Numerous studies have shown that children with mild to moderate hearing loss experience significant difficulties in multiple areas (e.g. communication, psychosocial, emotional, academic) when compared to children with normal hearing (Bess et al, 1998; Davis et al, 1986; Eisenberg et al, 2007; Elfenbein et al, 1994; Moeller, 2007; Moeller et al, 2007; Porter et al, 2013). Many of these difficulties likely arise from the children’s compromised speech perception abilities. For instance, Ross and Giolas (1971) measured monosyllabic word recognition for phonetically-balanced words presented at 65 dB SPL to children with unaided late-identified mild hearing loss and with normal hearing and reported mean scores of 46% correct and 91% for the hearing-impaired and normal hearing children, respectively. Additionally, Hicks and Tharpe (2002) evaluated speech recognition in 14 children with mild to moderate high-frequency hearing loss, and reported that their aided word recognition in quiet and in noise was significantly poorer than children of the same age with normal hearing.

In the same study, Hicks and Tharpe (2002) reported that children with mild to moderate high-frequency hearing loss experienced more effort when participating in listening tasks as compared to their normal-hearing counterparts. Furthermore, in a classic paper describing speech recognition of children with varying degrees of hearing loss, Boothroyd (1984) reported that even children with moderate degrees of high-frequency hearing loss experience difficulty with recognition of consonants. Specifically, Boothroyd noted that children with moderate hearing loss are only able to correctly recognize consonants on the basis of place cues at a 75% accuracy rate.
Some researchers have specifically focused on the ability of children with moderate hearing loss to recognize the high-frequency phoneme /s/ (Stelmachowicz et al., 2001, 2002, 2004). Stelmachowicz and colleagues (2001) evaluated the perception of the phoneme /s/ for 20 children with normal hearing and 20 children with moderate high-frequency hearing loss. Nonsense syllables were low-pass filtered with varying cut-off frequencies ranging from 2000 to 9000 Hz (2000, 3000, 4000, 5000, 6000, and 9000 Hz) and the perception of /s/ spoken by a male, female, and child talker was evaluated for each bandwidth. Stelmachowicz et al. (2001) showed that children with moderate degrees of high-frequency hearing loss perform poorer than children with normal hearing and adults with a similar degree of hearing loss. It was also determined that children with moderate hearing loss require a bandwidth extending to 9000 Hz to achieve their maximum performance for recognition of the phoneme /s/. Stelmachowicz and colleagues (2001) expressed concern that ITE hearing aids are often unlikely to provide sufficient high-frequency gain to provide children with moderate hearing loss with sufficient audibility for high-frequency phonemes such as /s/.

Many researchers have sought to explore solutions to improve access to high-frequency speech sounds for children with hearing loss (Auriemma et al., 2009; Glista et al., 2009; Wolfe et al., 2010, 2011). Specifically, researchers have explored the potential of using frequency-lowering processing to improve the perception of high-frequency phonemes. For instance, Auriemma et al. (2009) evaluated speech recognition in quiet for a group of ten children who had severe-to-profound high-frequency hearing loss and who used Widex Inteo hearing aids with a type of frequency lowering referred to as linear frequency transposition (LFT). Performance was measured with LFT disabled, immediately after LFT was enabled, and after six weeks of use of LFT and periodic auditory training focusing on the recognition of high-frequency phonemes. Auriemma and colleagues (2009) showed no improvement when performance was measured at the session at which LFT enabled. However, they did report an improvement of almost 20 percentage points in consonant recognition on a nonsense syllable test (NST) when stimuli were presented at 30 dB HL. Vowel recognition at a presentation level of 30 dB HL was not similar between the two conditions. Also, there were not significant differences between the LFT enabled and disabled conditions in vowel recognition at presentation levels of 30 and 50 dB HL, nor in consonant recognition at a presentation level of 50 dB HL.

Glista et al. (2009) also measured speech recognition in quiet and in noise for a group of 11 children with hearing loss. Most of these subjects had severe to profound high-frequency hearing loss, but two did possess a moderate high-frequency hearing loss (i.e., high-frequency pure-tone average > 50 dB HL). Glista and colleagues (2009) reported improvements in fricative detection and recognition as well as in consonant recognition with the use of non-linear frequency compression (NLFC) as compared to the NLFC disabled condition. Furthermore, Glista et al. (2009) noted a trend toward greater benefit from NLFC for subjects with greater degrees of high-frequency hearing loss.

Wolfe and colleagues (2009, 2010, 2011) examined the potential benefit of NLFC for children with moderate to moderately severe high-frequency hearing. They evaluated speech recognition in quiet and in noise for a group of 15 children ranging in age from 6 to 13 years old. Specifically, Wolfe et al. (2010) evaluated speech recognition in quiet and in noise after these children wore hearing aids for six weeks with NLFC and six weeks without NLFC. The order of NLFC use was counter-balanced across subjects to prevent learning effect and acclimatization effects from biasing results. Wolfe and colleagues (2010) found an average of 5–10 dB improvement in detection thresholds for warble tones at 4000, 6000, and 8000 Hz and for the speech sounds /sh/ and /s/ with NLFC compared the NLFC-disabled condition.

Speech recognition in quiet was assessed in open-set with the University of Western Ontario plurals test (Glista & Scollie, 2012), and subjects scored significantly better with NLFC (99% compared to 83% correct without NLFC). Speech recognition in quiet was also assessed with the phoneme perception test, which utilized an adaptive, computer-controlled approach to determine the threshold (dB SPL) for nonsense syllable recognition in a closed-set (e.g., /asa/ with /s/ center frequency at 6000 Hz, /asha/, /aka/, /afa/, /ata/, /asa/, and /asa/ with /s/ center frequency at 9000 Hz). Recognition thresholds were significantly lower for the /asa/ and /asa/ (center frequency at 9000 Hz) stimuli with NLFC enabled versus disabled. Sentence recognition in noise was also evaluated using the BKB-SIN test, and no difference in speech recognition in noise was observed between the NLFC-enabled and NLFC-disabled conditions.

