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# Investigation of Extended Bandwidth Hearing Aid Amplification on Speech Intelligibility and Sound Quality in Adults with Mild-to-Moderate Hearing Loss

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**Abstract**

**Background:** Advances in digital signal processing have made it possible to provide a wide-band frequency response with smooth, precise spectral shaping. Several manufacturers have introduced hearing aids that are claimed to provide gain for frequencies up to 10–12 kHz. However, there is currently limited evidence and very few independent studies evaluating the performance of the extended bandwidth hearing aids that have recently become available.

**Purpose:** This study investigated an extended bandwidth hearing aid using measures of speech intelligibility and sound quality to find out whether there was a significant benefit of extended bandwidth amplification over standard amplification.

**Research Design:** Repeated measures study designed to examine the efficacy of extended bandwidth amplification compared to standard bandwidth amplification.

**Study Sample:** Sixteen adult participants with mild-to-moderate sensorineural hearing loss.

**Intervention:** Participants were bilaterally fit with a pair of Widex Mind 440 behind-the-ear hearing aids programmed with a standard bandwidth fitting and an extended bandwidth fitting; the latter provided gain up to 10 kHz.

**Data Collection and Analysis:** For each fitting, and an unaided condition, participants completed two speech measures of aided benefit, the Quick Speech-in-Noise test (QuickSIN™) and the Phonak Phoneme Perception Test (PPT; high-frequency perception in quiet), and a measure of sound quality rating.

**Results:** There were no significant differences found between unaided and aided conditions for QuickSIN™ scores. For the PPT, there were statistically significantly lower (improved) detection thresholds at high frequencies (6 and 9 kHz) with the extended bandwidth fitting. Although not statistically significant, participants were able to distinguish between 6 and 9 kHz 50% better with extended bandwidth. No significant difference was found in ability to recognize phonemes in quiet between the unaided and aided conditions when phonemes only contained frequency content $<$6 kHz. However significant benefit was found with the extended bandwidth fitting for recognition of 9-kHz phonemes. No significant difference in sound quality preference was found between the standard bandwidth and extended bandwidth fittings.

**Conclusions:** This study demonstrated that a pair of currently available extended bandwidth hearing aids was technically capable of delivering high-frequency amplification that was both audible and useable to listeners with mild-to-moderate hearing loss. This amplification was of acceptable sound quality. Further research, particularly field trials, is required to ascertain the real-world benefit of high-frequency amplification.

**Key Words:** hearing aids, high frequency, speech in noise, speech perception

**Abbreviations:** ANOVA = analysis of variance; M = mean; PPT = Phoneme Perception Test; QuickSIN™ = Quick Speech-in-Noise test; SD = standard deviation; SEM = standard error of mean; SNR = signal-to-noise ratio

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## INTRODUCTION

Although the technology for extended bandwidth hearing aids has existed for >40 yr (Killion and Tillman, 1982; Killion, 2004), it is only fairly recently that manufacturers have begun to offer devices with upper frequency limits of >6 kHz (Baekgaard and Kuk, 2008). Several manufacturers have introduced hearing aids that are claimed to provide gain for frequencies up to 10–12 kHz.

A number of studies have demonstrated the benefit of high-frequency amplification for understanding speech, with a particular advantage when speech is presented with background noise (Turner and Henry, 2002; Hornsby and Ricketts, 2003; 2006; Horwitz et al, 2008; Füllgrabe et al, 2010). Extended bandwidth has been shown to improve localization ability (Best et al, 2005) and also improve subjective ratings of sound quality (Killion, 2004). However, not all studies have shown such a clear benefit of high-frequency amplification. Hearing-impaired users with hearing loss greater than moderate in the high frequencies tend not to benefit from high-frequency amplification (Murray and Byrne, 1986; Ching et al, 1998; Hogan and Turner, 1998; Turner and Cummings, 1999; Amos and Humes, 2007). This may be because with higher degrees of hearing loss, it is more likely that there are "cochlear dead regions," that is, areas of the cochlea where inner hair cells have been irreparably damaged and therefore activation of afferent nerve fibers does not occur (Moore, 2001). Persons with cochlear dead regions may find increased amplification only increases loudness and not intelligibility (Vickers et al, 2001; Baer et al, 2002).

Thus there is still contention over the benefit and optimal degree of high-frequency amplification for individuals with high-frequency hearing loss. The number of studies investigating the benefit of high-frequency amplification is limited with differing definitions of "high frequency." Most studies to date have only focused up to 6 kHz with few investigating up to ≥10 kHz (Franks, 1982; Murray and Byrne, 1986; Plyler and Fleck, 2006). Furthermore, many of the aforementioned studies used calibrated headphones and not hearing aids in situ to deliver high-frequency amplification (Dittberner et al, 2008). There is currently limited evidence and very few independent studies evaluating objective and subjective performance of extended bandwidth hearing aids that have recently become available on the market.

This study investigates the benefit of a new extended bandwidth hearing aid using measures of speech intelligibility and subjective measures of perceptual qualities.

It was hypothesized that:

1. Speech perception would be improved with wider bandwidth amplification.
2. Narrower bandwidth would be rated as having higher sound quality.

## METHOD

The methods were approved by The University of Auckland Human Participants Ethics Committee.

### Participants

Sixteen adults (nine males and seven females) between 24 and 75 yr of age ($\bar{X} = 64$, standard deviation [SD] = 14.9) participated in this investigation. All participants had symmetrical sensorineural hearing loss no greater than mild in the low frequencies and sloping to no more than moderately severe up to 6 kHz, reflecting the fitting range of the extended bandwidth hearing aids used. Eleven participants were hearing aid wearers with an average duration of use of 5.3 yr (SD = 2.9). Participants were required to be fluent in written and spoken English. Participants were recruited by letter via the University of Auckland, Audiology Section Volunteer Database or by advertisement flyer.

