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*Published in:*  
Journal of Speech, Language, and Hearing Research

*Link to article, DOI:*  
[10.1044/2020\\_JSLHR-20-00271](https://doi.org/10.1044/2020_JSLHR-20-00271)

*Publication date:*  
2020

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Van Eeckhoutte, M. C., Scollie, S., O'Hagan, R., & Glista, D. (2020). Perceptual Benefits of Extended Bandwidth Hearing Aids With Children: A Within-Subject Design Using Clinically Available Hearing Aids. *Journal of Speech, Language, and Hearing Research*, 63(11), 3834-3846. [https://doi.org/10.1044/2020\\_JSLHR-20-00271](https://doi.org/10.1044/2020_JSLHR-20-00271)

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## Research Article

# Perceptual Benefits of Extended Bandwidth Hearing Aids With Children: A Within-Subject Design Using Clinically Available Hearing Aids

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**Purpose:** The aim of the study was to investigate the achieved audibility with clinically available, modern, high-end, behind-the-ear hearing aids fitted using the Desired Sensation Level v5.0 child prescription for a clinical sample of children with hearing impairment and the effect of the extended bandwidth provided by the hearing aids on several outcome measures.

**Method:** The achieved audibility was measured using the maximum audible output frequency method. Twenty-eight children (7–17 years old) with mild to severe hearing losses completed this study. Two hearing aid conditions were fitted for each participant: an extended bandwidth condition, which was fitted to targets as closely as possible, and a restricted bandwidth condition, for which aided output was restricted above 4.5 kHz. Consonant discrimination in noise, subjective preference, aided loudness growth, and preferred listening levels were evaluated in both conditions.

**Results:** The extended bandwidth hearing aid fittings provided speech audibility above 4.5 kHz for all children, with an average maximum audible output frequency of 7376 Hz ( $SD = 1669$  Hz). When compared to a restricted bandwidth, the extended bandwidth condition led to an improvement of 5.4% for consonant discrimination in noise scores, mostly attributable to /s/, /z/, and /t/ phoneme perception. Aided loudness results and preferred listening levels were not significantly different across bandwidth conditions; however, 65% of the children indicated a subjective preference for the extended bandwidth.

**Conclusion:** The study suggests that providing the full bandwidth available, with modern, behind-the-ear hearing aids, leads to improved audibility, when compared to restricted bandwidth hearing aids, and that it leads to beneficial outcomes for children who use hearing aids, fitted to the Desired Sensation Level v5.0 child prescription, without causing significant increases in their loudness perception.

In the early 2000s, hearing aids provided maximum achievable audibility to 5–6 kHz at most (Moore et al., 2001; Stelmachowicz et al., 2004). Today, hearing aids are generally specified as being able to provide a greater bandwidth than this, which may translate to greater audibility. This limited bandwidth was proposed as a contributing factor in delays of speech recognition, fricative production, and phonological development in children with hearing loss, particularly when listening to female speech (Moeller et al., 2007; Stelmachowicz et al., 2001, 2004). In some languages, including English, the /s/ and /z/ high-frequency fricatives are used for possession, plurality, and tense markers (Glista & Scollie, 2012; Mines et al., 1978; Stelmachowicz et al., 2004). Consequently, access to an extended bandwidth (EBW) of speech is often recommended (e.g., American Academy of Audiology [AAA], 2013). Provision of an audible band of speech that extends to the 9-

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Editor-in-Chief: Frederick (Erick) Gallun

Editor: Christian E. Stilp

Received May 19, 2020

Revision received July 17, 2020

Accepted July 31, 2020

[https://doi.org/10.1044/2020\\_JSLHR-20-00271](https://doi.org/10.1044/2020_JSLHR-20-00271)

**Disclosure:** The authors have declared that no competing interests existed at the time of publication.

10-kHz range has been extensively studied in laboratory settings using hearing aid simulators or by examining individual differences in bandwidth across participants. These approaches have limitations for predicting real-world performance, and individual differences across participants can be confounded by differences in audiometric configuration, listening experience, or both. A review article by Hunter et al. (2020) provides an overview of the relevance and implications of extended high-frequency hearing and speech perception, primarily focusing on the benefits for normal-hearing adults and children. For children with normal hearing and hearing loss, an EBW to about 9 kHz versus a 4- to 5-kHz setting has been associated with increased speech recognition and rates of short-term word learning, with the conclusion that children require more audibility than adults to achieve similar performance levels (Pittman, 2008; Stelmachowicz et al., 2000, 2001). Given this evidence, some practice guidelines for children recommend fitting EBW hearing aids to include 9 kHz (AAA, 2013). More recent real-world trials have indicated that long-term speech and language development may be facilitated by improved hearing aid audibility in the high frequencies (McCreery et al., 2017).