Wolfe et al. (2011) also measured speech recognition in quiet and in noise after the children in the aforementioned study used NLFC for an additional six months to evaluate if performance improved with experience (i.e., acclimatization). At the six month assessment, significant improvement between the NLFC enabled and disabled conditions were once again observed for the UWO plurals test (Glista & Scollie, 2012) and aided thresholds (e.g. for the phonemes /s/ and /sh/ as well as for warble tones at 4000, 6000, and 8000 Hz). However, significant improvements were also observed on the phoneme perception test for the tokens /asa/ with /s/ centered at 6000 and 9000 Hz, /afa/, /ata/, and /ada/, suggesting a period of acclimatization longer than six weeks may be need for optimization of performance with NLFC in children. Additionally, at the six month assessment, a significant improvement in speech recognition in noise on the BKB-SIN test was observed between the NLFC enabled and disabled conditions.

Another alternative for improving audibility of high-frequency speech sounds for children with mild hearing loss is the use of hearing aids with a wideband frequency response. Although the hearing-aid industry provides no formal consensus on what constitutes a wideband frequency response, most experts define a wideband response...
as one that extends out to at least 8000 Hz (Beck & Olsen, 2008; Kuk & Backgaard, 2009). It is important to note that the hearing-aid bandwidth a manufacturer reports for a particular device is based on the ANSI S3.22 definition of gain-frequency response, which states that the frequency response of a hearing aid is measured in a 2 cc coupler and is defined by the lowest and highest frequencies whose gains are 20 dB below the high-frequency average gain (at 1000, 1600, and 2500 Hz) when measured with the volume control in the reference test position. This reported bandwidth may not necessarily reflect the point at which the frequency response begins to roll-off when the aid is worn in the ear.

There is a paucity of research examining the potential of any type of hearing aid technology to improve the detection and recognition of high-frequency speech sounds of children with mild to moderate hearing loss. Specifically, there are no published reports in the peer-reviewed literature describing the benefits or limitations of wideband hearing aids for children with mild to moderate hearing loss. Additionally, there are no published studies that have formally examined the effectiveness of frequency-lowering hearing-aid technology for children with mild to moderate high-frequency hearing loss. Indeed, experts in the area of pediatric hearing loss and amplification have identified the need for studies to evaluate the effectiveness of these technologies for children with mild to moderate high-frequency hearing loss (Eisenberg et al, 2007).

Considering the difficulties children with mild to moderate high-frequency hearing loss experience with speech recognition and production, academics, and psychosocial/emotional domains as well as the benefits that children with moderate to moderately severe high-frequency hearing loss received from the use of NLFC, the objective of this study was to evaluate the potential benefits and limitations of NLFC for children with mild to moderate high-frequency hearing loss. Because the current alternative to NLFC for providing access to high-frequency sounds is wideband amplification (i.e. a hearing aid with a bandwidth extending toward 8000 Hz), speech recognition in quiet and noise was evaluated with a hearing aid utilizing NLFC and a wideband hearing aid with a reported bandwidth of 8000 Hz.

**Methods**

**Participant characteristics**

Eleven children (eight male, three female) recruited from the patient population of the Hearts for Hearing Foundation in Oklahoma City, USA served as participants. Informed consent was obtained from all participants and parents prior to data collection. The study was approved as human subjects research by the University of Oklahoma Health Sciences Center Institutional Review Board, IRB #14439.

All children had mild to moderate high-frequency sensorineural hearing losses (see Figure 1 for mean audiometric thresholds and Figure 2 for a box and whisker plot of audiometric data). In order to be included in the study, the children met the following criteria:

1. Pure-tone average in the better ear could not exceed 50 dB HL
2. Pure-tone threshold at 8000 Hz in the better ear could not exceed 55 dB HL.

**Figure 1.** Mean audiogram (n = 11).

**Figure 2.** Box and whisker plot of audiometric data for the left and right ears of the subjects who participated in this study.
Between the ages of 6 to 13 years
3. Consistent users of amplification
4. Use of English spoken language as primary mode of communication
5. No cognitive or behavioral disabilities that would prevent completion of the tests used in the study
6. No conductive or auditory neuropathy spectrum disorder hearing loss

Participants ranged in age from 7.4 to 13.2 years, with a mean age of 10.1 (SD = 1.9). The mean pure-tone average of the better ear was 39.55 dB HL, and the mean air conduction pure-tone threshold at 4000, 6000, and 8000 Hz for the better ear was 48.6, 41, and 42.7 dB HL, respectively. In short, the subjects in this study possessed markedly better high-frequency hearing sensitivity than the subjects in the previous Wolfe et al study (2009, 2010, 2011), in which mean air conduction pure-tone thresholds at 4000, 6000, and 8000 Hz were 60.7, 61.7, and 64.1, respectively. The hearing aids that the children used prior to inclusion into the current study are shown in Table 1.

All participants were fitted binaurally with Oticon Safari 300 and Phonak Nios S III behind-the-ear (BTE) hearing aids. The Oticon Safari 300 hearing aid possesses a reported bandwidth of 8000 Hz, which refers to the upper limit of the digital signal processor (2 cc coupler response: 100–6800 Hz) (Oticon, 2013). The reported bandwidth for the Phonak Nios S H2O III device is 7100 Hz (2 cc coupler response: 100–7100 Hz) (Phonak, 2013). Hearing aids were coupled to the participants’ ears using their own existing earmolds.

### Table 1. Subjects’ hearing aids that were used prior to their inclusion into the current study.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Make/model of hearing instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Widex Senso Diva 9</td>
</tr>
<tr>
<td>2</td>
<td>Phonak Nios micro III</td>
</tr>
<tr>
<td>3</td>
<td>Phonak Nios micro V</td>
</tr>
<tr>
<td>4</td>
<td>Widex Senso Diva 9</td>
</tr>
<tr>
<td>5</td>
<td>Widex Senso Diva 9</td>
</tr>
<tr>
<td>6</td>
<td>Phonak micro Sivia 100 dSZ</td>
</tr>
<tr>
<td>7</td>
<td>Phonak micro Sivia 100 dSZ</td>
</tr>
<tr>
<td>8</td>
<td>Phonak Eleva 211 dAZ</td>
</tr>
<tr>
<td>9</td>
<td>Widex Senso Diva 9</td>
</tr>
<tr>
<td>10</td>
<td>Widex Senso Diva 9</td>
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<tr>
<td>11</td>
<td>Phonak Eleva 211 dAZ</td>
</tr>
</tbody>
</table>

For both the Oticon and Phonak hearing devices, simulated probe microphone measures with measured real-ear-to-coupler differences (RECD) were conducted on the Audioscan Verifit hearing aid analyser to evaluate the output of the hearing aids. Simulated probe microphone measures were used in this study to reduce the chances of test-retest error associated with fitting two different hearing instruments with in-situ probe microphone measures (Dillon, 2001). Simulated measurements performed in a 2cc coupler allowed the clinician to examine the hearing-aid frequency response to 8000 Hz, whereas standing wave effects present with in situ real ear measures often complicate the measurement of hearing-aid output beyond 6000 Hz (Dillon, 2001). As a result, simulated real measures with measured RECD were used to fit the hearing aids in this study rather than in situ real ear measures.