### Research Design

A repeated measures study was designed to examine the efficacy of extended bandwidth amplification compared to standard bandwidth amplification. Each participant served as their own control and was blinded to the type of fitting (extended bandwidth or standard bandwidth amplification). The study design allowed for a number of variables such as learning effects when performing objective tests, order and fatigue effects when testing, and as much as possible, controlling for different acoustic parameters.

Testing was divided into two separate sessions: "Unaided Measures and Hearing Aid Fittings" and "Aided Measures." Each stage consisted of a single 2-hour session, with the two sessions completed within 2 weeks. Testing was divided in this way to minimize participant time commitment in a given day and to reduce participant fatigue.

There were two fittings (extended bandwidth amplification and standard bandwidth) and therefore two aided conditions. For each condition (unaided, standard bandwidth, and extended bandwidth) participants completed three different tests: two measures of aided benefit—the Quick Speech-in-Noise test (QuickSIN™) speech perception in noise test (Killion et al, 2004) and the Phonak Phoneme Perception Test (PPT) (Phonak, 2012)—and one subjective measure of sound quality. Participants were blinded to fitting to minimize potential participant biases. The initial amplification condition was counterbalanced between participants and the order of each aided test was randomized for participants and fittings.

All testing was conducted in the Audiology Teaching and Research Rooms, Section of Audiology, School of Population Health, at the University of Auckland's Tamaki Campus. Sound-field measures were carried out in a test room of dimensions 2.7 m × 5.6 m with acoustic treatment; the ambient noise level was 37 dBA and the reverberation time 0.4 msec.

### Hearing Assessment

A brief audiological history was conducted to explore the nature of the participant's hearing loss and previous hearing aid use. Audiometry was conducted using the modified Hughson–Westlake technique (Carhart and Jerger, 1959) with a GSI-61 audiometer (Grason-Stadler Inc., Eden Prairie, MN). Air-conduction thresholds (250 Hz to 8 kHz) were determined with E-A-RTONE (ER-3A) insert tips (3M Company, Maplewood, MN) or Telephonics Dynamic Headphones (TDH-39; Farmingdale, NY). High-frequency pure-tone air-conduction audiometry was also conducted bilaterally at six frequencies (9, 10, 11.2, 12.5, 14, and 16 kHz) using HDA200 circumaural headphones (Sennheiser, Germany). Bone-conduction thresholds were determined as required from 500 Hz to 4 kHz using a Radioear (B-71) bone conductor (New Eagle, PA). Tympanometry was performed using a GSI Tympstar Middle Ear Analyzer (Grason-Stadler Inc), with a 226-Hz probe tone, to exclude participants with middle-ear pathologies.

### Speech Perception in Noise Assessment

Speech perception in noise (four-talker babble) testing was conducted in the sound field using the Etymotic Research Incorporated QuickSIN™ recordings (version 1.3; Elk Grove Village, IL) (Killion et al, 2004). The QuickSIN™ was presented via a Dell OptiPlex GX280 computer (Round Rock, TX), using Adobe Audition, connected to an amplifier (Aiwa Stereo Receiver MX-NAVH1200; Chicago, IL) and single GSI speaker, positioned at 0° azimuth and at a vertical distance of 120 cm and a distance of 1 m to the participant's approximate head position (also at a vertical distance of 120 cm). The QuickSIN™ recordings were presented in the sound field at 70 dB HL. All participants completed List 13 first as a practice list for task familiarization. For the test lists, each participant was randomly assigned 6 of the 12 standard lists. The first two lists assigned were for unaided testing with the remaining four used for the two aided conditions (two lists each). Participants' scores for each list were recorded as signal-to-noise ratio (SNR) loss; for greater accuracy, scores for lists administered under the same condition were averaged.

### PPT

Testing of high-frequency speech phoneme perception in quiet was conducted in the sound field using PPT software version 2.1 (Phonak, 2012). The PPT was presented via an E-machines E640 laptop computer (Irvine, CA) connected to an amplifier (Aiwa Stereo Receiver MX-NAVH1200) and single GSI speaker. The speaker setup was the same as that used for the QuickSIN™. The PPT was calibrated as per the PPT Handbook (Phonak, 2012) such that each phoneme was calibrated to a presentation level of 70 dBA SPL, with the exception of the 8-kHz phonemes calibrated to 61 dBA SPL.

The PPT consists of three subtests: detection, distinction, and recognition. The detection test determined detection thresholds (down to a minimum of 25 dB SPL) for the phonemes /sh/ at 3 kHz, /sh/ at 5 kHz, /s/ at 6 kHz, and /s/ at 9 kHz. Participants were instructed to verbally respond "Yes" whenever they could hear a speech sound. Where maximum speech phoneme levels had been reached (75 dB SPL) but the participant had still not responded, this was recorded as "Not Audible."

The distinction test assessed participants' ability to distinguish between the high-frequency speech sounds /sh/ and /s/. Participants were presented with a series of four phonemes, one of which was different from the other three, for example, /sh/, /sh/, /s/, /sh/. Two levels of frequency distinction were tested: the first was distinguishing between 5 and 6 kHz; the second test was distinguishing between 6 and 9 kHz. Phonemes were presented in the sound field at audible levels for the participant based on their detection thresholds. If no detection thresholds were obtained, that is, the participant did not respond at maximum levels, the distinction test was not applicable and the participant moved on to the recognition test. Participants were required to verbally indicate which phoneme was different by saying a number from one to four. This test was preceded by training to allow participants to practice doing the task to become familiar with the sounds, test procedure, and what was expected of them.

The recognition test assessed participants' ability to recognize high-frequency speech phonemes, for example, /sh/ or /s/. The phonemes /d/, /f/, /h/, /k/, /m/, /s/, and /sh/ were embedded in a pair of vowels, forming nonsense words like /a-sh-a/. Participants heard a series of these nonsense words and had to indicate what the middle phoneme was they heard by pointing to the corresponding letter from a short closed list of letters. This test was also preceded by training to allow participants to practice doing the task to become familiar with the sounds, test procedure, and what was expected of them.