EBW in hearing aids may impact hearing aid outcomes in a variety of perceptual domains, including speech recognition, loudness, sound quality, and subjective measures of preference and acceptable noise level. Considering speech recognition, early studies in adults reported a degradation in speech recognition with EBWs for listeners whose thresholds exceeded 80 dB HL at 4 kHz (Ching et al., 1998; Hogan & Turner, 1998), while later studies have mainly shown small but beneficial effects of EBW on speech discrimination (Amos & Humes, 2007; Cox et al., 2011; Füllgrabe et al., 2010; Hornsby et al., 2011; Hornsby & Ricketts, 2003; Levy et al., 2015; Mackersie et al., 2004; McCreery & Stelmachowicz, 2011; Plyler & Fleck, 2006; Simpson et al., 2005; Turner & Cummings, 1999; Turner & Henry, 2002). Recent reports also have shown that extended high frequencies contribute to the perception of speech in noise and in challenging, more ecologically relevant situations (Monson et al., 2019; Motlagh Zadeh et al., 2019). Additional studies have considered other domains of outcome. For example, some adults report subjective preference for EBW versus restricted bandwidth (RBW; Brennan et al., 2014; Füllgrabe et al., 2010; Moore, 2012; Moore et al., 2011; Moore & Tan, 2003; Plyler & Fleck, 2006; Ricketts et al., 2008). More recently, Seeto and Searchfield (2018) reported improved detection of high-frequency phonemes in quiet with EBW versus RBW fittings in adults, with no difference in sound quality preference (Seeto & Searchfield, 2018). Subjectively, users of EBW light-driven direct-drive hearing devices had scores similar to users' own aids, with a slight improvement in the ease of communication and no change in aversiveness (Arbogast et al., 2019). These more recent adult studies illustrate the relevance of considering outcomes other than speech recognition when evaluating the impact of EBW fittings, as well as the need for further research to compare the outcomes of EBW versus RBW hearing aid fittings in children.

The provision of an EBW via modern devices yielded beneficial results in a recent multi-outcome study with adult hearing aid users (Van Eeckhoutte et al., 2020). This study demonstrated better perception of high-frequency phonemes (/s/, /z/, and /t/) in noise, with no adverse changes in loudness perception or preferred listening levels (PLLs). In terms of subjective preference, most listeners preferred the full bandwidth available (46%) or were indifferent about the provided bandwidth (33%). The outcomes of this clinical study indicated that the speech recognition benefits of EBW in wearable hearing aids were largely in line with those reported in previous studies and that the fittings were acceptable in real-world use and for aided loudness levels. All the adult participants in the study of Van Eeckhoutte et al. (2020) had mild-to-moderately severe sensorineural hearing loss and were fitted with receiver-in-canal (RIC) devices to the Desired Sensation Level (DSL) v5.0 adult prescription. While these results may be typical for adults, one might expect differences in a clinical population of aided children. First, substantial differences in audiological characteristics exist for children with hearing impairment when compared to adults, including a large mix of audiometric severities and configurations, with most variability in the higher frequencies (Pittman & Stelmachowicz, 2003). Those configuration differences might lead to a larger achieved bandwidth compared to adults with a high-frequency sloping hearing loss. Second, children are more likely to be fitted with higher levels of gain and output than is prescribed for adults, whether they are fitted with the DSL v5.0 child prescription (Scollie et al., 2005) or the NAL-NL2 prescription (Keidser et al., 2012). If enrolled in an early intervention program (Joint Committee on Infant Hearing, 2019), aided children may present with greater hearing aid experience levels, when compared to aided adults. Third, children are typically fitted with behind-the-ear (BTE) hearing aids connected to custom earmolds (AAA, 2013), which may be less likely to provide EBW compared to RIC devices that are commonly used with adults. Recently, BTE devices have been advertised by manufacturers to provide gain over a bandwidth that exceeds 10 kHz (Kimlinger et al., 2015). Measurements of audibility in the extended high-frequency range (maximum audible output frequency [MAOF]) using a range of BTE devices, audiometric configurations, and stimuli have indicated that the achievable bandwidth across commercial devices varies, with audible bandwidths from 3.5 kHz to beyond 8 kHz (Kimlinger et al., 2015). These results indicate that real-world feasibility and the impact of achieving the recommended 9-kHz bandwidth for children requires further investigation.