The fitting clinician attempted to program the hearing-aid output to match the DSL v5.0 target (± 5 dB) at 250, 500, 1000, 2000, 4000, and 6000 Hz for the target standard speech signal presented at 55, 65, and 75 dB SPL. This match was approximated for all subjects who participated in this study, and for both the 55 and 65 dB SPL standard speech signal, the output of both hearing aids exceeded each subject’s threshold at 6000 Hz. The highest-frequency gain handle of each of the hearing aids evaluated in this study was used to increase high-frequency gain in an attempt to optimize high-frequency audibility beyond 6000 Hz without encountering acoustic feedback or exceeding (by more than 5 dB) the DSL v5.0 prescriptive target at 4000 and 6000 Hz. Furthermore, the maximum output was measured to an 85 dB SPL swept pure tone, and the clinician ensured that it did not exceed the DSL v5.0 targets for the 85 dB SPL swept tone. Examples of the probe microphone results for the mean audiogram of the subjects in this study are shown in Figure 3.

### Figure 3. Simulated probe microphone results for the (A) Oticon Safari 300, and (B) Phonak Nios S H2O III behind-the-ear hearing aids. Each is programmed to desired sensation level (DSL) v5.0 prescriptive target for children. Average real-ear-to-coupler difference (RECD) values for a 10 year-old child, which was the mean age of children participating in this study.
For the Phonak device, these initial probe microphone measurements were made while NLFC was disabled. This is consistent with recommendations in professional guidelines (AAA, 2013). Then, probe microphone measures were performed with NLFC enabled to ensure that the 6300 Hz frequency-lowering verification stimulus of the Audioscan Verifit was sufficiently audible (i.e., the compressed signal met or exceeded the DSL v5.0 target at the destination frequency). The Audioscan frequency-lowering verification stimuli were developed by Audioscan specifically for the purposes of examining the audibility of speech sounds that have been reduced in frequency by a frequency-lowering processor. These signals are intended for use when insufficient high-frequency audibility is indicated by probe microphone measurements with the standard speech signal (i.e., audibility for the standard speech signal is not provided in the high-frequency range with use of conventional amplification) (Glista & Scollie, 2009).

For this study, when NLFC was enabled, the clinician ensured that the output for the 6300 Hz frequency lowering verification stimulus was positioned within the frequency response of the hearing aid when NLFC was disabled (i.e., the output for the 6300 Hz FLVS was positioned prior to the roll-off of the frequency response in the NLFC-Off mode); see Figure 4 for an illustration of the results of this procedure for a hearing aid programmed for the mean audiogram of the subjects in this study. Based on probe microphone measures, the crossover frequency of NLFC was set lower than the manufacturer’s default for five of the children. NLFC parameters used for the children in this study are provided in Table 2.

To ensure that NLFC parameters were fitted appropriately for the children, the examiners made certain that the children could discriminate between /sh/ and /s/ without visual cues when spoken at an average conversational speech level from 12 feet (3.6 meters) away. None of the children exhibited confusion of the /s/ for /sh/ phonemes, and none reported poor sound quality with NLFC enabled. This finding is in contrast to Glista and colleagues’ experiences using NLFC with persons with severe to profound high-frequency hearing loss, who occasionally showed /sh/ for /s/ confusion when NLFC parameters were set aggressively (Glista et al, 2009).

Finally, digital noise reduction, directional microphones, and additional noise reduction/reverberation reduction features were disabled in both hearing aids. However, the acoustic feedback cancellation features of both hearing aids were active. Also, the acoustic feedback calibration test was conducted in situ with both hearing aids for each

| Table 2. Non-linear frequency compression (NLFC) parameters for the children who participated in this study. NA = Not applicable, because NLFC settings were not adjusted from the software default setting. |
|-----------------|-----------------|-----------------|
| Subject | Default NLFC parameters (crossover frequency/compression ratio) | Adjusted NLFC parameters (crossover frequency/compression ratio) |
| 1 | 3.2/2.4:1 | 2.7/3.1:1 |
| 2 | 3.3/3.0:1 | NA |
| 3 | 3.3/3.0:1 | NA |
| 4 | 3.3/3.0:1 | 3.1/3.4:1 |
| 5 | 3.3/3.1:1 | NA |
| 6 | 3.3/3.2:1 | NA |
| 7 | 3.3/3.2:1 | 3.0/3.6:1 |
| 8 | 3.4/2.3:1 | NA |
| 9 | 3.4/2.6:1 | 3.1/3.0:1 |
| 10 | 3.4/2.7:1 | NA |
| 11 | 3.4/2.8:1 | 2.8/3.6:1 |

Figure 4. Simulated probe microphone results illustrating the output of the Phonak Nios S H20 III hearing aid with and without non-linear frequency compression (NLFC) to the Audioscan Verifit 6300 Hz frequency lowering verification stimulus.
subject prior to fitting the output of the hearing aid to the DSL v5.0 prescriptive target.

Study design
The study included three 4–6 week crossover trial periods in which the subjects used the hearing aids in one of three conditions: (1) Oticon Safari 300 wideband, (2) Phonak Nios S H2O III with NLFC disabled, (3) Phonak Nios S H2O III with NLFC enabled. The order in which the NLFC was utilized was randomly counterbalanced across participants, with four of the participants beginning the first six-week trial with NLFC enabled, three beginning with the Phonak hearing aid with NLFC disabled, and the other four children beginning with the Oticon hearing aid with the wideband frequency response. The participants and their parents were blinded to hearing-aid condition. The study hearing aids were identified using generic names and the NLFC enabled/disabled conditions were randomly assigned a label for each participant as program one or program two.