### Hearing Aid Fitting

The hearing aids used were Widex mind440 m4-m-CB BTE digital devices (Lynge, Denmark) that had a bandwidth of 100–10000 Hz. Participants were fit bilaterally with the hearing devices with appropriately sized slim tubes and open domes. The hearing aids were connected to a Dell OptiPlex GX280 computer via HiPro programming cables and programmer box. Each participant was entered in the Compass® software (Widex) as a separate "client" and their audiogram (air-conduction thresholds from 250 Hz to 8 kHz, interoctaves if measured) was entered and saved. The Compass® software was used to auto-fit gain targets based on the audiogram. The compression parameters were determined by the Compass® software and varied from participant to participant based on their audiometric data.

The Compass® software's initial fit was used as a starting point to program the hearing aids to the NAL-NL1 prescription procedure (Byrne et al, 2001). Real-ear measures using an Audioscan® Verifit™ (Dorchester, ON, Canada) were conducted to verify the devices' gain was meeting NAL-NL1 targets and gain was adjusted in the Compass® software accordingly. If feedback was experienced, fine-tuning using appropriate software changes was carried out and the feedback cancellation activated if necessary. Seven of 16 participants had feedback cancellation activated for the standard bandwidth fitting and 12 of 16 participants had feedback cancellation activated for the extended bandwidth fitting. Noise reduction features were disabled.

Extended bandwidth amplification was programmed by applying the "Clearband" feature to the standard bandwidth amplification fitting. This allows gain to be manually applied in two extra high-frequency channels: 5–7 and 7–10 kHz. For the extended bandwidth amplification fitting, both the 5–7 and 7–10 kHz channels were adjusted to maximize gain, that is, 15 dB HL of gain was applied in each channel or as much as could be applied before feedback. The settings were then saved under program 2 of the hearing aid.

### Subjective Assessments of Sound Quality

Stimuli used for sound quality assessments consisted of five different listening scenarios (speech in quiet, speech in noise, background noise [multi-talker babble)], traffic noise [environmental noise], forest noise [environmental noise], and the participants' own voice). When assessing their own voice participants read aloud two short paragraphs from the book *Matilda* by Roald Dahl. This extract was selected as it was at children's literacy levels, had a range of phonetic sounds to aid own voice assessments, and when read aloud took ~1 min, which was consistent with presentation lengths of the five other stimuli.

The five sound quality stimuli were presented via a Dell OptiPlex GX280 computer, using Adobe Audition, connected to an amplifier (Aiwa Stereo Receiver MX-NAVH1200) and two GSI speakers. The speakers were positioned at 45° and 315° azimuth at a vertical distance of 120 cm. The speakers were 100 cm from the participant's approximate head position (calibrated position) at a vertical distance of 120 cm. Sound presentation levels varied for each scenario ranging from 61.5 to 65.9 LAeq (dBA) and are summarized in Appendix A.

Before presentation of the sound excerpts, participants were given written and verbal instructions about what listening scenarios they were about to hear and how to assess them. For the five sound stimuli, participants were asked to imagine they were listening to the following scenarios: Quiet Cafe, Busy Cafe, Wine Cellar, Busy Street, and In the Forest, respectively. For the sixth stimulus, participants were asked to read aloud the provided *Matilda* passage. See Appendix B for a full explanation of the listening scenarios and the written and verbal instructions provided to participants. Reading and question time was allocated before stimuli presentation.

As they listened to each sound excerpt, participants were asked to assess the comfort, clarity, loudness, and overall impression of sound quality by marking on the scales from 1 = Very Poor to 9 = Excellent on the Participant Response Form (Appendix C). All stimuli were presented once while participants completed the rating scales. For the sixth stimulus (reading aloud), additional time was provided to complete the scales after the participant finished reading the passage.

### Data Treatment and Statistical Analysis

All statistical analyses were conducted using IBM SPSS (version 22; Armonk, NY) software. Analysis of variance (ANOVA) tests with adjusted degrees of freedom were used where necessary to reduce inflation of type I error rates associated with violations of the sphericity assumption (as indicated by a significant result with Mauchly's test of sphericity). If the estimate of sphericity (epsilon) was $<0.75$, the Greenhouse–Geisser correction was applied; if epsilon was $>0.75$ then the Huynh–Feldt correction was used. When Student's $t$ tests were conducted, equality of variances was checked using Levene's test of equality of variance. If Levene's test was significant, the $t$ test was conducted without assuming equal variances. Pairwise Pearson correlations were used for data exploration and correlations were considered significant at the 5% level (two tailed). Bonferroni corrections were used.

## RESULTS

### Sample Characteristics

#### *Pure-Tone Audiometry*

The pure-tone hearing thresholds (250 Hz to 8 kHz) for the 16 participants (Figure 1) fell within the fitting range of the hearing aids bilaterally. High-frequency

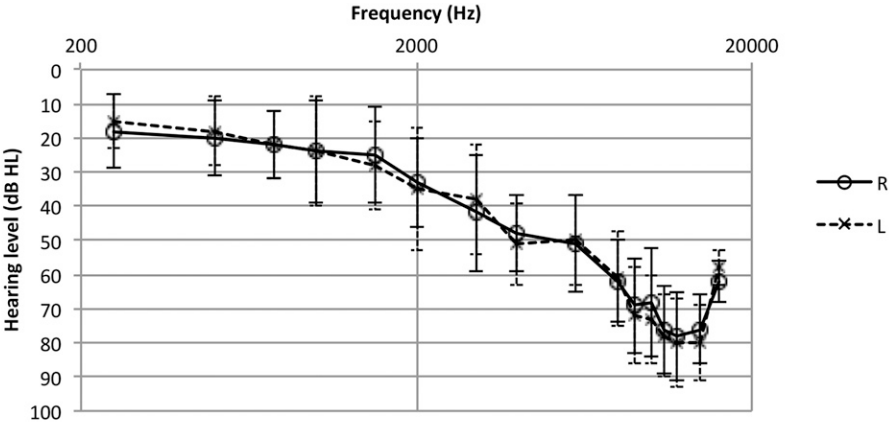

**Figure 1.** Mean audiograms for right (R) and left (L) ears (n = 16). Error bars represent ±1 SD of the mean.

audiometric thresholds were consistent with each participant's hearing loss.

