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Paired Comparisons of Nonlinear Frequency Compression, Extended Bandwidth, and Restricted Bandwidth Hearing Aid Processing for Children and Adults with Hearing Loss

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Abstract

Background: Preference for speech and music processed with nonlinear frequency compression (NFC) and two controls (restricted bandwidth [RBW] and extended bandwidth [EBW] hearing aid processing) was examined in adults and children with hearing loss.

Purpose: The purpose of this study was to determine if stimulus type (music, sentences), age (children, adults), and degree of hearing loss influence listener preference for NFC, RBW, and EBW.

Research Design: Design was a within-participant, quasi-experimental study. Using a round-robin procedure, participants listened to amplified stimuli that were (1) frequency lowered using NFC, (2) low-pass filtered at 5 kHz to simulate the RBW of conventional hearing aid processing, or (3) low-pass filtered at 11 kHz to simulate EBW amplification. The examiner and participants were blinded to the type of processing. Using a two-alternative forced-choice task, participants selected the preferred music or sentence passage.

Study Sample: Participants included 16 children (ages 8–16 yr) and 16 adults (ages 19–65 yr) with mild to severe sensorineural hearing loss.

Intervention: All participants listened to speech and music processed using a hearing aid simulator fit to the Desired Sensation Level algorithm v5.0a.

Results: Children and adults did not differ in their preferences. For speech, participants preferred EBW to both NFC and RBW. Participants also preferred NFC to RBW. Preference was not related to the degree of hearing loss. For music, listeners did not show a preference. However, participants with greater hearing loss preferred NFC to RBW more than participants with less hearing loss. Conversely, participants with greater hearing loss were less likely to prefer EBW to RBW.

Conclusions: Both age groups preferred access to high-frequency sounds, as demonstrated by their preference for either the EBW or NFC conditions over the RBW condition. Preference for EBW can be limited for those with greater degrees of hearing loss, but participants with greater hearing loss may be more likely to prefer NFC. Further investigation using participants with more severe hearing loss may be warranted.

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Key Words: Auditory rehabilitation, hearing aids and assistive listening devices, pediatric audiology

Abbreviations: ANOVA = analysis of variance; APHAB = Abbreviated Profile of Hearing Aid Benefit; DSL = Desired Sensation Level algorithm; EBW = extended bandwidth; KEMAR = Knowles Electronic Manikin for Acoustic Research; LTASS = long-term average speech spectrum; NFC = nonlinear frequency compression; PTA = pure-tone average; RBW = restricted bandwidth; SL = sensation level; WDRC = wide-dynamic range compression

INTRODUCTION

Sound quality is based on a judgment of the accuracy, appreciation, or intelligibility of audio output from an electronic device, such as a hearing aid. The sound quality of hearing aids has been identified as an important factor in hearing aid users' satisfaction with amplification (Humes, 1999; Kochkin, 2005). Findings suggest that sound quality may be related to speech recognition, but involves separate processes. Although some listeners rate conditions with the highest speech intelligibility as also having the best sound quality (van Buuren et al, 1999), this does not seem to be the norm (Harford and Fox, 1978; Plyler et al, 2005; Rosengard et al, 2005).

Because the satisfaction of hearing aid users is related, at least in part, to sound quality, there is an interest in the effect of different hearing aid parameters on sound quality. In this study, the maximum audible frequency (bandwidth) with amplification is defined as the highest frequency at which the listener can hear conversational speech with amplification. The maximum audible frequency is determined by measuring the hearing aid output for conversational speech and then determining the point at which the root mean square level crosses the listener's hearing threshold to become inaudible. The bandwidth with amplification is one factor that has been shown to influence both sound quality and speech recognition (Ricketts et al, 2008; Füllgrabe et al, 2010). Increasing the bandwidth has been found to improve objective measures of speech recognition for both children (Stelmachowicz et al, 2001, 2004) and adults (Ching et al, 1998; Hornsby et al, 2011), with children requiring greater bandwidth than adults in order to achieve equivalent performance. Adult listeners also indicate a subjective preference for increased bandwidth (Moore and Tan, 2003; Ricketts et al, 2008; Füllgrabe et al, 2010), but that preference is influenced by the stimuli used and degree of hearing loss. Specifically, adults with normal hearing prefer wider bandwidths for music passages than for speech stimuli (Moore and Tan, 2003). Ricketts et al (2008) found that listeners with less high-frequency hearing loss, as measured by the slope of the hearing loss, more consistently preferred speech and music with wideband processing (5.5 versus 9 kHz) than listeners with more high-frequency hearing loss. Similar observations have been made for speech recognition, wherein listeners with less hearing loss are more likely to demonstrate benefit with increases in bandwidth than listeners with greater hearing loss (Ching et al, 1998; Hogan and Turner, 1998; Turner and Cummings, 1999; Ching et al, 2001).

However, extending the bandwidth with a hearing aid using conventional amplification, hereafter referred to as extended bandwidth (EBW), can be difficult to achieve in practice. Bandwidth can be restricted in the high frequencies because of the degree of hearing loss, the upper frequency limit of amplification, or both (Moore et al, 2008). The bandwidth traditionally available with hearing aid amplification, 5–6 kHz (Dillon, 2001), is hereafter referred to as restricted bandwidth (RBW). A recent advance in hearing aid signal processing, frequency lowering, has made it possible to provide information about speech over a greater bandwidth than is traditionally available to hearing aid users (see Alexander, 2013 for a review of frequency-lowering approaches). By shifting high-frequency sounds to lower frequencies, frequency lowering potentially increases the audibility of information originating from the higher frequencies. One approach to frequency lowering is nonlinear frequency compression (NFC). With NFC, the input signal is filtered into a low-frequency and a high-frequency band. The crossover point between the two bands is referred to as the start frequency. Below the start frequency, the signal is amplified without frequency compression, whereas above the start frequency, the signal is compressed in frequency. The amount of frequency compression applied is specified by the compression ratio.

Although NFC has the potential to increase high-frequency audibility, the resulting spectral distortion in lower-frequency regions where the information is moved to could have detrimental effects on speech recognition. Studies of NFC do not consistently demonstrate improved speech recognition when compared with RBW (Simpson et al, 2005, 2006; Glista et al, 2009; Wolfe et al, 2010, 2011; Souza et al, 2013). However, as noted by Alexander (2013), differences in participant populations, hearing aid technology, stimuli, and fitting methods across studies may have contributed to the variability in outcomes. For example, although Simpson et al (2005) found improved consonant-vowel-consonant recognition with NFC, a follow-up study by Simpson et al (2006) did not. Although participants in both studies had severe to profound hearing loss, participants in the 2005 study had less hearing

loss than participants in the 2006 study. Therefore, the participants in the 2006 study did not demonstrate the same benefit observed for the participants in the 2005 study, potentially because the compressed portion of the signal would have been less audible for the latter study. Because real-ear measures were not performed, it is difficult to determine how the audibility in each study affected speech recognition. Another factor that may have influenced differences between the studies is the start frequency. Start frequencies were lower (1.25 or 1.60 kHz) in the 2006 study than in the 2005 study (with a few exceptions, ≥2.0 kHz), which may have adversely affected the perception of low-frequency information such as fundamental frequency and formant ratios.

Some differences in outcomes across studies also may be related to the age of the participants. Stelmachowicz et al (2001, 2004) demonstrated that children require greater bandwidth than adults in order to maximize speech perception, because of a greater reliance on acoustic-phonetic cues. Consistent with that finding, speech recognition results with children indicate that children may benefit more than adults from the provision of NFC when compared with RBW (Glista et al, 2009). Although studies by Wolfe et al (2010, 2011) did not include adult listeners, they did demonstrate that children consistently showed improved speech recognition from NFC. Findings with adults in the aforementioned NFC studies were not as consistently positive.