Recognition of speech sounds in quiet, speech recognition in noise, and aided thresholds for speech tokens were evaluated following each 4- to 6-week trial to allow for a comparison of performance with wideband amplification to performance versus NLFC. On versus NLFC Off. Study hearing aids were locked into the hearing-aid condition under test using a single program; participants were not able to change hearing-aid settings during the study. Prior to testing at each appointment, investigators verified that the study hearing aids were programmed correctly using Phonak Target and Oticon Genie fitting software suites.

Study measures
All audiometric outcome measures were repeated at each of the three test intervals of the study (i.e. after each of the four to six-week periods with NLFC enabled and disabled and after the four to six-week period with the Oticon wideband hearing aid). All assessments were performed in the binaural aided condition using sound field stimuli. Testing was conducted in a sound-treated booth meeting ANSI S3.1-1999 (R2008) standards for permissible ambient noise levels during testing with ears uncovered. Measurement of ambient noise was conducted with a type 1 sound level meter by a trained calibration contractor approximately one month prior to the start of testing. Test assessments consisted of:

**ASSESSMENT OF HIGH-FREQUENCY SPEECH DETECTION AND RECOGNITION**

Consonant detection and recognition were evaluated using three tasks: the University of Western Ontario (UWO) plurals test (Glista & Scollie, 2012), the University of Western Ontario distinctive features differences test (UWO-DFD) (Cheesman & Jamieson, 1996), and the phoneme perception test (Boretzki & Kegel, 2009). The UWO plurals test is an open-set, speech-recognition task developed by researchers at UWO to evaluate a hearing-aid wearer’s ability to detect the high-frequency phonemes /s/ and /z/ as bound morphemes indicating plurality in the word-final position (Glista et al, 2009). In the present study, the UWO test was administered across all three hearing-aid conditions. This test contains 15 separate words that should be familiar to the typical school-aged child. The words are included in both the singular and plural form (ant[s], balloon[s], book[s], butterfly[ies], crab[s], crayon[s], cup[s], dog[s], fly[ies], flower[s], frog[s], pig[s], skunk[s], sock[s], and shoe[s]).

Test items are spoken by a female talker and presented in recorded format, so it is imperative that children have access to acoustic energy beyond 6000 Hz for correct identification of the plural in each word. In fact, the centroid frequency of the /s/ phoneme in the final position of the target words occurs at approximately 7050 Hz. The UWO plurals test was presented at a level of 50 dBA. The test stimuli were generated from a JVC XLFZ-258 compact disc (CD) player, which was coupled to the Madsen Orbiter 922 audiometer by an interface cable. The test stimuli were then presented from a JBL Control 5 loudspeaker located one metre directly in front of the child and at the approximate plane of the child’s head. A 1000-Hz calibration tone provided with the UWO plurals test was initially used to set the V.U meter to 0 dB. Then, a Type 2 sound level meter was used at the beginning of the assessment period with each child to confirm that the calibration signal provided on the UWO plurals test CD corresponded to the desired presentation level (when measured with the microphone placed at the location of the child’s head during the test session) of each speech stimulus. Participants provided oral responses to the test stimuli, which were scored in open-set by the investigators as correct or incorrect. The children were instructed to repeat the words that they heard, and they were not aware that their task was to recognize the bound morpheme /s/ or /z/ that may exist at each word. Two randomly-selected 30-word lists of the UWO plurals test were presented for a total of 60 words in each condition.

Consonant detection and recognition thresholds were also evaluated using the detection and recognition tasks, respectively, of the phoneme perception test (PPT). The PPT was developed by hearing scientists and audio engineers of Phonak AG in Switzerland (Boretzki & Kegel, 2009) and features three sub-tests, (1) a detection task, (2) a recognition task, and (3) an identification task. Only the detection and recognition tasks were employed for the present study. For these two sub-tests of the PPT, stimuli were presented by a Windows-enabled computer via line out to a Crown D-75A two-channel amplifier and a JBL Control 5 loudspeaker located at head level one metre directly in front of the subject. A Type 2 sound level meter was used at the outset of the assessment period with each subject to confirm that the broadband calibration signal produced by the PPT software output was set to the software-indicated 70 dBA. Subsequent sound level measurements were conducted to verify the appropriate presentation level of the stimuli at regular intervals.

The detection task involves the determination of threshold (in dB SPL) for four phonemes, (1) /sh/ low, (2) /sh/ high, (3) /s/ low, and (4) /s/ high. The /sh/ low stimulus is intended to acoustically approximate the /sh/ when spoken by an adult male and possesses a center frequency around 3000 Hz. The /sh/ high stimulus possesses a center frequency near 5000 Hz in order to simulate the /sh/ phoneme when spoken by a female. The /s/ low and /s/ high stimuli possess center frequencies of 5000 and 9000 Hz, respectively, in an attempt to approximate the male and female /s/, respectively.

A Hughson-Westlake clinical method of ascending limits was used to evaluate detection thresholds for each of the aforementioned stimuli. Stimuli were adjusted in an up 5 / down 10 dB approach until two responses were obtained at the same level in an ascending presentation level. Next, the stimuli were adjusted in an up 1 dB / down 2 dB approach, and threshold was defined as the lowest level in which two responses were obtained in an ascending presentation level.

The recognition subtest of the PPT involved the adaptive presentation of seven nonsense tokens (/asa/, /ada/, /afa/, /aka/, /asha/, and /aha/, and /ama/) presented by a female speaker and included at the end of the carrier phrase ‘My name is [token]’. The center frequency
of the /sh/ and /s/ phonemes in the /asha/ and /asa/ were positioned at approximately 5000 and 9000 Hz, respectively, which is typical for female speech. Two extra stimuli, referred to as ‘asha5K’ and ‘asa6K’, were filtered so that the center frequencies were positioned at 5000 and 6000 Hz, respectively, which more closely approximates the center frequency of /sh/ and /s/ when spoken by a male.