### *Prior Hearing Aid Use*

All participants with prior hearing aid use (n = 11) wore bilateral hearing aids for an average duration of 5.3 yr (ranging from 1.5 to 11 yr). Self-reported frequency of hearing aid use ranged from "sometimes" (36%) to "always" (45%). Average hearing loss between hearing aid users and non–hearing aid users was compared by looking at mean pure-tone averages of left and right ears. An independent samples $t$ test assuming equal variances revealed a statistically significant difference ($t_{14} = 2.76, p < 0.05$) in mean pure-tone averages, with hearing aid users having greater degrees of hearing loss, on average (Mean [M] = 30.63, standard error of mean [SEM] = 3.77), than non–hearing aid users (M = 13.40, SEM = 3.97). The participants did not have any experience with extended bandwidth hearing aids.

## Speech in Noise Perception: QuickSIN™

There was no significant difference between SNR loss scores across the unaided, standard bandwidth, and extended bandwidth conditions [$F_{(2,30)} = 0.27, p > 0.05$]. However, there was considerable individual variation as can be seen in Figure 2. Seven of 16 participants demonstrated an improvement in SNR loss score (negative difference) with the standard bandwidth fitting, that is, SNR loss score was lower with the standard bandwidth fitting than unaided (Figure 2A). However, 7 of 16 participants also demonstrated worse speech in noise perception with the standard bandwidth fitting, that is, SNR loss score was higher with the standard bandwidth fitting than unaided. For the extended bandwidth fitting (Figure 2B), only 4 of 16 participants demonstrated an improvement (negative difference) in SNR loss score with the extended bandwidth fitting over unaided. The remaining participants performed worse (higher SNR loss score) with the extended bandwidth fitting compared to unaided.

## PPT: Detection Thresholds

The mean differences in phoneme detection thresholds between the unaided, standard bandwidth, and extended bandwidth aided conditions were statistically significant [$F_{(1.13,16.98)} = 60.14, p < 0.001$]. Post hoc tests using the Bonferroni correction revealed that the standard bandwidth fitting (M = 42.22, SEM = 1.37) gave a statistically significant reduction (improvement) in phoneme detection threshold ($p < 0.001$) compared to the unaided condition (M = 50.80, SEM = 2.43). Also the extended bandwidth fitting (M = 38.34, SEM = 1.16) gave a statistically significant reduction ($p < 0.001$) in phoneme detection threshold compared to the unaided condition (M = 50.80, SEM = 2.43). Additionally, the extended bandwidth fitting (M = 38.34, SEM = 1.16) gave a statistically significant reduction in phoneme detection threshold ($p < 0.001$) compared to the standard bandwidth fitting ($X$= 42.22, SEM = 1.37).

## PPT Distinction Scores

The mean difference in phoneme distinction scores between the unaided, standard bandwidth, and extended bandwidth aided conditions were statistically significant [$F_{(2,30)} = 4.17, p < 0.05$]. Post hoc tests using the Bonferroni correction revealed that the extended bandwidth fitting (M = 79.4, SEM = 5.5), gave a statistically significant improvement in phoneme distinction score ($p < 0.05$) compared to the unaided condition (M = 60, SEM = 5.3). There was no significant difference between unaided fitting (M = 60, SEM = 5.3) and standard bandwidth fittings (M = 72.5, SEM = 5.9) or standard bandwidth and extended bandwidth fittings (M = 79.4, SEM = 5.5).