As with objective measures of speech recognition, outcomes of studies investigating subjective preference for NFC or RBW vary. Simpson et al (2006) measured preference for NFC versus RBW using the Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox and Alexander, 1995), but only included adult listeners. Although a statistical analysis of the subjective ratings for the APHAB was not reported, confidence intervals were provided by Cox and Alexander. None of the changes in ratings described by Simpson and colleagues were greater than the 90% confidence intervals, suggesting that their adult listeners did not perceive differences in benefit between NFC and RBW when compared with the normative sample for the APHAB.

The settings used for NFC are another factor that might influence preference over RBW. Studies where listeners preferred NFC (Glista et al, 2009; Wolfe et al, 2010, 2011) used the minimum settings (highest start frequency and/or lowest compression ratio) that simultaneously achieved audibility of the compressed portion of speech and avoided spectral overlap of /s/ and /ʃ/. Studies where listeners preferred RBW to NFC (Parsa et al, 2013; Souza et al, 2013) systematically adjusted the start frequency and compression ratio to determine the extent to which the listeners would tolerate the distortion caused by NFC. Audibility of the compressed portion was not measured. Therefore, it may have been that some of the settings selected (those with low start frequencies and high compression ratios) produced greater spectral distortion without additional gains in audibility of the compressed portion of the signal. Caution is warranted in comparing findings from Souza et al with those clinical hearing aids with NFC, because only the most intense frequency components were lowered, which differs from the current commercial implementations of NFC, where all frequency components above the start frequency are lowered.

Age also may have affected preference differences across studies. Although few studies have compared adults and children, the majority of the children in the study by Glista et al (2009) had a preference for NFC, whereas the adults did not have a preference for one or the other (NFC or RBW). In contrast, Parsa et al (2013) found that both adults and children had a preference for RBW, but as mentioned previously, the settings used may have resulted in increased distortion without increased audibility. Together, these studies suggest that selecting the minimum NFC settings necessary to achieve audibility of the compressed portion of speech may be more likely to lead to a preference for NFC than NFC settings that use lower start frequencies and higher compression ratios.

Although improvements in speech recognition with either NFC or EBW over RBW amplification have been demonstrated for some participant populations (Ching et al, 1998; Stelmachowicz et al, 2001, 2004; Simpson et al, 2005; Glista et al, 2009; Hornsby et al, 2011; Wolfe et al, 2010, 2011), there have been no direct comparisons of sound quality between EBW and NFC for either music or speech. It is our prediction that, because NFC distorts the frequency spectrum of the input signal, listeners will prefer EBW to NFC. Because differences in preference for EBW have been previously observed between speech and music (e.g., Moore and Tan, 2003), both were included. Lastly, although it is well known that children require a greater bandwidth than adults to achieve equivalent speech understanding, no studies have compared preference for EBW, NFC, and RBW in children and adults. Knowing which technology is preferred would be useful in helping clinicians determine candidacy and in counseling patients.

The purpose of the present study was to compare preferences for hearing aid processing using EBW, NFC, and RBW in children and adults. Adults and children with primarily mild to severe hearing loss were included because (1) previous NFC studies have demonstrated speech recognition benefit for listeners with milder degrees of hearing loss (e.g., Wolfe et al, 2010, 2011) and (2) this allowed for a hearing aid simulator and headphone arrangement to achieve audibility through 8 kHz for the EBW condition. Music passages and speech-in-quiet were included to ascertain the effect of the processing type on listeners' preferences.

Paired comparisons were selected to determine the direction of the preference.

METHODS

Participants

Because the method of fitting the simulated hearing aid was based on audibility, participants were only included if higher audibility could be achieved with EBW and NFC than RBW for at least one ear. Hearing thresholds were measured for all participants at octave frequencies from 0.25–8 kHz and at 6 kHz using an audiometer (GSI-61) with insert earphones (ER3A) or supra-aural earphones (TDH-50P). If a conductive component was present when using TDH-50P, thresholds were remeasured with insert earphones to ensure that it was not related to a collapsed ear canal. Hearing thresholds were also measured at interoctave frequencies when consecutive octave frequencies differed by at least 20 dB. Participants with high-frequency (2, 4, 6 kHz) pure-tone average (PTA) of 25 dB HL or less in either ear, asymmetric hearing loss (PTA difference ≥15 dB), or those who would have had asymmetric NFC settings because of differences in the bandwidth, were excluded. Three of the children were tested monaurally because higher audibility could not be achieved with either EBW or NFC than RBW in the nontest ear. One child was excluded because of an error during data collection. The remaining participants consisted of 16 children (mean age: 12 yr, age range: 8–16 yr) and 16 adults (mean age: 54 yr, age range: 19–65 yr) with mild to severe hearing loss. Figure 1 shows the hearing thresholds for the participants. Tables 1 and 2 show participant demographics for adults and children, respectively. Of the participants who wore hearing aids, all except participant 9A (adult) and participant 15C (child) wore binaural hearing aids.

Stimuli

Speech stimuli were 15 sentences, spoken by an adult female, which included at least 3 fricatives per sentence (see Appendix). The sentence duration averaged 3.8 sec and ranged from 2.9–4.4 sec. The sentences were recorded digitally using a Shure Beta 53 microphone with the standard filter cap. The sentences were presented in quiet. Eight different music passages were used (see Appendix). The passages were extracted from a compact disc using Adobe Audition 3.0. The average duration was 8 sec and ranged from 7–11 sec. Stimuli were presented at 60 dB SPL to the input of the hearing aid simulator, described next.

Amplification

Signal Processing

Stimuli were processed using a hearing aid simulator programmed by author JA using MATLAB (R2009b) with a sampling rate of 22.05 kHz (see McCreery et al, 2013; Alexander and Masterson, in press). Hearing aid amplification was simulated in order to maintain greater control over the NFC parameters and audibility. The stages in the program included a broadband input limiter circuit, NFC (when appropriate), filter bank, wide-dynamic range compression (WDRC), multichannel output compression, and a broadband output limiter. Table 3 describes the compression characteristics for the hearing aid simulator. All compression characteristics are referenced to the American National Standards Institute (ANSI; 2009) standard. The gain control circuit was implemented using Equation 8.1 of Kates (2008)

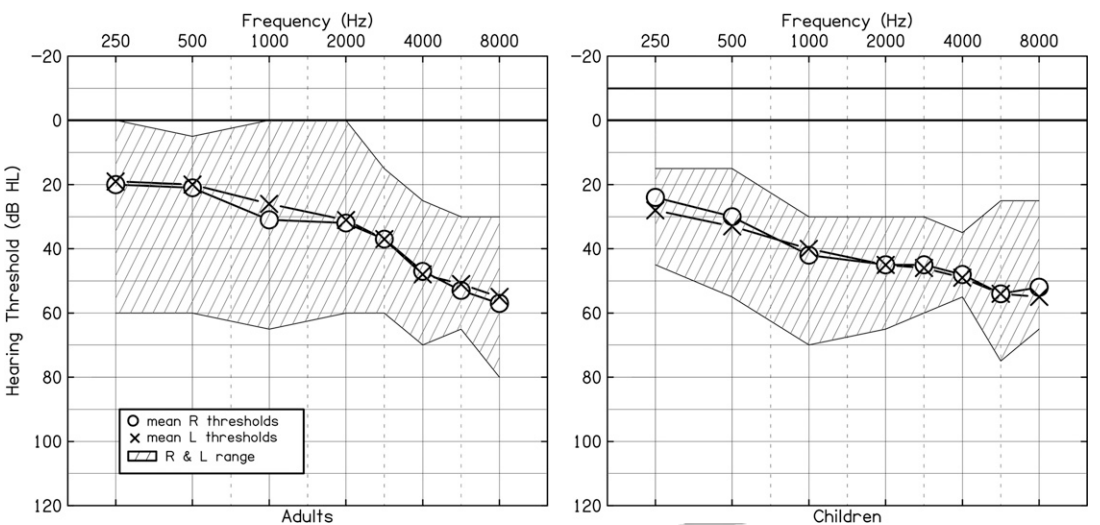

Figure 1. Mean hearing thresholds for the left ear (X) and the right ear (O) for the adults (left) and children (right). The shaded area represents the range of hearing thresholds.