The aim of the current study was to (a) investigate the achievable maximum frequency of audibility with modern BTE devices with a clinical sample of children who use hearing aids and (b) investigate the effect of providing the available EBW compared to the RBW, with a multi-outcome battery that included speech sound recognition in noise, subjective preference, loudness perception, and PLLs. The outcomes were evaluated using commercially available, wearable hearing aids marketed for use with children. The

two experimental bandwidth conditions were implemented within the same hearing device to hold other device parameters constant.

## Method

### Participants

We recruited 28 children (18 boys and 10 girls) who were between 7 and 17 years old ( $M = 12.1$ ,  $SD = 2.8$  years), who reported regular use of hearing aids. The children were involved in a large study exploring multiple research questions and were tested in the Child Amplification Laboratory at the National Centre for Audiology. Most children visited the lab 5 times. The Western University Research Ethics Board granted approval for the study. Depending on the participant's age, the children signed a letter of information and consent (13–17 years old) or an assent letter (7–12 years old). The parents signed a consent form for all children. Participants received compensation for their time and were able to keep the hearing aids upon completion of the study.

Audiometric assessments were completed with all children and included otoscopy, audiometric thresholds at octave and interoctave frequencies between 0.125 and 8 kHz (GSI-61 audiometer with ER-3A insert earphones coupled to participants' own occluded earmolds), and middle ear analyses (Madsen Zodiac 901). Cerumen management and impressions for new earmolds were completed when required. All children had middle ear status within a normal tympanometric range (British Society of Audiology, 2013). The children presented with variable audiometric configurations and degrees of hearing loss (see Figure 1). The four-frequency pure-tone average (PTA; 0.5, 1, 2, and 4 kHz), averaged across ears, indicated that seven children were within the

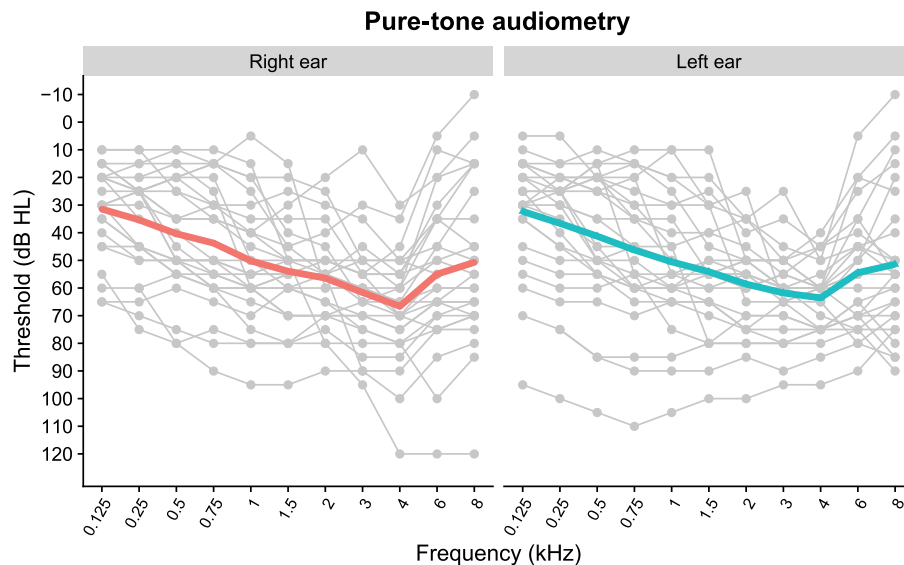
American Speech-Language-Hearing Association ranges for mild hearing loss, 11 for moderate, seven for moderately severe, and three for severe hearing loss (American Speech-Language-Hearing Association, 2015). One participant had no measurable thresholds for the test frequencies between 4 and 8 kHz in the poorer ear, and these thresholds were coded as 120 dB HL. The between-ear difference in PTA was  $\leq 15$  dB for most children, except for four who had between-ears differences between 16 and 30 dB.

### Hearing Aid Fitting and Verification

Real-ear-to-coupler differences (RECDs) were measured using personal earmolds. In some cases, an RECD from the child's clinician, obtained within a 6-month period, was accepted for use in the study.