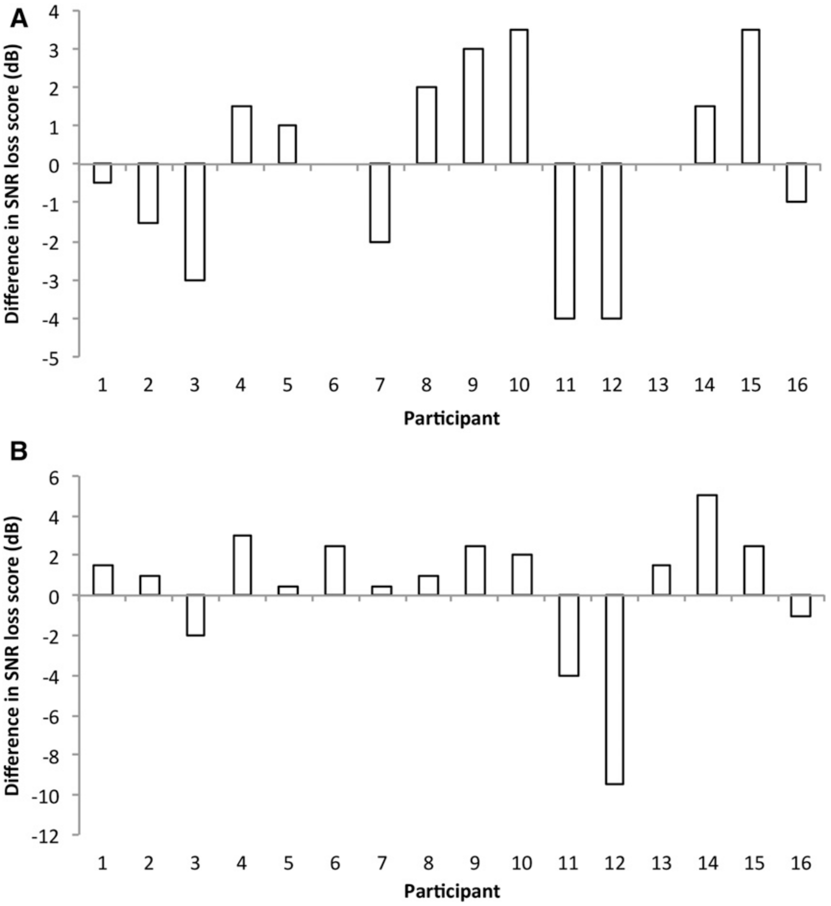

**Figure 2.** (A) Difference in SNR loss scores between standard bandwidth and unaided conditions for each participant (n = 16). (B) Difference in SNR loss scores between extended bandwidth and unaided conditions for each participant.

As well as a main effect of aiding condition, a main effect of frequency was also observed [$F_{(1,15)} = 48$, $p < 0.001$]. Phoneme distinction scores for the 5–6 kHz test (M = 95.8, SEM = 1.2) were significantly higher than those for the 6–9 kHz test (M = 45.4, SEM = 7.5).

A significant interaction effect was also observed between aiding condition and frequency [$F_{(2,30)} = 7.54$, $p = 0.002$] (Figure 3). The scores across conditions to 5–6 kHz stimuli were similar, while performance improved for 6–9 kHz from unaided to standard to extended frequency amplification. To further explore the interaction effect of aiding condition and frequency, simple effects analyses were conducted. A repeated measures ANOVA with Greenhouse–Geisser correction was performed on the 5- to 6-kHz frequency condition alone. This showed that for this frequency, there was no significant difference across aiding conditions [$F_{(1.48,22.13)} = 1.39$, $p > 0.05$].

For the 6- to 9-kHz frequency condition, a repeated measures ANOVA with equal variance assumed revealed that there was a statistically significant effect of aiding condition [$F_{(2,30)} = 6.04$, $p < 0.05$]. Subsequent post hoc pairwise comparisons using the Bonferroni correction revealed mean phoneme distinction scores were significantly ($p < 0.05$) worse (higher) when unaided (M = 23.75, SEM = 10.68) compared to extended bandwidth (M = 66.25, SEM = 8.51, $p = 0.005$) but were not statistically different from standard bandwidth (M = 46.25, SEM = 11.51). There was no statistically significant difference between mean phoneme distinction scores of standard bandwidth (M = 46.25, SEM = 11.51) and extended bandwidth (M = 66.25, SEM = 8.51) fittings.

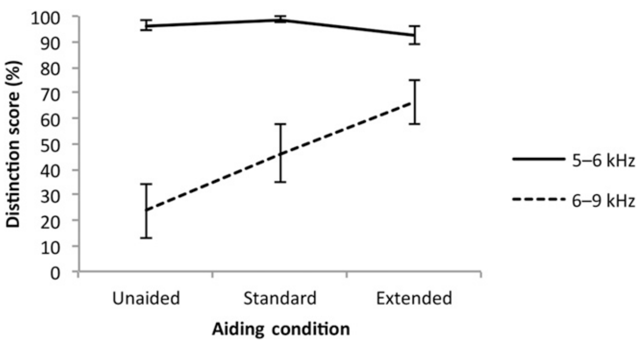

**Figure 3.** Mean phoneme distinction scores per aiding condition per frequency (n = 16). Error bars represent ±1 SD of the mean.

### PPT Recognition Scores

For recognition of phonemes up to 6 kHz in frequency, there was no mean difference in phoneme recognition scores between the unaided, standard bandwidth, and extended bandwidth aided conditions [$F_{(2,30)} = 0.189$, $p > 0.05$]. A separate analysis was conducted comparing recognition ability of the 9 kHz /s/ alone, as some participants were unable to detect the 9 kHz /s/ phoneme when unaided, and sometimes still unable to when aided with the standard bandwidth fitting (Figure 4). If participants were unable to detect 9 kHz (no response at 75 dB SPL), they were assigned 0% for their recognition score. Mean recognition scores for 9 kHz /s/, between the unaided, standard bandwidth, and extended bandwidth aided conditions, were statistically different [$F_{(2,30)} = 15.55$, $p < 0.001$]. Specifically, post hoc pairwise comparisons using the Bonferroni correction revealed that the extended bandwidth fitting (M = 60.88, SEM = 7.92), gave a significantly ($p < 0.001$) greater (improved) mean recognition score compared to the unaided condition (M = 10.6, SEM = 6.4). Mean recognition scores for the extended bandwidth fitting were also greater than scores for the standard bandwidth fitting (M = 27.69, s = 9.17) and this was statistically significant ($p < 0.05$). However mean recognition scores between the unaided condition (M = 10.63, SEM = 6.45) and standard bandwidth fitting (M = 27.69, SEM = 9.17) were not significantly different.

### Subjective Rating Scores

To investigate whether bandwidth had any effect on sound quality judgments, a repeated measures, aided condition (standard bandwidth, extended bandwidth) by listening scenario (speech in quiet, speech in noise, background noise, traffic noise, forest noise, own voice) by sound quality dimension (comfort, clarity, loudness, and overall impression) ANOVA with Greenhouse–Geisser correction was conducted. Analyses revealed no significant main effect for aided condition [$F_{(1,15)} = 0.038, p > 0.05$]. There was no significant interaction effect of aided condition and listening scenario [$F_{(5,75)} = 2.77, p > 0.05$] nor for aided condition and sound quality dimension [$F_{(3,45)} = 1.45, p > 0.05$]. Despite the use of a range of different listening scenarios, bandwidth had no apparent impact on sound quality perception for any of the sound quality dimensions measured: comfort, clarity, loudness, and overall. The listening scenario speech in quiet consistently rated highest for all dimensions of sound quality followed by other quiet scenarios forest noise and own voice. The three noisier scenarios—speech in noise, background noise, and traffic noise—consistently rated the lowest for all dimensions of sound quality (Figure 5).