The PPT was administered using a computer-controlled adaptive procedure in which the listener was asked to respond to stimuli by selecting (via the use of a wireless computer mouse) one of the seven tokens displayed on a monitor in the test booth as buttons labeled ADA, AFA, AK, ASA, ASHA, AMA, and AHA. The PPT adaptive procedure is described by Boretzki and Kegel (2009) and Wolfe et al (2010). Briefly, the PPT test uses an ascending-descending procedure to determine the presentation level for 50% correct performance. For each test administration, approximately 100 to 130 stimuli are presented, with the actual number varying based on the reliability of participant responses. The PPT test software then calculates the participant’s threshold in dB SPL for 50% identification of /s/ low, /s/ high, /sh/ low, and /sh/ high nonsense syllables.

The UWO-DFD task was presented using test software installed on a Linux-enabled laptop PC. Signals were routed from the line-out channel of the laptop via a Crown D-75A two-channel amplifier to a JBL Control 5 loudspeaker located one metre directly in front of the child and at the approximate plane of the child’s head. Closed-set test stimuli, which consisted of 16 phonemes embedded in medial position within the nonsense token /a il/, were presented at 60 dBA by alternating male and female recorded voices. The subject’s task was to use the computer mouse to select the consonant heard in the stimulus-medial position from a set of 21 consonants and consonant clusters displayed on a monitor (B, CH, D, F, G, H, J, K, L, M, N, P, R, S, SH, T, TH, V, W, Y, Z). A practice list was administered prior to beginning scoring to orient participants to the task. The UWO-DFD test was administered in the NLFC On and Oticon wideband conditions. A total of 42 stimuli were presented in each condition and a percentage-correct score was calculated. For a more complete description of the UWO-DFD, the reader is referred to Cheesman and Jameson (1996).

Assessment of speech recognition in noise

The signal-to-noise ratio required for 50% correct sentence recognition was determined by administering two randomly-selected list pairs from the BKB-SIN test (Bench et al, 1979). Testing was conducted according to the procedures described in the BKB-SIN test manual (Etymotic Research, 2005). Specifically, the sentences were generated from a JVC XL-FZ258 compact disc changer routed to a Madsen Orbiter 922 audiometer, Crown D-75A two channel amplifier, and JBL Control 5 loudspeaker located at head level one metre directly in front of the subject. Presentation of BKB-SIN stimuli was at a fixed level (50 dB HL in this study) and the level of the multitalker competing noise signal increased throughout each list of the test. The sentences and competing noise were both presented from the same loudspeaker, located at head level, one metre directly in front of the participant, and the signal-to-noise ratio for 50% correct performance was determined.

Study measures were conducted during 60–90 minute sessions. The order of task presentation was randomized across and within each child. Children were given the opportunity to take breaks throughout each test session. A type 1 sound level meter (Ivie IE-45 audio analyser with Bruel & Kjaer model 4940 0.5-inch microphone) was used to verify and calibrate presentation levels for signals used in all study measures prior to data collection on each testing day.

Rationale for the inclusion of the measures selected for the assessment battery of this study

A battery of outcome measures was chosen for evaluation of differences between hearing-aid conditions in this study. Measures were chosen to evaluate both detection and recognition in quiet and in noise. The outcome measures used in this study ranged in difficulty and purpose as follows. First, tests were chosen to include outcome measures at the levels of both speech sound detection and speech recognition. Detection measures were included to provide assessment of differences in audible bandwidth across fittings and to permit comparison to previous studies in the literature. Specifically, aided thresholds for high-frequency speech phonemes were measured using adaptive procedures, which permit assessment of frequency-specific changes in low-level sound detection and comparison to previous studies with NLFC (Wolfe et al, 2009, 2010, 2011).

The detection task within the Phonak phoneme test (PPT) is a measure that uses an adaptive test of phoneme detection. This test was chosen for inclusion in our battery because it is adaptive, and therefore should be free of ceiling effects within the limits of the audiometric test system, and because it uses high-frequency speech sounds which should be highly sensitivity to any potential differences in performance that may be achieved with the technologies included in this study.

Another detection task used in this study was the UWO plurals test, which assesses detection changes of high frequency phonemes that are embedded in speech. This test is non-adaptive, so it may be affected by ceiling effects. The UWO plurals test was presented at a fixed level that represents soft to conversation level speech. As a result, it provides an assessment of speech sound detection within a task that may generalize more readily to real world benefit. Inclusion of this task also permits comparison to previous studies of children with greater degrees of hearing loss than those tested in the present study, which may provide information on candidacy for bandwidth versus NLFC (Glista et al, 2009; Wolfe et al, 2010, 2011).

We hypothesized that extended bandwidth and NLFC fittings would show improved scores on the adaptive measures used within this battery, compared to the restricted bandwidth condition (i.e. NLFC Off). Additionally, we hypothesized that greater differences between the NLFC On and wideband conditions versus the NLFC Off conditions would be observed for the higher frequency stimuli (i.e. /h/). Further, we hypothesized that extended bandwidth and NLFC technologies may show improvements on the UWO plurals test unless ceiling performance (at 90% correct or above) is achieved. Cases in which ceiling performance is achieved on this test may indicate that benefits obtained on the adaptive measures suggest that benefits are restricted to low level stimuli.

The remaining measures in the battery were included to provide assessment of differences in speech recognition obtained with the various hearing-aid conditions used in this study. The recognition portion of the PPT test was included as a measure of the minimum threshold required for correct identification of fricatives. This test was expected to be the most sensitive test among recognition measures because it employs both male and female fricative stimuli and it uses adaptive test procedures. Comparisons between male and female fricative recognition results have been shown to be sensitive to the effects of bandwidth in past studies (Stelmachowicz et al, 2001).

Because the recognition task within the PPT test provides data on only a small number of specific phonemes, we also chose another measure (the UWO DFD test) that possesses a larger number of
phonemes and that may generalize more readily to speech recognition in daily communication. The UWO DFD provides a broad assessment of recognition of all consonants in speech and uses both male and female stimuli. It was presented at a fixed conversational level to assess the impact of hearing-aid differences in understanding consonants in conversation-level speech.