Table 1. Participant Demographics, Adults

						Hearing Aid Simulator Information							
						Right				Left			
ID	Age (yr)	Age ID	Amp (yr)	Type	Music Exp	MAF (RBW)	SF	CR	MAF (NFC)	MAF (RBW)	SF	CR	MAF (NFC)
1A	63	53	NA	None	2	5000	3800	2.6	8240	5000	3800	2.6	8240
2A	24	0	1	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
3A	54	21	47	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
4A	56	53	NA	None	1	5000	3800	2.6	8240	5000	3800	2.6	8240
5A	64	58	NA	None	1	5000	3800	2.6	8240	5000	3800	2.6	8240
6A	38	8	9	WDRC	2	5000	3800	2.6	8240	5000	3800	2.6	8240
7A	57	56	NA	None	2	5000	3800	2.6	8240	5000	3800	2.6	8240
8A	64	45	NA	None	1	4000	2700	2.3	6960	4000	2700	2.3	6960
9A	59	9	35	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
10A	60	45	NA	None	2	5000	3800	2.6	8240	5000	3800	2.6	8240
11A	56	25	NA	None	2	5000	3800	2.6	8240	5000	3800	2.6	8240
12A	61	61	NA	None	1	5000	3800	2.6	8240	5000	3800	2.6	8240
13A	65	48	55	WDRC	2	5000	3800	2.6	8240	5000	3800	2.6	8240
14A	62	62	NA	None	2	5000	3800	2.6	8240	5000	3800	2.6	8240
15A	58	58	NA	None	2	5000	3800	2.6	5899	5000	3800	2.6	8240
16A	19	10	NA	None	1	4000	2700	2.3	6960	4000	2700	2.3	6960

Notes: Age ID = age that hearing loss was identified. Amp = age at which amplification was provided. For music experience 1 = 0–4 years of music lessons, 2 = 5–10 years of music lessons. CR = frequency compression ratio; exp = experience; MAF = maximum audible frequency; NA = not applicable (in the Amp column this indicates participants who do not wear hearing aids), NK = not known; NT = ear not tested; NFC = nonlinear frequency compression with WDRC; SF = start frequency.

$$
\begin{aligned}
&if\,|x(n)| \geq d(n-1)\\
&d(n) = \alpha d(n-1) + (1-\alpha)|x(n)|\\
&else\\
&d(n) = \beta d(n-1)\\
&end
\end{aligned}
\tag{1}
$$

where n is the sampling time point, $x(n)$ is the acoustic input signal, $d(n)$ is the local mean level used to generate the gain signal which was applied to $x(n)$ to form the output signal, α is a constant derived from the attack time, and β is a constant derived from the release time. Gain decreased when the signal level increased and increased when the signal level decreased.

When NFC was used, two output signals were formed by separate application of low-pass and high-pass filters to the signal, with the cutoff frequency equal to the start frequency. The high-pass signal was processed using

Table 2. Participant Demographics, Children

						Hearing Aid Simulator Information							
						Right				Left			
ID	Age (yr)	Age ID	Amp (yr)	Type	Music Exp	MAF (RBW)	SF	CR	MAF (NFC)	MAF (RBW)	SF	CR	MAF (NFC)
1C	16	1	NA	None	1	5000	3800	2.6	8240	5000	3800	2.6	8240
2C	15	0	3	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
3C	11	4	4	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
4C	10	0	2	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
5C	16	NK	NA	None	1	5000	3800	2.6	8240	5000	3800	2.6	8240
6C	9	NK	NA	NFC	1	NT	NT	NT	NT	5000	3800	2.6	8240
7C	12	3	3	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
8C	8	0	7	NFC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
9C	11	9	8	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
10C	12	5	5	NFC	1	NT	NT	NT	NT	5000	3800	2.6	8240
11C	9	4	4	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
12C	9	4	4	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
13C	15	0	0	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
14C	11	0	3	WDRC	1	5000	3800	2.6	8240	5000	3800	2.6	8240
15C	14	5	12	WDRC	1	NT	NT	NT	NT	5000	3800	2.6	8240
16C	12	4	5	WDRC	2	5000	3800	2.6	8240	5000	3800	2.6	8240

Note: See Table 1 caption for detailed explanation.

Table 3. Hearing Aid Simulator Settings

Circuit	Settings
Input Limiter	1 msec attack time, 50 msec release time, 10:1 CR, 105 dB SPL CT
Filter Bank	8 overlapping channels with center frequencies and, in parenthesis, cutoff frequencies (–6 dB) of 0.25 (0, 0.36), 0.4 (0.28, 0.56), 0.63 (0.42, 0.81), 1 (0.78, 1.24), 1.6 (1.24, 1.99), 2.5 (1.99, 3.16), 4 (3.17, 5.03), and 6.3 (5.03, Nyquist) kHz
WDRC	5 msec attack time, 50 msec release time, CRs and CTs as prescribed by DSL, linear amplification provided below the CTs
BOLT/Output Limiter	1 msec attack time, 50 msec release time, 10:1 CR, CTs as prescribed by DSL

Notes: BOLT = broadband output limiting threshold; CR = compression ratio; CT = compression threshold.

overlapping blocks of 256 samples. Blocks were windowed in the time domain using the product of a Hamming and a sinc function. Magnitude and phase information at 32-sample intervals were obtained by submitting this 256-point window to the spectrogram function in MATLAB with 224 points of overlap (7/8) and 128 points used to calculate the discrete Fourier transforms. The instantaneous frequency, phase, and magnitude of each frequency bin above the start frequency, spanning a ~4.5 kHz region, was used to modulate sine-wave carriers using the following equation adopted from Simpson et al (2005)

$$F_{out} = (SF^{1-1/FCR})x(F_{in}^{(1/FCR)}) \quad (2)$$

where F_{out} = output frequency, SF = start frequency, FCR = frequency-compression ratio, and F_{in} = instantaneous input frequency.

DSL Settings

For each participant, the Desired Sensation Level (DSL) algorithm v.5.0a (Scollie et al, 2005) generated the prescribed settings for the real-ear aided response for average conversational speech (65 dB SPL), compression threshold, compression ratio, and maximum power output that were used to program the simulator. Absolute threshold in dB SPL at the tympanic membrane for each listener was estimated using a transfer function of the TDH 50 earphones (used for the audiometric testing) on an IEC 711 Zwislocki Coupler and KEMAR (Knowles Electronic Manikin for Acoustic Research; Burkhard and Sachs, 1975). These thresholds were subsequently entered into the DSL program. DSL settings were generated for a BTE hearing aid style with 8-channel WDRC, no venting, and no binaural correction. The recommended real-ear aided-response targets were used for the two age groups, which were lower for the adult prescription than for the pediatric prescription. Because DSL does not provide a target sensation level (SL) at 8 kHz, the target SL at 6 kHz was used for 8 kHz. To prevent an unusually steep frequency response, the resultant target level was limited to the level of the 6000 Hz target plus 10 dB.

Simulator

The output for each participant was adjusted using two iterations of the following steps. Gain for each channel was automatically tuned to targets using the "Carrot Passage" from Audioscan (Dorchester, ON). Specifically, the 12.8 sec speech passage was analyzed using one-third octave filters specified by ANSI S1.11 (ANSI, 2004). A transfer function for the headphones used in this study (Sennheiser HD-25, Ireland) on an IEC 711 Zwislocki Coupler and KEMAR was used to estimate the real-ear aided response. The resulting long-term average speech spectrum was then compared with the prescribed DSL m(I/O) v5.0a targets for a 60 dB SPL presentation level. The average level per WDRC channel was computed by averaging, for each channel, the levels for the one-third octave filters that fell within that particular channel. The level instead of the power was averaged to more closely mimic what would be done in the clinic. In the clinic, the clinician can take an average when "eyeballing" the match to target. Maximum gain was limited to 65 dB, and minimum gain was limited to 0 dB (after accounting for the headphone transfer function). To prevent summation due to filter overlap, gain for channels centered below 500 Hz were decreased by 9 dB.