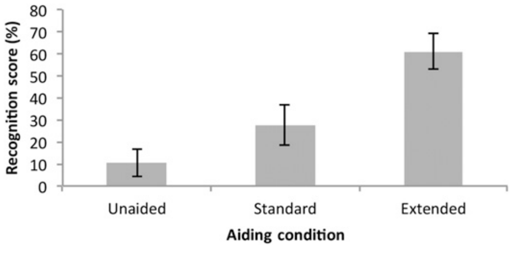

**Figure 4.** Mean 9-kHz phoneme recognition scores per aiding condition. Error bars represent ±1 SD of the mean.

## DISCUSSION

This study investigated the performance of a pair of extended bandwidth hearing aids currently available on the market in adults with mild-to-moderate hearing loss. The hypothesis that speech perception would be improved with wider bandwidth amplification was supported for high-frequency phonemes but not speech in noise. The hypothesis that narrower bandwidth amplification would have superior sound quality was not supported. The extended bandwidth fitting conferred extra benefit in ability to detect soft-level phoneme sounds at high frequencies (6 and 9 kHz), with detection thresholds significantly lower (improved) for the extended bandwidth condition when compared to the standard bandwidth condition. No significant difference was found in ability to recognize phonemes in quiet between the unaided, standard bandwidth, and extended bandwidth fittings when phonemes only contained frequency content <6 kHz; however, significant benefit was found with the extended bandwidth fitting over standard bandwidth and unaided for recognition of 9-kHz phonemes. Subjective measures revealed no significant difference in sound quality preference between the standard bandwidth and extended bandwidth fittings.

Previous studies examining the effect of bandwidth on speech recognition were limited to hearing aids with bandwidths not exceeding 6 kHz (Murray and Byrne, 1986; Simpson et al, 2005; Plyler and Fleck, 2006) or used headphones (Dittberner et al, 2008). The current study investigated a pair of extended bandwidth hearing aids with a specified frequency range of 100–10000 Hz. One of the purposes of the study was to examine whether using actual hearing aids, bilaterally fit to optimize audibility in each individual, would produce similar results to studies that had simulated extended bandwidth amplification using monaural headphones. The hearing aids used in this study had an extended bandwidth feature allowing the researcher to manually apply gain from 5 to 10 kHz, above what was conventionally prescribed by the software's first fit (minimal to no gain >6 kHz). Each participant was provided individualized amplification based on their hearing thresholds