Additionally, the BKB-SIN was chosen to provide an assessment of understanding of speech in a background of babble. We hypothesized that extended bandwidth and NLFC fittings would show improved scores on the adaptive measures used within this battery, compared to the restricted bandwidth condition, with a greater likelihood of differences for the most high frequency stimuli such as female fricatives. Given the mild to moderate degree of hearing loss of children in this study, hypotheses about potential differences in the UWO-DFD and BKB-SIN tests are more tentative: these tests are included to allow evaluation of the real-world significance of any differences observed on the more sensitive PPT test. Benefits obtained only on the PPT test may indicate that benefits are restricted to low level stimuli.

In summary, the test battery chosen spans the domains of detection and recognition as well as speech in quiet and speech in noise, and this battery evaluates subject performance at the phoneme, word, and sentence level. This broad approach was chosen to evaluate the impact of these technologies across a wide range of speech tasks that differ in their difficulty levels, generalizability, and scope of interpretation to real world outcome. Overall, this approach is consistent with guidelines (AAA, 2013) recommending that the impact of frequency lowering on the audibility of speech be evaluated with behavioral measures, but it also acknowledges that speech sound detection and recognition are both important aspects of a comprehensive test battery to consider in hearing-aid feature evaluation.

Results

**UWO plurals test**

Mean percent-correct scores on the UWO plurals test as a function of amplification condition are displayed in Figure 5. Because performance on the UWO plurals test approached ceiling performance (100% correct), scores were converted to rationalized arc sine units (RAU, Studebaker, 1985) prior to analysis. A repeated-measures ANOVA for the effect of amplification across the three fitting conditions on RAU-converted UWO plurals test performance was not significant ($F[2,20] = 0.848, p = .44, \eta^2_p = .122$).

**UWO distinctive features difference test**

Mean percent-correct scores on UWO DFD test as a function of amplification condition are displayed in Figure 6. A repeated-measures ANOVA for the effect of amplification between the WB and NLFC on conditions on UWO-DFD test performance was not significant ($F[1,10] = 3.54, p = .09, \eta^2_p = .261$). Note that the UWO DFD test was not administered in the NLFC Off condition due to limited access to test equipment during the study. Percent correct scores on all phonemes included in the UWO DFD test were high in both conditions, with average scores of 80% and 84% correct in the wideband and NLFC conditions, respectively. Percent correct scores for fricatives and affricates were high in both conditions, with scores of 71% and 75%, respectively.

**PPT detection test**

Mean sound-field detection thresholds for high-frequency consonant tokens as a function of amplification condition are displayed in Figure 7. A $4 \times 3$ ANOVA was performed to test for the effect of test token (/s/ low, /s/ high, /sh/ low, /sh/ high) and the three amplification conditions on high-frequency phoneme detection threshold. This analysis revealed significant effects of token ($F[3,30] = 18.17, p < .001, \eta^2_p = .645$), condition ($F[2,20] = 10.36, p = .001, \eta^2_p = .509$), and the interaction term ($F[6,60] = 10.31, p < .001, \eta^2_p = .508$).

Figure 5. Percent correct scores on UWO plurals test by hearing-aid condition. No significant difference across amplification conditions was seen.

Figure 6. Percent correct scores on UWO distinctive features difference test by hearing-aid condition. No significant difference across amplification conditions was seen.

Figure 7. Aided thresholds (dB SPL) for detection of high-frequency consonant tokens on the PPT detection subtest by hearing-aid condition (*$p < .05$).
Post hoc testing using Tukey’s HSD test found thresholds for the /s/ high token to be significantly higher (worse) than thresholds for the /s/ low (p < .001), /sh/ high (p < .001), and the /sh/ low (p = .001) tokens. No significant difference was seen among the /s/ low, /sh/ high, and /sh/ low tokens (all p > .05).

Post hoc testing using Tukey’s HSD test found thresholds obtained in the WB condition were significantly higher (worse) than thresholds obtained in the NLFC On condition (p < .001). Furthermore, thresholds obtained in the NLFC Off condition were also significantly higher than thresholds obtained in the NLFC On condition (p = .009); no significant difference was seen between thresholds obtained in the WB and NLFC Off conditions (p = .24).

Post hoc testing using Tukey’s HSD was also conducted for significant interaction terms, revealing the following: for the /s/ high, /sh/ high, and /sh/ low tokens, performance in the NLFC On condition was significantly better than in the NLFC Off and WB conditions (all p < .05); no significant difference was seen between the NLFC Off and WB conditions for these tokens. For the /s/ low token, performance in the NLFC On condition was significantly better than in the WB condition only (p < .05). No difference was seen in detection of this token between NLFC On and NLFC Off or between NLFC Off and WB.

**PPT recognition test**

Mean sound-field closed-set recognition thresholds for high-frequency consonant tokens as a function of amplification condition are displayed in Figure 8. A 4 x 3 ANOVA was performed to test the effect the four test tokens and the three amplification conditions on high-frequency phoneme detection threshold. This analysis revealed significant effects of token (F[3,30] = 11.96, p < .001, \( \eta_p^2 = .545 \)), condition (F[2,20] = 17.91, p < .001, \( \eta_p^2 = .642 \)), and the interaction term (F[6,60] = 11.94, p < .001, \( \eta_p^2 = .544 \)).

Post hoc testing using Tukey’s HSD test found thresholds for the /s/ high token to be significantly higher (worse) than thresholds for the /s/ low (p = .001), /sh/ high (p = .003), and the /sh/ low (p = .003) tokens. No significant difference was seen among the /s/ low, /sh/ high, and /sh/ low tokens (all p > .05).

Post hoc testing using Tukey’s HSD test found thresholds obtained in the WB condition were significantly higher (worse) than thresholds obtained in the NLFC On condition (p < .001). Furthermore, thresholds obtained in the NLFC Off condition were also significantly higher than thresholds obtained in the NLFC On condition (p = .009); no significant difference was seen between thresholds obtained in the WB and NLFC Off conditions (p = .052), though this comparison approached significance.