Figure 2 depicts the fit-to-target data. These data were derived by computing the output level for the "carrot passage" for each frequency band using one-third octave-wide filters based on the ANSI (2004) standard and then subtracting the DSL target level from the level of the carrot passage. The values for the left and right ears were averaged, except for those fitted monaurally. For adults, the mean deviations from target were 3.6, –0.8, 1.2, and 0.6 dB at 0.5, 1, 2, and 4 kHz, respectively. For children, the mean deviations from target were 1.0, –1.3, 1.2, and 1.3 dB at 0.5, 1, 2, and 4 kHz, respectively. The greatest variability occurred at 250 Hz with the adults. This occurred because DSL sometimes prescribed gain less than 0 dB when hearing thresholds were normal for the adults and gain in the hearing aid simulator was prevented from going below zero dB, which occasionally resulted in a poor fit-to-target value.

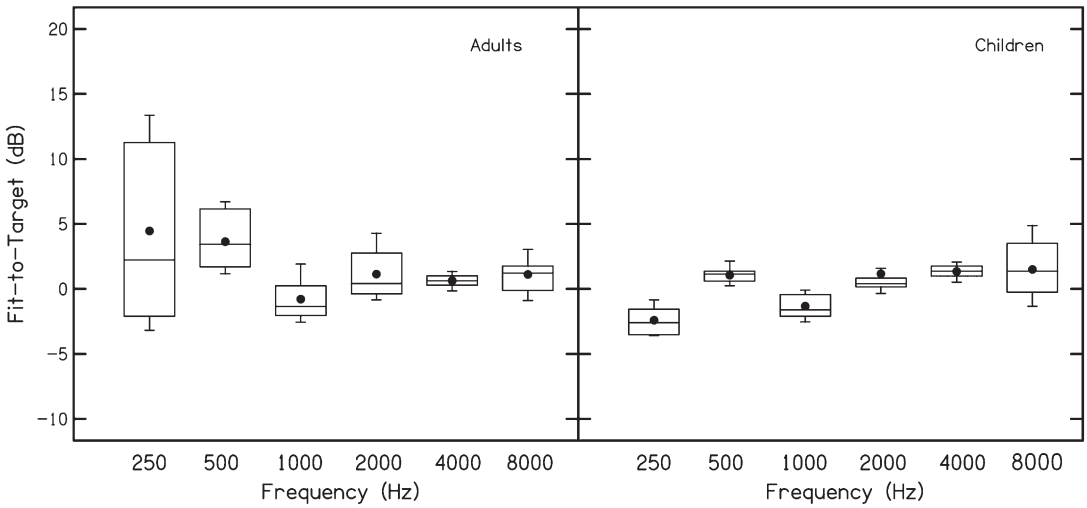

Figure 2. Fit-to-target (difference between hearing aid output and DSL target level for adults (left panel) and children (right panel). Positive numbers indicate that the output was higher than the target level. For this and remaining box and whisker plots, boxes represent the interquartile range and whiskers represent the 10th and 90th percentiles. For each box, lines represent the median and filled circles represent the mean scores.

RBW, EBW, and NFC settings

The simulator was programmed for three different conditions: RBW, EBW, and NFC. For the RBW and NFC conditions, 0 dB gain was applied above 5 kHz and a 1024-tap low-pass filter was applied at 5000 Hz that reduced the output by 80–100 dB at 5500 Hz. For the EBW condition, the antialiasing filter limited the highest frequency to approximately the Nyquist frequency (11.025 kHz). The maximum input frequency with NFC was set individually and was limited in the simulator to that available in the Phonak Naída SP (10 kHz or 4.5 kHz above the start frequency, whichever was lower). As is the case with the commercial implementation of NFC, the start frequency and compression ratio were selected from a predetermined set of combinations provided by the iPFG v2.0 (Phonak LLC, Chicago, IL) fitting software. The combinations consisted of those available in the fitting software and two interpolated combinations. The start frequency and compression ratio combination selected for each participant were based on a method described in Alexander (2013) and McCreery et al (2013), which gives highest priority to maximizing the bandwidth following NFC. Two steps were used to estimate audibility with NFC:

1. The first step determined the highest frequency that the hearing aid simulator could make audible to the participant *without* NFC (maximum audible frequency with RBW). This was operationally defined as the frequency where the participant's threshold intersected the amplified LTASS (shown in Figure 3 for a representative participant). One-third octave filters were used to analyze the LTASS.
2. The second step determined the highest frequency that the hearing aid simulator could make audible to the participant *with* NFC (maximum audible frequency with NFC). This was accomplished by using the SoundRecover Fitting Assistant v1.10 (Joshua Alexander, Purdue University, IN). The SoundRecover Fitting Assistant estimates the maximum audible frequency with NFC by calculating the input frequency that would be lowered to the same frequency as the maximum audible frequency with RBW. That estimate is based on measurements that were taken with actual hearing aids, including the Naída SP (the same hearing aid that was used to select the available NFC settings for the current study).

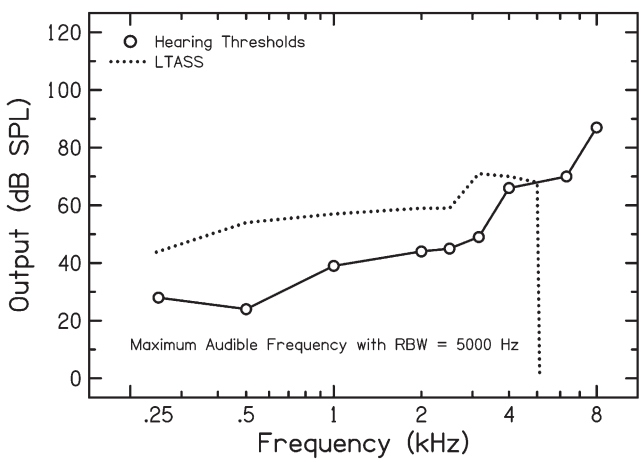

Figure 3. Amplified LTASS for a representative participant. The dashed line represents the amplified LTASS and the circles represent behavioral thresholds. The frequency at which the thresholds intersect the LTASS is the maximum audible frequency for restricted bandwidth (RBW: for this participant 5000 Hz).

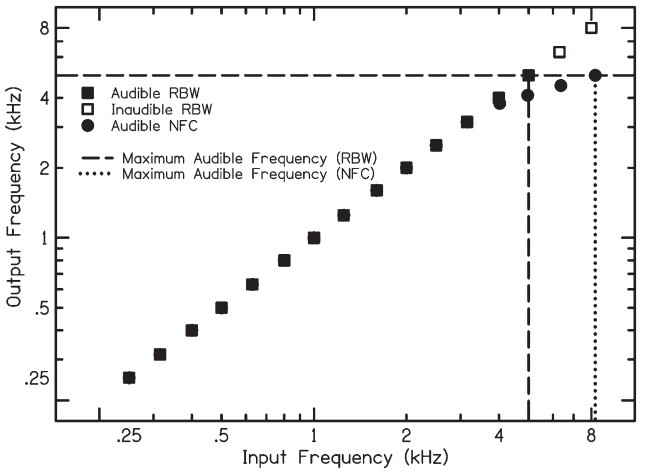

Figure 4. Frequency input/output function for the same representative participant as for Figure 3. The maximum audible frequency with RBW was 5000 Hz. The output frequency as a function of the input frequency with NFC is displayed for a 3.8 kHz start frequency and a 2.6 compression ratio. The maximum audible frequency with NFC for this listener was 8240 Hz.