Using the earmold audiometric thresholds and RECD values, each participant was fitted with study-worn BTE hearing aids: Phonak Sky V90 devices, which were power, superpower, or ultrapower, depending on the required fitting range. The hearing aids were fitted according to the DSL v5.0 child prescription (Bagatto et al., 2005; Scollie et al., 2005), and coupler-based verification was completed with the Audioscan Verifit 2 prior to testing. Fine tuning was completed using the International Speech Test Signal (ISTS) speech signal (Holube et al., 2010) at input levels of 55, 65, and 75 dB SPL and for tone bursts at 90 dB SPL to assess the maximum power output targets. The feedback manager was activated for three participants. All other hearing aid features were disabled. Fit-to-target deviations were within 2-dB root-mean-square error (RMSE) using 0.5, 1, 2, and 4 kHz, for speech input levels at 55, 65, and 75 dB SPL, within 4-dB RMSE when including 6 kHz and within 10 dB when including 8 kHz. These values are within the recommended

**Figure 1.** Audiometric thresholds for all 28 children measured with occluded earmolds. Individual thresholds are plotted, as well as the group mean (thick line, red and blue in the online version).



5-dB RMSE for frequencies up to 6 kHz for hearing aid fitting (Baker & Jenstad, 2017; Brennan et al., 2017; McCreery, Bentler, et al., 2013). For the maximum power output test signal, the values were within 3 dB for frequencies up to 4 kHz, within 5 dB for up to 6 kHz and within 12 dB up to 8 kHz.

Two experimental bandwidth conditions were created for this study: (a) an EBW condition, in which the full hearing aid bandwidth was provided as described above, and (b) an RBW condition, for which gain was minimized above 4.5 kHz. This condition was created by adjusting the gain handles at and above the 4.8-kHz gain handle in the manufacturer's software to the lowest possible gain setting. All other gain handles were maintained and verified according to the recommended fit to target. The EBW and RBW conditions were stored as separate programs in the hearing aids. Verification of aided output for a 65-dB SPL ISTS stimulus indicated that the EBW and RBW conditions provided aided output levels that were matched within 2, 4, and 7 dB at 4, 4.24, and 4.5 kHz and that the RBW fitting had 26 and 41 dB less output than the EBW condition at 5 and 6 kHz, respectively. The hearing aid output was measured in the test box to illustrate the difference between the EBW and RBW conditions for one participant. Figure 2 shows that the programming strategy successfully removed the high-frequency energy in the RBW condition.

To verify high-frequency audibility in the EBW condition, the MAOF was measured for the better hearing ear, according to each child's four-frequency PTA value, and by examining the verified simulated real-ear aided response for an ISTS speech input at 60 dB SPL. The highest frequency at which the child's audiometric thresholds intersected with both the peak levels (99th percentiles) of speech, and the RMS levels of speech were measured (Kimlinger et al., 2015; McCreery, Brennan, et al., 2013; Scollie et al., 2016). If the speech RMS and peak levels fell above thresholds at all frequencies, the MAOF was coded as 10 kHz, which represents the processing limit of the hearing aid.