Post hoc testing using Tukey’s HSD was also conducted for significant interaction terms, revealing the following: for the /s/ high and /sh/ low tokens, performance in the NLFC On condition was significantly better than in the NLFC Off and WB conditions (all p < .05); no significant difference was seen between the NLFC Off and WB conditions for these two tokens. For the /s/ low token, performance in the NLFC On condition was significantly better than in the WB condition only (p < .05). No difference was seen in detection of this token between NLFC On and NLFC Off or between NLFC Off and WB.

**BKB-SIN test**

Mean SNR thresholds for 50% correct identification of BKB-SIN sentences in noise as a function of amplification condition are displayed in Figure 9. A repeated-measures ANOVA for the effect of amplification across the three fitting conditions on BKB-SIN performance was not significant (F[2,20] = 0.33, p = .72, \( \eta_p^2 = .032 \)).

**Discussion**

**Brief overview of study methods and results**

Speech recognition in quiet and in noise were assessed while children with mild to moderate high-frequency hearing loss used an Oticon Safari 300 BTE hearing aid with a wideband frequency response (extended to 8000 Hz) and a Phonak Nios S H2O BTE hearing aid with NLFC disabled and NLFC enabled. These comparisons were conducted in an effort to detect any significant impact of NLFC On performance (NLFC On vs. Off, NLFC On vs. WB) apart from differences across hearing aids from two manufacturers (NLFC Off vs. WB). The hearing aids were fitted using procedures supported by professional guidelines (AAA, 2013) and similar to those typically used by clinicians who fit hearing aids for children with hearing loss. No significant difference among amplification conditions was seen in detection or recognition in quiet for measures conducted at fixed presentation levels (e.g., UWO plurals and UWO DFD tests). Effect sizes were small to medium (\( \eta_p^2 = .12 \) for the UWO plurals test, \( \eta_p^2 = .26 \) for the UWO DFD test). Additionally, no differences were obtained in the BKB-SIN test.
Among technology conditions were observed for speech recognition in noise (e.g. BKB-SIN). The effect size was small ($\eta^2_p = .03$) for this measure.

In short, these results indicate that children with mild to moderate hearing loss have good access to speech consonants in both word-medial and word-final positions when speech is presented at fixed soft and conversational levels of 50 to 60 dBA, when audible speech cues were provided following recommended verification procedures (AAA, 2013) with either a wideband strategy or with NLFC enabled or disabled. Similarly, sentence recognition in noise did not vary across conditions, indicating that these varying hearing-aid fitting strategies were equally successful in providing access to speech in noise. These results indicate that good real world benefits are possible with a variety of strategies as long as a broad bandwidth of audibility is provided by the hearing aids. In the present study, the hearing-aid bandwidth was supported both by the use of two modern signal processors that include a broad bandwidth in their signal processing, and by the use of a prescriptive formula that attempts to provide audibility of speech across frequencies. These findings also indicate that the individualized settings of NLFC used in this study did not negatively impact speech recognition across a broad range of task types.

A significant advantage was seen for the NLFC-enabled Phonak Nios hearing aids (relative to both the wideband hearing aid and the NLFC-disabled Phonak hearing aid) for measures that were administered via an adaptive format (e.g. PPT high-frequency phoneme detection and recognition tasks). The effect sizes for these differences were large (greater than .5 for both the detection and recognition tasks). In particular, children displayed significantly lower (better) thresholds for detection and recognition of the high-frequency fricative tokens /s/ and /sh/ when using NLFC compared to conventional amplification and a hearing aid with a wideband frequency response.

Although there were no differences in performance across hearing-aid technologies when evaluated with measures administered at fixed presentation levels, the results on adaptive measures do suggest that children with mild to moderate high-frequency hearing loss may have better access to low-level, high-frequency speech sounds (e.g. /sh/ and /s/) with use of NLFC.

**Explanation of study findings**

The fact that improvement in detection and recognition with NLFC was observed for the adaptive measures but not for measures administered at fixed levels may be attributed to multiple factors. First, the PPT measures involved the attainment of a threshold for high-frequency phonemes, and as a result, these measures were most likely to be the most sensitive measures of audibility and access to high-frequency speech sounds. Taken together, these results indicate that subtle differences in access to high frequency fricatives may vary, particularly for very low level or distant talkers, across measurements and hearing technologies that vary in their high frequency signal delivery. This finding may relate to hearing specific sounds in the speech of female talkers who are being overheard from a distance in a quiet environment. Previous studies have found that children may prefer a hearing-aid fitting that provides more audibility of speech because it aids in hearing soft or distant talkers, even when fixed-level laboratory measures of speech recognition are not sensitive to differences (Ching et al, 2010). The impacts of overhearing and/or distance hearing were not evaluated directly in this study, but it is possible that the results from the adaptive phoneme recognition and detection testing may warrant further study to determine whether they are predictive of real world preference for a given signal processor.

Speech recognition in noise was similar between the NLFC condition and the two different wideband conditions. This finding is similar to that of Wolfe and colleagues (2009) who found no difference in speech recognition in noise between NLFC Off and On conditions for a group of 15 children who had moderate hearing loss and used BTE hearing aids with a six-week interval with NLFC On and a six-week interval with NLFC Off. Sufficient audibility of high-frequency speech sounds is likely to be better for the children with mild hearing loss, so the fact that no significant difference on the BKB-SIN test was seen in the present study is not surprising. It should be noted that Wolfe et al (2011) did report that children with moderate hearing loss did show improved speech recognition in noise after an additional six months of NLFC use compared to the NLFC Off condition. Wolfe et al (2010) hypothesized that an extended period of NLFC use may be necessary for acclimatization to occur along with a subsequent improvement in speech recognition in noise. Glista et al (2012) demonstrated that some children with greater degrees of hearing loss demonstrated significant increases in performance following a period of acclimatization, with changes appearing after six to eight weeks of use. Notably, the differences described by Glista and colleagues appeared to be task-dependent, suggesting that any assessment of acclimatization to NLFC (and potentially other amplification strategies) may depend upon the stimuli and task employed. Additional research is needed to determine whether an extended wearing trial with NLFC would have resulted in improved speech recognition in noise for children with mild hearing loss.