The program also plots a frequency input-output function, as depicted in Figure 4 for the same representative participant used for Figure 3. The horizontal dashed line at 5000 Hz represents the participant's maximum audible frequency. Open symbols above that line represent frequencies that are inaudible, whereas the filled symbols below it represent audible frequencies. The circles and squares represent the output frequency as a function of the input frequency for the selected RBW and NFC settings, respectively. The vertical dashed lines represent the maximum audible frequency for the RBW (5000 Hz) and NFC (8240 Hz) conditions. For each participant, frequency input-output functions for different combinations of start frequencies and compression ratios were plotted. To avoid "strong" NFC settings, combinations that restricted the output frequency to a frequency that was less than 7% of that participant's maximum audible frequency with RBW (determined in step 1) were *not* considered. The combination that resulted in the highest maximum audible frequency with NFC was then selected. In the rare case that multiple combinations fit these criteria, the combination with the highest start frequency was used in order to minimize potential spectral distortion of vowel formants. Using this procedure allowed us to document the highest frequency that was audible with NFC, prevent excessive spectral distortion, and place the output with NFC within each listener's audible bandwidth.

Audibility for the high frequencies with EBW, RBW and NFC is shown in Figure 5. Results for speech and music are in the left and right columns, respectively, and results for children and adults are in the top and bottom rows, respectively. To calculate the SL, first the SPL for frequency bands one-third octave wide (ANSI, 2004) was computed for each stimulus. Second, each participant's absolute thresholds in dB HL were interpolated to the center frequencies for one-third octave wide filters (Pittman and Stelmachowicz, 2000). These thresholds were converted to dB SPL (Bentler and Pavlovic, 1989), adjusted to account for the internal noise spectrum (ANSI, 1997) and transformed to one-third octave band levels (Pavlovic, 1987). Fourth, the dB SL was computed for each stimulus by subtracting threshold from the stimulus level, and then the mean level across stimuli was computed.

Procedure

Sound files from the output of the hearing aid simulator were presented using custom software on a personal computer. They were converted from a digital to an analog signal using a Lynx Studio Technology Lynx Two B sound card (Costa Mesa, CA), routed using a MiniMon Mon 800 monitor matrix mixer (Behringer, Germany), amplified with a PreSonus HP4 headphone preamplifier (Baton Rouge, LA), and delivered to the participants via Sennheiser HD-25 headphones. The participants were seated in an audiometric sound booth in front of a touchscreen monitor, which was used by each participant to indicate the preferred condition. Participants were instructed to select the interval that contained the clearest speech or the interval that contained the best-sounding music. To assist the children in understanding the term *clarity*, a visual demonstration was provided on the touch-screen monitor to all participants. The visual demonstration consisted of eight pairs of pictures, one of each pair with higher resolution and the other with lower resolution. Each participant was instructed to point to the picture that was clearer.

Using a round-robin procedure, we made paired comparisons for the three processing conditions (EBW/RBW, NFC/RBW, EBW/NFC). For each trial, if the participant chose the condition that resulted in higher audibility (EBW to RBW, NFC to RBW, or EBW to NFC), then the preference was recorded as a 1. Otherwise, the preference was recorded as a 0. Participants were provided with a practice session for each of the music and speech conditions. The order of these comparisons was counterbalanced across participants within a stimulus type. The stimuli were blocked by processing comparison with the music condition run first, followed by the speech condition. Within a block, the order of the type of processing (e.g., EBW/RBW or RBW/EBW) was randomly assigned for each trial. Each participant listened to 2 trials of 15 speech and 8 music passages for each processing comparison for a total of 138 comparisons (2 trials, 3 processing comparisons, 15 speech and 8 music passages).

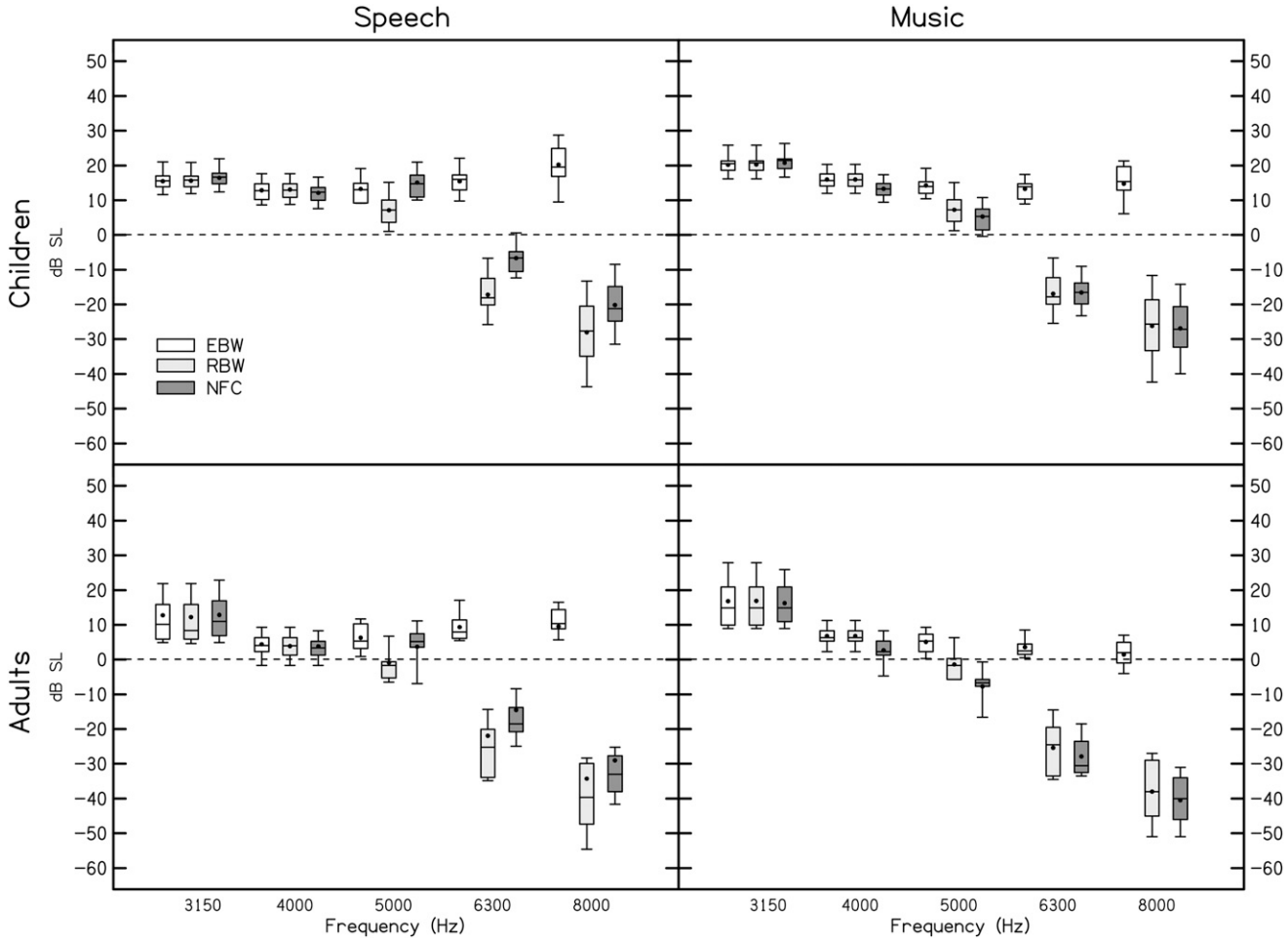

Figure 5. SL in dB for children (top row) and adults (bottom row). The left column shows SL for speech and the right column depicts SL for music. Sensation level with NFC was computed based on the output frequency. To conserve space, the SLs for frequencies below 3150 Hz were omitted because the SL was identical across the three types of processing.