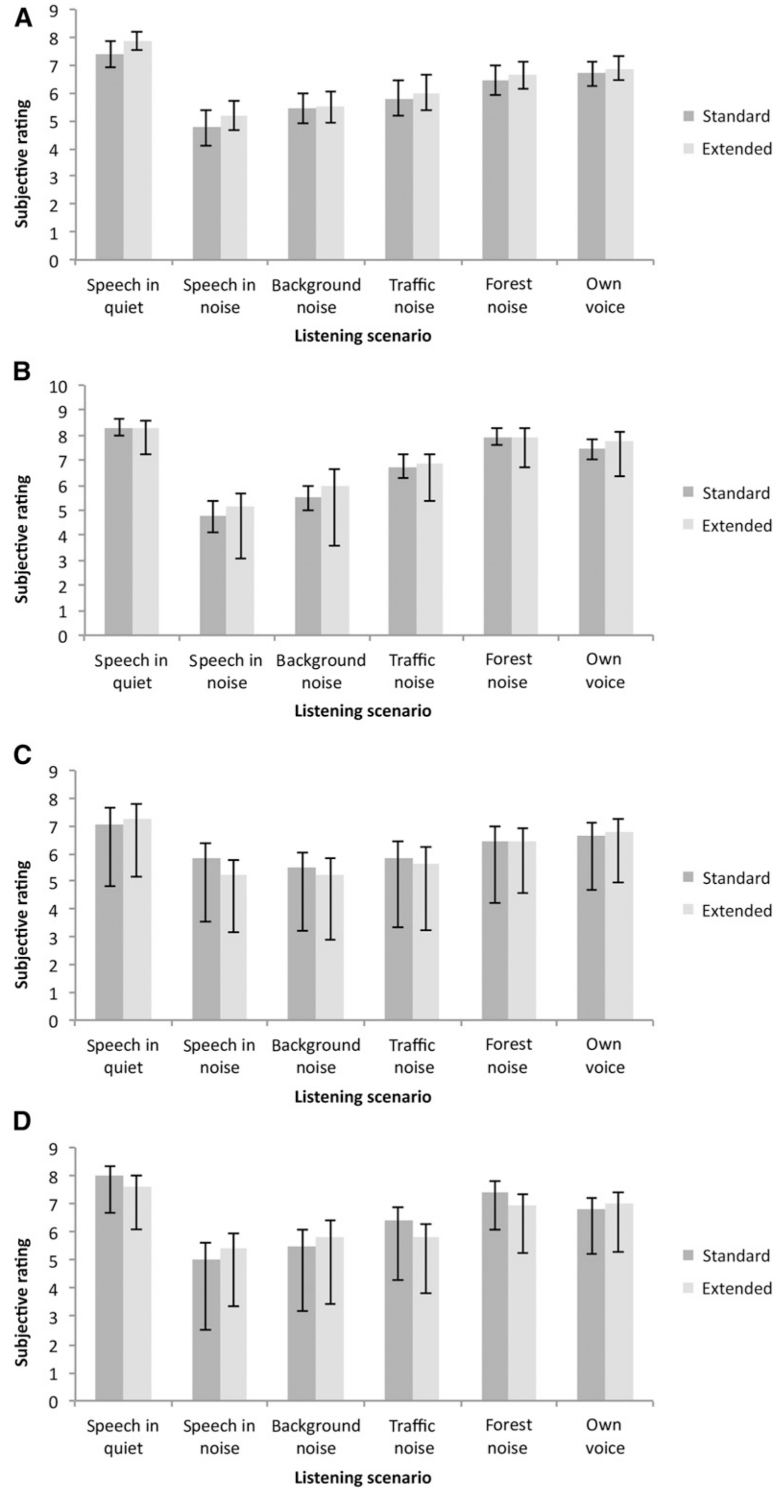

**Figure 5.** Mean subjective ratings of (A) comfort, (B) clarity, (C) loudness, (D) overall sound quality across different listening scenarios for standard and extended bandwidth (n = 16). Error bars represent ±1 SEM.

using the NAL-NL1 prescription. This hearing aid prescription procedure was selected because of its goal of maximizing speech intelligibility at an individual's most comfortable listening level (Byrne and Dillon, 1986; Byrne et al, 2001).

Measures of speech performance were conducted to explore whether adults with mild-to-moderate high-frequency hearing loss were able to make use of extra high-frequency amplification. The Phonak PPT (Phonak, 2012), which involved detection, discrimination, and recognition of frequency speech phonemes, for example, /s/ at 3, 6, and 9 kHz, was used as a measure of objective speech performance. This test was selected to elucidate the benefit of high-frequency amplification and overcome problems such as ceiling effects seen when using speech materials such as sentences or low-frequency phonemes. The results demonstrate that extended bandwidth hearing aids provided gain sufficient to make previously inaudible phonemes audible to hearing-impaired listeners with mild-to-moderate high-frequency hearing loss, as demonstrated by significantly lower phoneme detection thresholds at 6 and 9 kHz. In addition, the high-frequency amplification provided was not only sufficient to make high-frequency phonemes audible, but hearing-impaired listeners were able to use these available cues to help them distinguish and recognize high-frequency stimuli (9 kHz) significantly better than they could with standard bandwidth.

Previous studies have shown improvements in speech recognition in noise with additional high-frequency information (Horwitz et al, 2002; Turner and Henry, 2002; Hornsby and Ricketts, 2003; 2006; Plyler and Fleck, 2006). However, these studies varied in the extent of high-frequency amplification provided. For instance, Turner and Henry (2002) were only able to demonstrate the benefit of audible speech for frequency bands of 2250–3500 and 3500–5600 Hz because "No data were available for the speech band of 5600–9000 Hz, as audible speech could not be provided to any of the hearing-impaired listeners for that frequency range without exceeding uncomfortable loudnesses for the participants" (Turner and Henry, 2002). Horwitz et al (2008) only tested up to 5.6 kHz but did find significant improvement in speech scores with the addition of the highest band (4.5–5.6 kHz). Similarly, Hornsby and Ricketts (2003) found an improvement in speech scores of ~16% on average, for hearing-impaired listeners with flat loss, when low-pass cut-off frequency was increased from 3150 to 6300 Hz. For hearing-impaired listeners with sloping loss, the improvement was less, on average 6% as low-pass cut-off frequency was increased from 3150 to 7069 Hz (Hornsby and Ricketts, 2006). It was of interest in this study to see whether providing additional gain from 5 to 10 kHz would confer additional benefit in speech recognition in noise compared to conventionally prescribed gain (up to 6 kHz). QuickSIN™ measures indicated no significant benefit from either the standard bandwidth or extended bandwidth hearing aid fittings on speech in noise perception as compared to unaided, although there was considerable individual variation, with some participants showing benefit with standard bandwidth and extended bandwidth.

Finally, it was of interest to investigate hearing-impaired listeners' subjective judgments of sound quality of bilaterally fit extended bandwidth hearing aids. One study reported that some hearing-impaired listeners commented that high-frequency sounds like /s/ and /t/ seemed to "jump out" or be overemphasized with high-frequency amplification (Füllgrabe et al, 2010). However, this may have been because of the linear amplification scheme used. Another study using commercially available open-fit hearing aids with extended bandwidth up to 10 kHz found participants generally preferred the 10-kHz bandwidth over the >8 kHz 59% of the time for both music and speech stimuli (Sjolander and Holmberg, 2009). We found that the sound quality of the extended bandwidth hearing aids was acceptable to the majority of participants in a range of situations from speech in quiet to noisy street traffic, with no significant difference in overall sound quality ratings from standard bandwidth. The use of rating scales in sound quality research is standard practice and has high face validity; however, the measures are not without limitations as they are subjective as is the response. The perceived sound quality of signals reproduced by transducers such as loudspeakers, headphones, and hearing aids is multidimensional, that is, there are a number of perceptual dimensions that together make up overall perception of sound quality.

The findings demonstrate that current available extended bandwidth hearing aids are technically capable of delivering high-frequency amplification that is both audible and useable to hearing-impaired listeners with mild-to-moderate hearing loss and this amplification is of acceptable sound quality (no distortion, feedback). However, real-world benefit and the effect of external factors such as background noise, SNR, reverberation time, and distance between the talker and the listener and interactions of any of these factors is yet to be determined. While benefit was seen in high-frequency tests in quiet, no apparent benefit was found for speech in noise recognition, a frequently encountered task that hearing-impaired listeners find the most difficult (Dubno et al, 1984; Helfer and Wilber, 1990; Crandell et al, 1991; Kochkin, 2002). However, previous studies have demonstrated the benefit of extended bandwidth in noise (Turner and Henry, 2002; Hornsby and Ricketts, 2006; Horwitz et al, 2008) particularly when the speech signal and noise are spatially separated (Moore et al, 2010; Ahlstrom et al, 2014), as would be more commonly encountered in a real-world situation.

