduction (including a directional microphone) algorithms and high input limits can improve speech understanding in high noise environments versus the unaided condition. The amount of aided benefit decreases as input level increases. At the 85 and 100 dB SPL input level, aided benefit varied from 5–18 rau depending on SNR with more benefit measured at the poorer SNR condition. Despite the decreasing benefits with increasing input levels, aided performance was almost always better than unaided performance. In addition, aided performance was only slightly poorer than that of NH listeners at very high levels.

REFERENCES