Analysis

Mean preference for each comparison was calculated by averaging preference across the trial data for each participant. The mean preference data were normally distributed about the mean. To determine if preference differed with processing comparison, stimulus condition, or age, results were subjected to a mixed-model analysis of variance (ANOVA) where the within-participant factors were processing comparison (EBW/RBW, NFC/RBW, EBW/NFC) and stimulus condition (music, speech) and the between-participants factor was age group (children, adults). Thus, the ANOVA informed us if the mean preference differed by processing comparison, stimulus condition (music, speech), or age group (children, adult). The ANOVA did not inform us if the mean preference differed significantly from no preference (0.5) or how many participants showed a preference for one type of processing over another.

To determine which type of processing the participants preferred for each processing comparison, one-sampled a priori t-tests were used to establish if preference significantly differed from chance. The number of participants exhibiting a preference was evaluated by assuming a binomial distribution (participants could only choose one option per comparison). The SD of the binomial distribution is $\frac{\sqrt{p \times q}}{\sqrt{n}}$ where p is the preference score, q is the preference for the other strategy (1-p), and n is the number of comparisons. The confidence interval was calculated for each participant in each condition by multiplying the resultant binomial distribution by 1.96 (value of the 97.5 percentile point for a normal distribution, which for this two-tailed test gives the 95% confidence interval). If the confidence interval did not overlap 0.5 (no preference), then it was concluded that the participant had a reliable preference for one strategy versus another.

The consistency of listeners' preferences across comparisons was assessed qualitatively by constructing bar plots and statistically by using Pearson correlations. The data also were analyzed to determine if

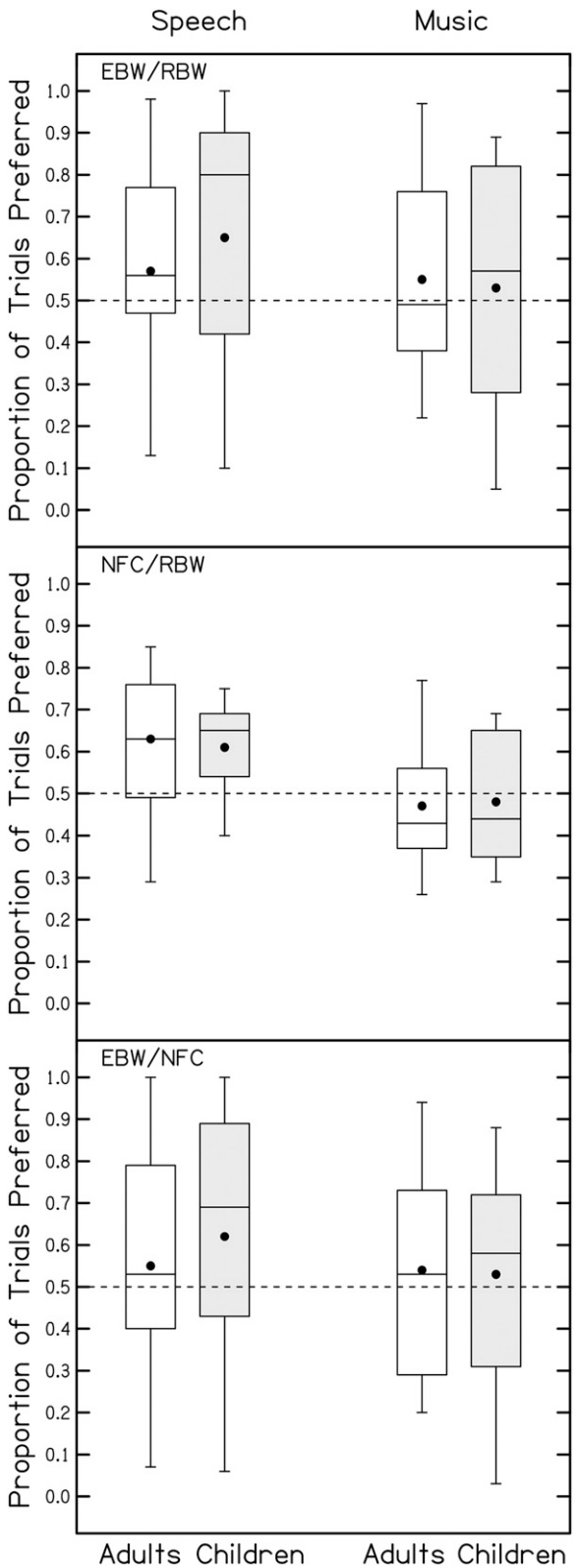

Figure 6. Proportion of trials preferred for EBW vs. RBW (top panel), NFC vs. RBW (middle panel) and EBW vs. NFC (bottom panel). Speech is shown in the left column and music is shown in the right. The unshaded boxes depict results for the adults and the shaded boxes depict results for the children.

high-frequency hearing loss (calculated PTA threshold for 4, 6, and 8 kHz) predicted preference ratings. Pearson correlations determined if PTA was associated with preference ratings.

RESULTS

Figure 6 depicts the proportion of times that participants preferred EBW compared with RBW, NFC compared with RBW, and EBW compared with NFC (top, middle, and bottom panels, respectively). For the comparisons with EBW, a proportion greater than 0.5 means that participants preferred EBW more often than they did the other type of processing (RBW or NFC). Similarly, for the comparison of NFC with RBW, a proportion greater than 0.5 indicates that NFC was preferred more often than RBW. The between-participants factor of age group was not statistically significant [$F_{(1,30)} = 0.091$, $p = 0.765$, $\eta_p^2 = 0.003$]. The main effect of stimulus condition $F_{(1,30)} = 8.543$, $p = 0.007$, $\eta_p^2 = 0.222$ was significant, with the mean proportion higher for speech (M = 0.61, SD = 0.26) than for music (M = 0.52, SD = 0.24). The main effect of processing comparison $F_{(2,60)} = 0.265$, $p = 0.768$, $\eta_p^2 = 0.009$ was not significant. The two-way interactions of stimulus condition with age group [$F_{(1,30)} = 0.691$, $p = 0.412$, $\eta_p^2 = 0.023$]; processing comparison with age group [$F_{(2,60)} = 0.107$, $p = 0.899$, $\eta_p^2 = 0.009$]; stimulus condition with processing comparison [$F_{(2,60)} = 1.489$, $p = 0.234$, $\eta_p^2 = 0.047$]; and the three-way interaction of stimulus condition, age group, and processing comparison [$F_{(2,60)} = 0.879$, $p = 0.420$, $\eta_p^2 = 0.028$] were not significant. These results demonstrate that, on average, the participants preferred EBW to NFC, EBW to RBW, and NFC to RBW equally. Children and adults had equivalent preferences. Participants more frequently preferred EBW to NFC, EBW to RBW, and NFC to RBW for speech than for music.

One-sampled *t*-tests were used to determine if participants significantly preferred EBW to NFC, EBW to RBW, and NFC to RBW for speech or music. Because the effect of age on preference was not significant, data were collapsed across age. For speech, participants significantly preferred EBW to RBW [$t_{(31)} = 2.106$, $p = 0.043$] and NFC to RBW [$t_{(31)} = 4.694$, $p < 0.001$] but not EBW to NFC [$t_{(31)} = 1.654$, $p = 0.108$]. For music, participants did not show a preference for EBW to RBW [$t_{(31)} = 0.862$, $p = 0.395$], NFC to RBW [$t_{(31)} = -0.904$, $p = 0.373$], or EBW to NFC [$t_{(32)} = 0.671$, $p = 0.507$]. These results demonstrate that participants preferred greater access to high-frequency information (EBW or NFC to RBW) for speech. Otherwise, participants did not demonstrate a preference.