One potential concern with frequency-lowering amplification is that it may distort speech sounds to the extent that they are no longer recognized by the hearing-aid wearer. No evidence of this concern
was observed in the study, as a phoneme-level analysis reveals that there was no deterioration in speech recognition with the use of NLFC. The mild amount of compression used for children with mild to moderate degrees of hearing loss does not appear to alter speech sounds to the point at which recognition suffers. Indeed, NLFC settings that are unnecessarily strong are inappropriate for children with mild hearing loss. In order to avoid substantial distortion of high-frequency phonemes, we recommend that clinicians aim to select the fitting software setting for NLFC that has the highest crossover frequency and lowest compression ratio that provide sufficient audibility for the hearing-aid wearer. The fitting and verification methods used in this study illustrate this type of fitting strategy.

**Limitations of this study**

The limitations of this study should be acknowledged.

First, many of the children in this study likely encountered ceiling effects on some of the measures used in this study, such as the UWO plurally test and the UWO DFD test. This fact may have limited the ability to identify potential differences that may have existed between the technologies evaluated in this study, and likely reflect real world performance for speech at moderate levels. For that reason, adaptive measures were also included in the test battery, and revealed technology differences for softer input levels.

Second, current hearing-aid analysers do not provide simple and effective means to evaluate audibility beyond 6000 Hz for ear-level hearing aids. Indeed, generic prescriptive methods (DSL v5.0/NAL-NL2) only provide fitting targets to 6000 Hz. As a result, the researchers of the current study attempted to optimize the delivery of high-frequency output by visually ensuring audibility for the standard speech signal at 6000 Hz and beyond. The highest-frequency gain handle of each of the hearing aids evaluated in this study was used to increase high-frequency gain in an attempt to optimize or extend high-frequency audibility without exceeding the DSL v5.0 prescriptive target at 4000 and 6000 Hz.

Hillock-Dunn and colleagues (2014) evaluated the effect of NLFC on high-frequency audibility for children with a wide range of high-frequency hearing loss and used the same Audioscan Verifit frequency-lowering verification stimulus that was used in the current study to evaluate audibility for one-third octave band stimuli with different center frequencies. The same stimulus (e.g., 6300 Hz Audioscan Verifit Frequency Lowering Verification Stimulus) was used in the current study to evaluate the effect of the NLFC used in this study, but it was not used to evaluate the wideband conditions. The Audioscan 6300 Hz FLVS resides within the same analysis band as the 6000 Hz target, so the additional information acquired from this measure is limited with the use of wideband hearing aids that have been already been fitted to the prescribed target at 6000 Hz. As previously indicated in the Methods section of this paper, the long-term average speech spectrum of the Audioscan Verifit Standard Speech Stimulus exceeded the threshold for every subject in this study and was also within ±5 dB of the DSL target at 6000 Hz for every subject in this study. As a result, high-frequency audibility was optimized for each subject in the wideband condition in this study to the extent to which it is currently possible with existing commercially available hearing aid analysers. Additional work is needed to develop objective electroacoustic methods to evaluate audibility for speech sounds to 8000 Hz and beyond.

Third, as shown in Figure 2 of this paper, there was a fairly wide range in high-frequency hearing sensitivity of the subjects in this study (with hearing thresholds at 6000 and 8000 Hz ranging from 20 to 55 dB HL across subjects. Additionally, this study contained a relatively small sample size. When considered collectively, these limitations may limit the generalizability of the results of this study.

Fourth, performance in this study was evaluated after four to six weeks of use with each technology. It is possible that a longer period of use would have allowed for further acclimatization to these technologies and an improvement in performance. Indeed, Wolfe et al. (2011) showed continued improvement in speech recognition in quiet and in noise between the six-week and six-month wearing intervals for a group of children who had moderate to moderately severe hearing loss and were fitted with NLFC. There are no published studies examining the influence of an acclimatization period with wideband amplification.

Fifth, simulated real-ear measures with measured RECD were used to fit the hearing aids that the children used in this study. In situ real-ear measures were not administered for several reasons. Simulated probe microphone measures were used in order to reduce the chances of test-retest error associated with fitting two different hearing instruments with in-situ probe microphone measures (Dillon, 2001). Also, simulated measurements performed in a 2cc coupler allowed the clinician to examine the hearing-aid frequency response to 8000 Hz, whereas standing wave effects present with in situ real-ear measures often complicate the measurement of hearing-aid output beyond 6000 Hz (Dillon, 2001). Additionally, numerous objective measurements of hearing-aid output were completed in this study. The maximum power output level real to a swept pure tone and the ear-aided response were measured for three input levels for each of three hearing-aid technologies used in this study. Furthermore, in the NLFC condition, measurements were made with the Audioscan Verifit FLVS. The authors of this paper were concerned that the children may have become restless if we attempted to complete this large number of measures using in situ real-ear measures, and as a result, they may have been less likely to remain still throughout the verification process, which is required for accurate in situ measures to be completed. However, even in light of the aforementioned considerations, it should be noted that the simulated real-ear measures used in this study may not have accounted for the acoustic effect of the children’s ear molds, and as a result, there may have been a difference that existed between the simulated output measured in this study compared to the actual output at the children’s ear drums.

**Conclusions**

The following conclusions can be drawn from this study with children with mild to moderate high-frequency hearing loss:

1. Children with mild to moderate high-frequency hearing loss have good access to speech consonants in both the word-medial and world-final positions when speech is presented at fixed soft and conversational levels of 50 to 60 dBA with either a wideband strategy or with NLFC enabled or disabled, when the hearing aid is fitted and verified using speech-based probe microphone measures and an audibility-focused prescription. For measures administered at the aforementioned fixed conversational levels, the detection and recognition of high-frequency consonants was similar with the use of wideband amplification and NLFC.

2. No differences in speech recognition in noise were observed between NLFC On and wideband amplification conditions.

3. Detection and recognition of high-frequency phonemes (/sh/ and /s/) was significantly better with NLFC relative to the NLFC Off and wideband conditions when performance was evaluated with
Adaptive measures designed to determine a threshold of audibility/recognition for low-level high-frequency speech sounds.

4. Further study is warranted to determine the role of the lower thresholds observed with use of NLFC and effects on real-world preference for a given signal processor.

5. No deterioration in performance was observed with use of NLFC on any measure used in this study.

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