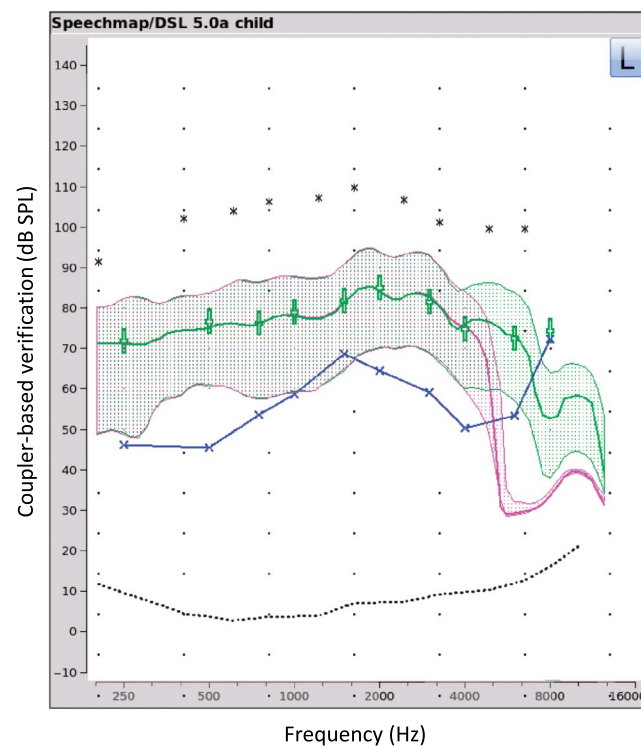
## Outcome Measures

Outcome measures were completed in a double-walled sound-treated booth, with the participants wearing the study hearing aids wired to the programming computer. Stimuli were presented from a loudspeaker at 0° azimuth. Outcome measures included a consonant discrimination in noise task, an aided loudness perception task, a paired comparisons task for subjective preference of bandwidth, and a PLL task. Outcome measures and test conditions were presented in a randomized order. The participants were also blinded to the test condition. Unless specifically stated, outcome measures were obtained binaurally. Regular rest breaks were given depending on the participants' needs. The data were analyzed in R Version 3.4.3.

## Consonant Discrimination in Noise

Consonant discrimination in noise was measured with the University of Western Ontario Distinctive Features

**Figure 2.** An illustration of the coupler-based verification of the extended bandwidth (EBW) and restricted bandwidth (RBW) conditions for the left ear of one participant in the study. Seen in the figure are the long-term average speech spectrum results for the EBW (green) and RBW (purple) condition, with the shaded area indicating the amplified speech area between the speech valleys (30th percentile) and the speech peaks (99th percentile), the Desired Sensation Level v5.0 targets shown in green open crosses, and the participant's hearing thresholds shown as blue crosses (color in the online version).



Differences Test (Cheesman & Jamieson, 1996). Similar to tests used in other recent studies of bandwidth on speech discrimination (Alexander & Rallapalli, 2017; McCreery et al., 2014; Van Eeckhoutte et al., 2020), this test presents nonsense words in the presence of background of noise. Stimuli were presented at 60 dB SPL, with background speech-shaped noise from loudspeakers at 90°, 180°, and 270°, with a +10 dB signal-to-noise ratio. The stimuli used an / $\Lambda$  C I // context, in which C is one of the 21 English consonants. Each word was spoken by two prerecorded female and male talkers, for a total of 84 items. The child had to choose which consonant was heard by clicking on one of the 21 response options shown on the computer screen. Custom software controlled the stimulus presentation, responses, and storage of response files.

## Aided Loudness Growth

Aided loudness growth was measured with an approach similar to that used in the study of Van Eeckhoutte et al. (2016) but modified for aided testing in the sound field. The stimulus was a sentence from a custom recording

of the Connected Speech Test (“A wolf looks like a skinny wild dog”; Cox et al., 1987; Saleh et al., 2020). Each time the stimulus was presented, the child had to judge the loudness of the sentence by choosing a position on a graphic rating scale (GRS), shown on a computer interface. A GRS is a continuous rating scale with loudness categories displayed purely as guidelines. For the purpose of this study, pediatric-friendly facial expressions were also used to depict loudness categories; these were displayed next to the continuum line (see Figure 3). The loudness categories were “Did not hear,” “Too soft,” “A bit soft,” “Just right,” “A bit loud,” “Too loud,” and “Much too loud.” The child could pick any position on the continuous scale using a computer mouse, either at or in between the written categories. Stimuli were presented between 52 and 80 dB SPL, with a step size of 2 dB and in pseudorandom order to avoid context effects (Brand & Hohmann, 2002). Specifically, stimuli were presented in random order, with the constraint that the level difference of two consecutive stimuli never exceeded 12 dB, which was about half of the range of stimulus levels used. A starting level of 66 dB SPL was used, with repetition of each level during testing for a total of 30 trials per loudness test. The software coded the chosen loudness position on the scale as a number between 0 and 1. The task was completed binaurally in the EBW and RBW conditions and repeated monaurally for the EBW condition for comparison.

### Subjective Preference

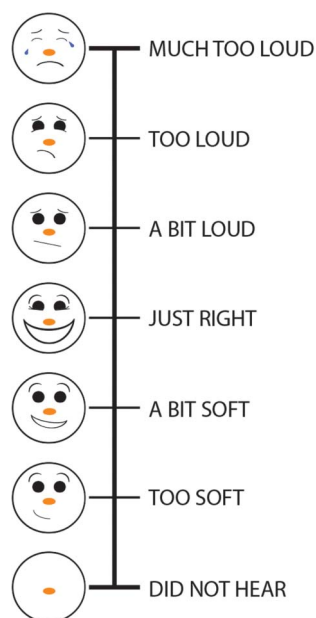
The children were asked to indicate their subjective preference for either EBW or RBW using a single-blind ABX paired comparison task (Eisenberg et al., 1997; Punch