The number of participants who showed a preference is depicted in Figure 7. More participants showed a preference with speech than with music. Although more

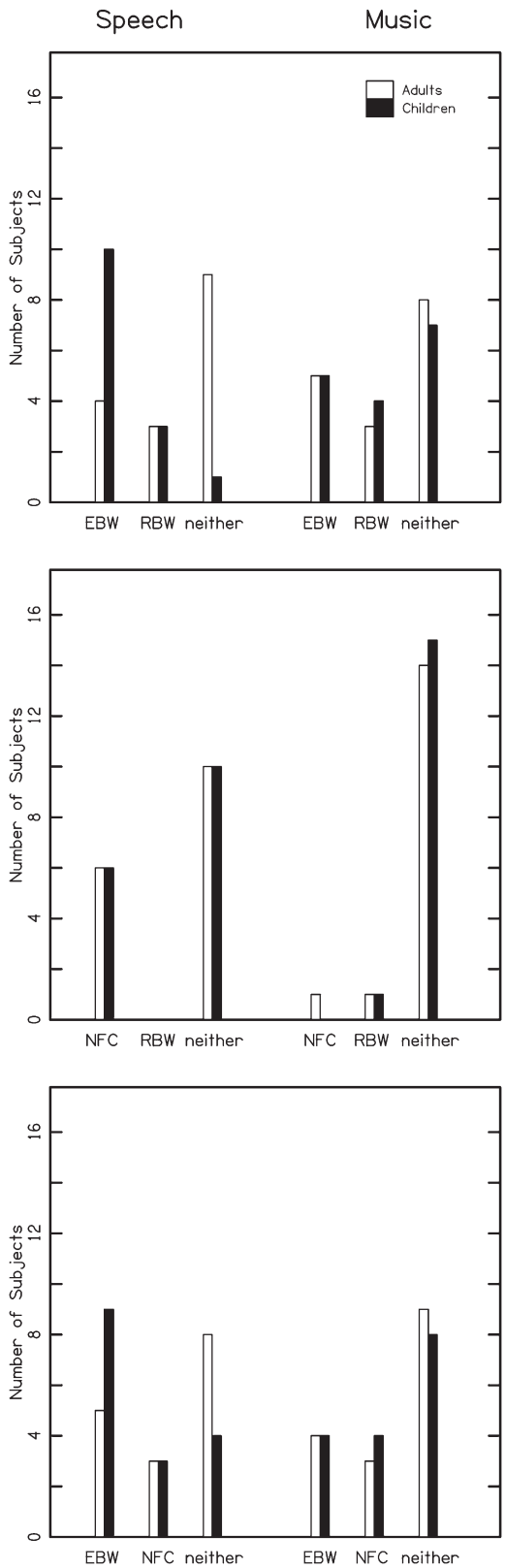

Figure 7. Number of participants with a preferred processing condition when comparing EBW vs. RBW (top panel), NFC vs. RBW (middle panel) and EBW vs. NFC (bottom panel). Speech is shown in the left column and music is shown in the right.

participants preferred access to high-frequency sounds (e.g., preferred EBW to RBW, NFC to RBW, and EBW to NFC), some participants showed the opposite preference or no preference.

The consistency of preferences was assessed by constructing bar plots (Fig. 8). The order of the participants is the same in each bar plot and was arranged based on their preference score for EBW compared with RBW for speech (upper left panel). Listeners who preferred EBW to RBW for speech also tended to prefer EBW to RBW for music [$r_{(32)} = 0.613, p < 0.001$]. These same listeners also tended to prefer EBW to NFC for both speech [$r_{(32)} = 0.864, p < 0.001$] and music [$r_{(32)} = 0.489, p = 0.004$]. A listener's preference for EBW to RBW for speech *did* predict their preference for NFC to RBW for speech [$r_{(32)} = 0.425, p = 0.015$] but *not* for music [$r_{(32)} = -0.013, p < 0.944$].

PTA was associated with preference for comparisons with music. Specifically, listeners with better PTA preferred EBW to RBW [$r_{(32)} = -0.411, p = 0.019$] and EBW to NFC [$r_{(32)} = -0.410, p = 0.020$]. Listeners with poorer PTA preferred NFC to RBW [$r_{(32)} = 0.357, p = 0.045$]. PTA did not predict preference for speech ($-0.209 \leq r \leq -0.147$, $0.250 \leq p \leq 0.421$). These results demonstrate that (1) listeners were reasonably consistent in their preference for (or against) audibility of the high frequencies with EBW and (2) the degree of high-frequency hearing loss was associated with preference.

DISCUSSION

Participants preferred EBW and NFC to RBW for speech, but otherwise did not show clear preferences overall. This is consistent with the hypothesis that participants will prefer the condition with the widest bandwidth. The present study is compatible with the extant literature with adults that found that listeners with hearing loss prefer EBW to RBW (Ricketts et al, 2008; Füllgrabe et al, 2010), when listeners have sufficient audibility of the signal. The results of this study also are consistent with previous research which found that listeners with better hearing in the high frequencies, as measured by the slope of the audiogram, were more likely to prefer EBW to RBW (Ricketts et al, 2008; Moore et al, 2011). Previous studies have determined that preference for EBW to RBW can increase for some participants when gain is decreased, with the caveat that audibility must be maintained (Moore et al, 2011). This trend suggests that participants in this study might have expressed a stronger preference for EBW if we used less gain than that prescribed by DSL.

In the present study, listeners also showed a slight preference for NFC to RBW. This occurred despite the potential for spectral distortion caused by NFC. This pattern is consistent with other studies of preference and