How much high-frequency amplification to prescribe for a person is still a question that is yet to be answered and currently requires some trial and error from patient to patient. However, the uncertainty regarding this should not deter the clinician from at least attempting to provide some high-frequency amplification to suitable candidates. Despite the rather arbitrary application of high-frequency gain in this study, all participants demonstrated improved audibility of high-frequency components (detection thresholds of 6 and

9 kHz improved significantly) when extended bandwidth was applied.

In conclusion, this study provided evidence that currently available extended bandwidth hearing aids are capable of delivering high-frequency amplification that is both audible and useable (at least in quiet situations) to hearing-impaired listeners with mild-to-moderate hearing loss with acceptable sound quality. Further research, particularly field trials, is required to ascertain the real-world benefit of high-frequency amplification.

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## APPENDIX A: Sound Presentation Levels of Sound Quality Stimuli

| Stimulus | LAeq (dBA) at the Calibrated Position |
|---|---|
| Speech in quiet | 62.2 |
| Speech in noise | 61.5 |
| Background noise | 64.7 |
| Traffic noise | 65.9 |
| Forest noise | 61.5 |

## APPENDIX B: Sound Quality Assessments—General Participant Instructions (written)

### Participant Instructions: Sound Quality Rating Scales

You will be given five listening scenarios and for each you will be played a short sound excerpt.

For a sixth listening scenario you need to read aloud a simple short passage from a children's book.

For each listening scenario, your task is to judge different sound properties using the scales on the "Participant Response Form" you have been given.

The scales can be further defined as follows:

**Clarity:** Your judgment on the clarity or "clearness" of the sound excerpt.

**Comfort:** Your judgment on how comfortable to sound excerpt is to listen to.

**Loudness:** Your judgment on how loud the sound excerpt is.

**Overall Impression:** Your overall judgment of the sound quality of the excerpt.

Instructions: You will need to judge the comfort, clarity, loudness, and overall impression as this listening scenario is played to you.

On the "Participant Response Form," draw a single, vertical line on each scale at the point that best represents your assessment.

Note: For each fitting of the hearing aids (there are two of these), **you will need to listen to all six listening scenarios and complete the ratings.**

Sound Quality Assessments: Listening Scenarios

### Listening Scenario 1: Quiet Cafe

You are sitting alone in an empty café with no other people around. Your friend, Emma now joins you at your table. She wants to tell you about her trip to Africa. There is no one else around.

This sound is 50 sec long.

### Listening Scenario 2: Busy Cafe

You are sitting alone in a busy café with lots of other people talking in the background. Your friend, Emma now joins you at your table. She wants to tell you about her trip to Africa. The café is still busy with lots of other people talking in the background.

This sound is 60 sec long.

### Listening Scenario 3: Wine Cellar

You are on a wine tour in a foreign country and go into the wine cellar with 20 other people. As the wine tasting starts the group begins to talk amongst themselves, you cannot understand anything as the language is foreign.

*Note the language spoken on the track is Slovak. Please let the researcher know if you understand Slovak.*

This sound is 60 sec long.

**Listening Scenario 4: Street Traffic**

You are on a footpath, facing the road waiting for a safe time to cross. The street is busy but the traffic is free flowing. You stand and listen to the sounds of the traffic as they dive past in front of you.

This sound is 50 sec long.

**Listening Scenario 5: In the Forest**

You are resting under a tree in a forest. As you sit, you listen to the sounds of the forest.

This sound is 50 sec long.

**Listening Scenario 6: Own Voice Assessment**

You will need to read aloud the short highlighted passage provided below. The passage is an extract from the children's book *Matilda*, by Roald Dahl.

Instructions: As you read aloud the passage provided, judge the ***comfort, clarity, loudness, and your overall impression*** of your own voice.

On the "Participant Response Form," draw a single, vertical line on each scale at the point that best represents your assessment.

Passage (to be read aloud):

"Matilda was a little late in starting school. Most children begin Primary School at five or even just before, but Matilda's parents, who weren't very concerned one way or another about their daughter's education, had forgotten to make proper arrangements in advance.

The village school for younger children was a bleak brick building called Crunchem Hall Primary School. It had about two hundred and fifty pupils aged from five to just under twelve years old. The head teacher, the boss, the supreme commander of the establishment was a formidable middle-aged lady whose name was Miss Trunchbull."

## APPENDIX C: Sound Quality Assessments: Participant Response Form (Rating Scale)

**Listening Scenario 1: Quiet Cafe**

Please assess and judge the listening *comfort, clarity, loudness, and overall quality* of the sound excerpt played to you. Indicate your selection by drawing a circle around one of the vertical lines that best represents your assessment.

**Listening Scenario 2: Busy Cafe**

Please assess and judge the listening *comfort, clarity, loudness, and overall quality* of the sound excerpt played to you. Indicate your selection by drawing a circle around one of the vertical lines that best represents your assessment.

**Listening Scenario 3: Wine Cellar**

Please assess and judge the listening *comfort, clarity, loudness, and overall quality* of the sound excerpt played to you. Indicate your selection by drawing a circle around one of the vertical lines that best represents your assessment.

**Listening Scenario 4: Street Traffic**

Please assess and judge the listening *comfort, clarity, loudness, and overall quality* of the sound excerpt played to you. Indicate your selection by drawing a circle around one of the vertical lines that best represents your assessment.

**Listening Scenario 5: In the Forest**

Please assess and judge the listening *comfort, clarity, loudness, and overall quality* of the sound excerpt played to you. Indicate your selection by drawing a circle around one of the vertical lines that best represents your assessment.

**Listening Condition: Own Voice Assessment**

Please recite the short passage provided to you aloud twice and as you do so assess and judge the listening *comfort, clarity, loudness, and overall quality* of your own voice. Indicate your selection on these by drawing a circle around one of the vertical lines that best represents your assessment.