et al., 2001). For this task, a speech passage consisting of multiple spoken custom-recorded Connected Speech Test sentences was presented at 60 dB SPL (Saleh et al., 2020). While the child was listening, bilaterally aided, the experimenter changed the hearing aid program to alternate between bandwidth conditions and to indicate if the child was listening to “Program 1” (counterbalanced to either the EBW or RBW condition) or “Program 2.” The starting program was counterbalanced, and each child listened to both programs twice, alternating between the programs. The child was blinded to the bandwidth condition that was associated with either program. After listening, the child was asked to indicate a preference for Program 1 or 2 or no preference. The paired comparison task was measured twice, and the results from the two trials were combined as follows: “a strong preference for EBW” or “a strong preference for RBW” was coded if the child indicated the same preference on both trials; the category “no preference” was coded if the child indicated no preference on both trials; “a weak preference for EBW” or “a weak preference for RBW” was coded if the child indicated no preference once and a preference for the respective condition once. If the child indicated opposite preferences on the two trials, a “no preference” result was recorded.

### PLLs

PLLs for the EBW and RBW conditions were measured and compared to the overall recommended listening levels (RLL or fit to targets) using an adjustment procedure (see Jesteadt 1980; Levitt, 1971; Van Wieringen & Wouters, 2001). During this task, the children listened to the same spoken speech passage that was used for the subjective preference task, presented at 60 dB SPL. To avoid a systematic bias toward the starting level (Van Eeckhoutte et al., 2018), the adjustment procedure was repeated from opposite perceptual sides. Specifically, the procedure was administered once starting from below PLL and once from above the estimated PLL, resulting in a PLL estimate of the “Up” track and “Down” track. The child was informed that the experimenter would adjust the hearing aids until the child verbally indicated that the hearing aids were at a volume that they would want to listen to all day, every day. The experimenter then decreased the overall gain of the hearing aids to be 15 software steps below the RLL setting for the Up track. Next, the experimenter increased the gain and bracketed the PLL, which was defined as the PLL of the Up track. The child was then instructed to indicate the first point where the level was no longer at their PLL while the experimenter carefully further increased the gain. This was done to establish a starting level that was clearly above the participant’s PLL, set slightly above the first point while avoiding excessive loudness. The starting level is not expected to influence the results, as long as both perceptual sides are included in testing (Van Eeckhoutte et al., 2018). From there, the PLL of the Down track was measured using the same procedure, but in the opposite direction. The experimenter recorded the coordinating software level (Phonak Target) at each setting. The measured

**Figure 3.** The graphic rating scale with categories and mood faces as guidelines for loudness judgments.



PLL for the Up and Down tracks were averaged together to determine the PLL to be used during hearing aid verification. Verification of the PLL level, across participants, was completed using the ISTS speech signal at 60 dB SPL, as well as the hearing aid output at the RLLs for comparison.

## Results

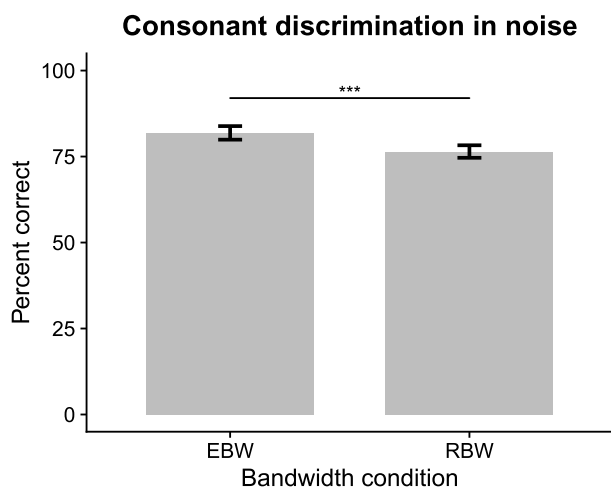
### Audibility

For seven participants, the MAOF was coded as 10 kHz, as the speech RMS and peak levels fell above thresholds (i.e., were likely audible) at all frequencies. Across participants, the RMS MAOF was, on average, 7376 Hz ( $SD = 1669$  Hz), and the peak MAOF was 8033 Hz ( $SD = 1262$  Hz). Both the RMS and peak MAOFs exceeded 4.5 kHz for each child, and the minimum peak MAOF was 6.1 kHz. These results indicate that audibility in excess of 4.5 kHz was achieved for all children in the EBW condition.