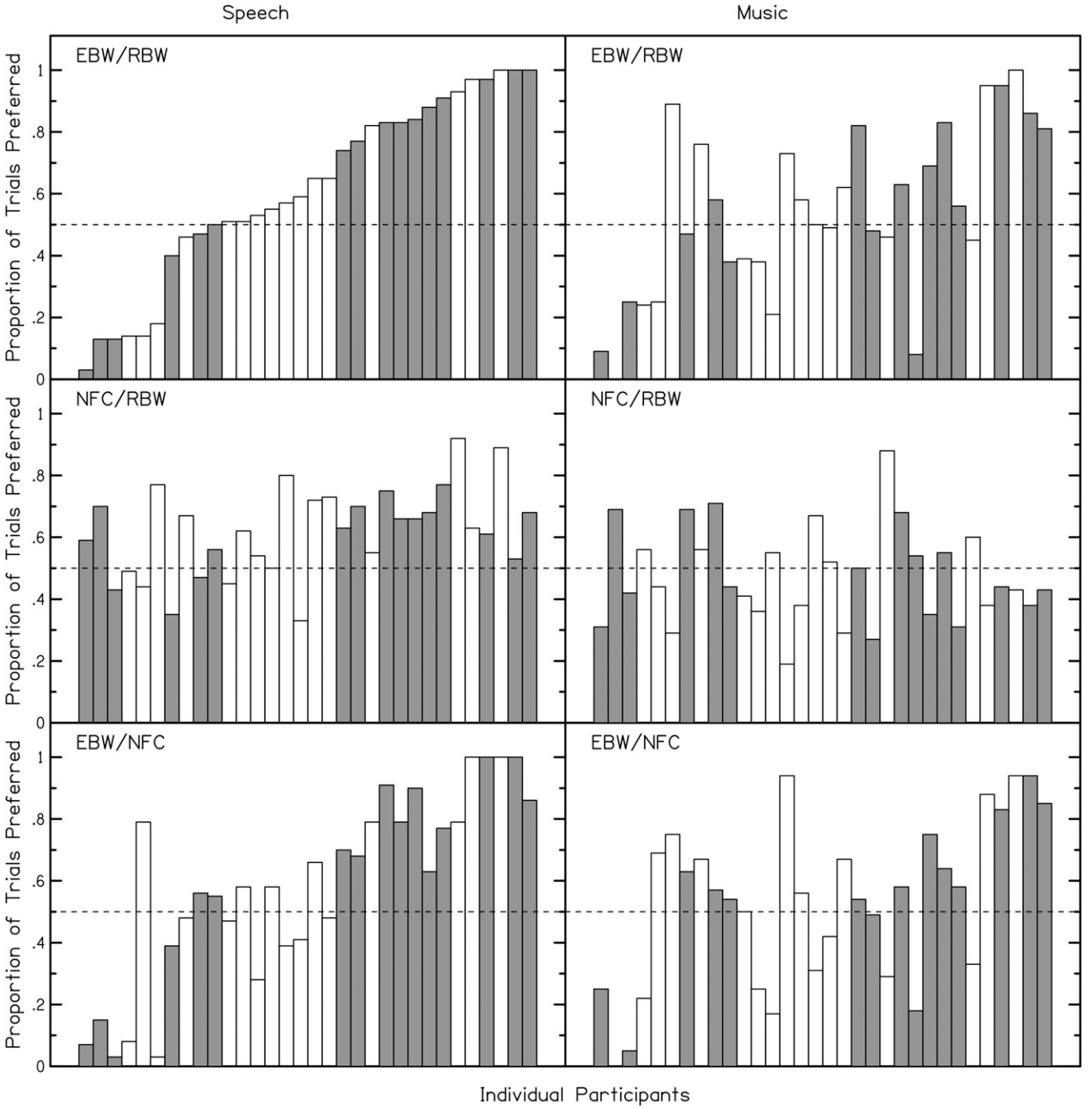

Figure 8. Preference ratings. Participants are rank ordered by preference for EBW vs. RBW with speech in the top-left panel. Results for speech and music conditions are shown in the left and right columns, respectively. The same order of participants was maintained for the remaining plotted comparisons. Unshaded bars represent adult data and shaded bars represent child data.

speech perception that selected the minimum NFC settings necessary to achieve audibility (Glista et al, 2009; Wolfe et al, 2010, 2011; Glista et al, 2012). Studies that found a preference for RBW to NFC (Simpson et al, 2006; Parsa et al, 2013; Souza et al, 2013) did not quantify audibility of the compressed portion and may have selected NFC settings that did not result in greater audibility or may have used stronger NFC settings (lower start frequencies, higher compression ratios) without giving more audibility than weaker NFC settings and at the cost of spectral distortion. Using speech recognition instead of preference as the outcome measure, Souza et al (2013) found that listeners with greater PTA were more likely to show improved speech recognition with NFC. Together, the findings of the current study and the study by Souza and colleagues suggest that listeners with greater high-frequency hearing loss are more likely to benefit from NFC.

Preference between EBW and NFC has not been reported previously in the literature. It was expected that the capacity for additional distortion by NFC would cause listeners to prefer EBW to NFC. Instead, this study found that listeners expressed equivalent preference for EBW and NFC. Listeners with less hearing loss, as measured by lower PTA, were more likely to prefer EBW to NFC. This, combined with the findings of Souza et al (2013), suggests that the increased distortion caused by NFC is offset by the increased audibility for listeners with greater hearing loss.

We also found that more listeners expressed a preference for EBW to RBW for speech than for music. This finding contrasts with other work in this area, which found that listeners with normal hearing preferred wider bandwidth (17 kHz) for music than for speech (11 kHz: Moore and Tan, 2003). If the present study had used a bandwidth wider than 10 kHz, the participants might have preferred a wider bandwidth for music than for speech. It is possible that the difference in instructions to listeners across the two stimulus types ("best sounding" for music and "clearest" for speech) influenced the results. Füllgrabe et al (2010) found that their listeners with hearing loss preferred RBW to EBW for pleasantness but preferred EBW for clarity. The direction of our finding is consistent with that of Füllgrabe and colleagues, in that ratings of clarity with speech were higher than those for "best sounding" for music. Because the music condition was followed by the speech condition, these results cannot inform us about whether the order of presentation influenced the findings. It is expected that if there was an order effect, the listeners would have been more likely to show a preference as they gained more experience. Instead, listeners expressed a preference for speech, which was the first stimulus condition, but not for music, which was second stimulus condition. The present study also used a wide range of music samples, which may have introduced greater variability in preference for music than for speech across participants than if a more limited number of music samples had been used.

Age did not influence preference in this study, despite research indicating that children require greater access to high-frequency sounds than adults in order to maintain equivalent speech understanding (Stelmachowicz et al, 2001). In this study, consistent with clinical practice, children were fit using a prescriptive method that resulted in a greater SL than the method used to fit the adults. Providing the children with the higher SL that they require may have resulted in equivalent judgments for the two age groups. Our findings contrast with those of Glista et al (2009), who found that children preferred NFC to RBW more often than adults despite also using separate DSL prescriptive approaches for children and adults. One possible difference was that the present study maintained similar bandwidth with NFC across the two age groups, whereas the bandwidth is unknown for the listeners who participated in the study by Glista and colleagues. Our results would suggest that differences in preference between adults and children might be eliminated when the children are provided with greater audibility and similar bandwidth.

Although our data indicate that listeners, on average, prefer greater bandwidth with minimal distortion, these results may not generalize to all hearing aid users. First, the pattern of results might not extend to listeners with greater degrees of hearing loss who would require lower start frequencies and higher frequency-compression ratios or who cannot realistically experience audibility in the high frequencies with EBW. Second, this study asked listeners to select the conditions that they felt were clearer for speech or that sounded better for music. Measuring other dimensions, such as "sharpness," might have revealed differences in sound quality that were not obtained here. Lastly, because strength of preference was not measured, it is not known how strongly our participants preferred EBW and NFC to RBW.

Clinically, the type of processing chosen should be the one that achieves the widest bandwidth while minimizing spectral distortion. Specifically, EBW should be used if the audible bandwidth can be improved compared with RBW. Otherwise, NFC could be used to improve audibility for higher frequencies. When fitting NFC, steps should be taken to ensure audibility of the compressed portion while simultaneously minimizing potential spectral distortion. This can be achieved, as was done in the present study, by selecting a higher start frequency or lower compression ratio when doing so does not affect the audible bandwidth with NFC. However, the large variability observed in the present study suggests that some listeners do not have a preference or may prefer a lower bandwidth (see Figures 6 and 7). Some of this variability was explained by PTA and suggests that listeners with greater hearing loss are more likely to prefer NFC and those with less hearing loss are more likely to prefer EBW.

CONCLUSIONS

These data suggest a preference for access to high-frequency sounds based on the observation that listeners preferred EBW and NFC to RBW. This preference occurred for speech but not for music. For music, participants with less high-frequency hearing loss were more likely to prefer EBW, whereas participants with greater high-frequency hearing loss were more likely to prefer NFC. One limitation of this study was that the listeners were restricted to those with mild to severe hearing loss. Therefore, the results should not be generalized to individuals with greater degrees of hearing loss who may require different NFC settings than those used in this study.

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Appendix

The sentences were as follows:

1. She sleeps late on Saturday
2. The short path is shady
3. The juice is delicious
4. School field trips are exciting
5. Think carefully about the answer
6. Some of the mushrooms are poisonous
7. Sally slipped on the ice
8. Never dive in shallow water
9. Let's go fishing next month
10. The peach was fresh
11. The chocolate is sweet and delicious
12. Beach vacations are special
13. Some children slurp ice cream
14. Ice skating can be dangerous
15. Snakes like to slither

The music passages were excerpts from the following CDs:

Artist	Album	Song	Label
Beatles	The Beatles	Ob-La-Di	Apple
Page O'Hara	Beauty and the Beast Soundtrack	Belle Reprise	Walt Disney
Mary McLaughlin	Daughter of Lir	You Saw His Eyes	Gourd Music
Not Available	The Greatest Works of Mendelssohn Handel	Allegro	Kalmus Music and Company Incorporated
James Taylor	In the Pocket	Shower the People	Warner Brothers
Vince Guaraldi Trio	Jazz for Peanuts	Linus and Lucy	Peak Records
Matthew Good	Vancouver	The Vancouver National Anthem	Universal Music Canada
Jackson 5	Greatest Hits	Never Can Say Goodbye	Motown