### Consonant Discrimination in Noise

The average scores on the consonant discrimination in noise task were 81.9% ( $SE = 2.0\%$ ) for the EBW condition and 76.5% ( $SE = 1.8\%$ ) for the RBW conditions (see Figure 4). Percent correct scores were transformed to rationalized arcsine units (rau) for statistical analysis (Sherbecoe & Studebaker, 2004). A linear mixed-effects model with bandwidth set as a repeated measure and participant as a random effect R v3.4.3 showed a significant effect of bandwidth on the rau scores,  $b = -6.92$ ,  $t(27) = -6.88$ ,  $p < .001$ , with a large effect size ( $r = .80$ ). Thus, compared to the RBW condition, the EBW condition led to a significant improvement in consonant recognition, with an average improvement of 5.4%.

**Figure 4.** The average consonant discrimination in noise scores for the two bandwidth conditions (EBW = extended bandwidth; RBW = restricted bandwidth). The stars indicate the level of significance ( $p < .001$ ). The standard errors of the mean are shown.



To further explore error patterns across bandwidth conditions, confusion matrices were calculated for each condition. Confusion matrices were then subtracted from each other to produce a difference matrix (see Table 1). The table shows positive numbers of 67, 42, and 48 on the diagonal for /s/, /t/, and /z/, respectively, meaning that those consonants were more often identified correctly in the EBW than in the RBW condition. Confusions between consonants are shown outside the diagonal. Negative numbers indicate the amount of responses that were more often confused in the RBW condition than in the EBW condition. As can be seen in the table, the participants confused /s/ for /f/ 48 times, /t/ for /k/ 38 times, and /z/ for /v/ 38 times more in the RBW condition than in the EBW condition. These are confusions of place of articulation with correct identification of manner and voicing of articulation. The /s/, /t/, and /z/ consonants all contain significant cues in the high-frequency spectral region. For each bandwidth condition, the rau scores were correlated with the better ear four-frequency PTA (with  $r = -.52$ ,  $p = .004$  for the EBW condition and  $r = -.56$ ,  $p = .004$  for the RBW condition) after Holm correction. These results indicate poorer speech recognition with increasing degree of hearing loss.

### Aided Loudness Growth

Aided loudness growth ratings were examined to remove outliers according to test–retest reliability, as follows. Across all participants, levels, and conditions, the differences between the first loudness response and second loudness response were calculated, yielding a mean difference of 0.01, with a standard deviation of 0.16. The range of  $\pm 2$  SDs corresponds to the distance of two loudness categories on the GRS. If a child’s test and retest loudness ratings differed by more than this criterion, these two loudness responses were removed from analyses for that given participant, condition, and level (leading to a total of 196 out of 3,360 points that were removed).

Next, each condition was fitted with a sigmoidal function (see Figure 5). Descriptively, higher loudness ratings were obtained in the binaural EBW condition. The magnitude of the loudness differences among conditions was assessed by comparing the input levels associated with specific loudness levels on these functions. From this, we observed that the children indicated a similar rating of “a bit soft” across all test conditions. Specifically, the input levels were 58.8, 59.6, 59.6, and 59.9 dB SPL for the binaural EBW condition, the binaural RBW condition, the monaural left condition, and monaural right condition, respectively. This corresponds to input-level differences of 0.8 and 1.1 dB between the monaural EBW conditions and the binaural EBW condition, and 0.8 between the binaural RBW condition and the binaural EBW condition. The chosen loudness category of “a bit loud” corresponded to 71.3, 72.4, 72.7, and 73.2 dB SPL for the binaural EBW condition, the binaural RBW condition, the monaural left condition, and monaural right condition, respectively. These differences were slightly larger, by 1.4 and 1.9 dB, between the monaural

**Table 1.** The consonant confusion matrix measured in reduced bandwidth was subtracted from the confusion matrix measured in extended bandwidth, and the remaining difference matrix is shown here.

Stimuli	Response differences																				
	B	CH	D	F	G	H	J	K	L	M	N	P	R	SH	S	TH	T	V	W	Y	Z
	/b/	/tʃ/	/d/	/f/	/g/	/h/	/dʒ/	/k/	/l/	/m/	/n/	/p/	/r/	/ʃ/	/s/	/θ/	/t/	/v/	/w/	/j/	/z/
B	<b>-9</b>	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	8	0	1	0
CH	0	<b>-4</b>	0	0	0	-1	0	0	1	0	0	0	0	3	-1	3	0	0	0	0	0
D	2	0	<b>-5</b>	0	2	1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
F	0	0	0	<b>4</b>	0	1	0	0	0	0	0	-2	0	0	-1	-2	0	1	0	0	0
G	0	0	4	-1	<b>-3</b>	0	-2	2	0	0	0	-1	0	0	0	0	0	1	0	0	0
H	0	0	0	-2	1	<b>2</b>	0	0	0	0	1	0	0	-1	0	0	0	1	0	-1	0
J	0	1	0	0	5	-1	<b>-5</b>	0	0	1	0	0	0	0	0	0	0	0	0	0	0
K	0	-1	0	0	1	0	0	<b>2</b>	0	0	0	-1	1	1	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	<b>3</b>	1	-1	0	-2	0	0	0	0	0	-1	-1	0
M	-1	-1	0	0	0	0	0	1	1	<b>6</b>	-4	0	0	-1	0	1	0	0	-1	0	0
N	0	0	-1	0	0	0	0	0	0	5	<b>-2</b>	0	0	0	0	0	0	0	1	-1	0
P	0	0	0	0	0	-1	0	6	0	0	0	<b>-8</b>	0	0	0	-1	3	0	0	0	1
R	0	0	0	0	0	0	0	0	2	1	0	0	<b>2</b>	0	0	0	0	-1	-1	-1	0
SH	0	1	0	0	0	0	0	0	0	0	0	0	1	<b>0</b>	2	-1	0	0	0	-1	-1
S	0	0	0	<b>-48</b>	0	-2	0	0	0	0	0	-7	0	-2	<b>67</b>	-5	0	-1	0	0	0
TH	-3	-1	2	0	-1	1	0	0	1	0	-1	1	0	0	0	<b>0</b>	0	3	-2	1	0
T	-1	0	0	0	0	-1	0	<b>-38</b>	0	1	0	-4	0	0	1	2	<b>42</b>	0	0	0	0
V	-2	0	1	-2	-1	-1	0	0	0	0	0	0	2	-1	0	-1	0	<b>4</b>	-2	0	3
W	0	0	0	0	0	1	0	0	-1	-1	-1	0	2	0	0	-1	0	-1	<b>2</b>	0	0
Y	0	0	1	0	-2	0	-1	0	0	0	0	1	2	0	1	0	0	1	1	<b>-3</b>	0
Z	0	0	0	0	1	0	0	0	-1	0	0	-2	0	0	7	-8	0	<b>-38</b>	-3	-1	<b>48</b>

Note. Absolute values equal to or more than 10 are indicated in bold.

EBW condition and the binaural EBW condition, and 1.1 between the binaural RBW condition and the binaural EBW condition.

In order to determine if these changes were significant, a linear mixed-effects model was conducted on the raw data with “level” and “condition” set as fixed effects (repeated-measure factors), “participant” set as a random effect, and the following contrasts: the contrast between binaural EBW and monaural EBW conditions, the contrast between monaural conditions, and the contrast between the binaural EBW and binaural RBW condition. The effect of level was significant ( $b = 0.02$ ,  $t = 93.3$ ,  $p < .001$ ), as was the contrast between the binaural EBW and monaural EBW conditions ( $b = -0.01$ ,  $t = -2.18$ ,  $p = .032$ ). All other contrasts were nonsignificant ( $p > .05$ ).

Furthermore, correlation coefficients were calculated to investigate the relationship between speech discrimination in noise scores and loudness perception for speech stimuli at 60 dB SPL. Better speech discrimination in noise scores were not associated with a perception of greater loudness in the EBW condition after Holm correction ( $r = .43$ ,  $p = .076$ ), nor in the RBW condition ( $r = .15$ ,  $p = .447$ ).

### Subjective Preference

More than half of the children had a strong preference for the EBW condition (15/28 or 54%), as shown in Figure 6. In contrast, only two children (7%) had a strong preference

for the RBW condition. Weak preferences were observed for three children (11%) in each of the RBW and EBW conditions, and five children (18%) had no preference for either bandwidth condition. A one-sample Kolmogorov–Smirnov test indicated a significant mean preference for the EBW condition ( $p = .001$ ). The children’s preference scores were not correlated with the four-frequency PTA of the better ear ( $r = -.14$ ,  $p = .473$ ). This is consistent with our previous findings in adults (Van Eeckhoutte et al., 2020).

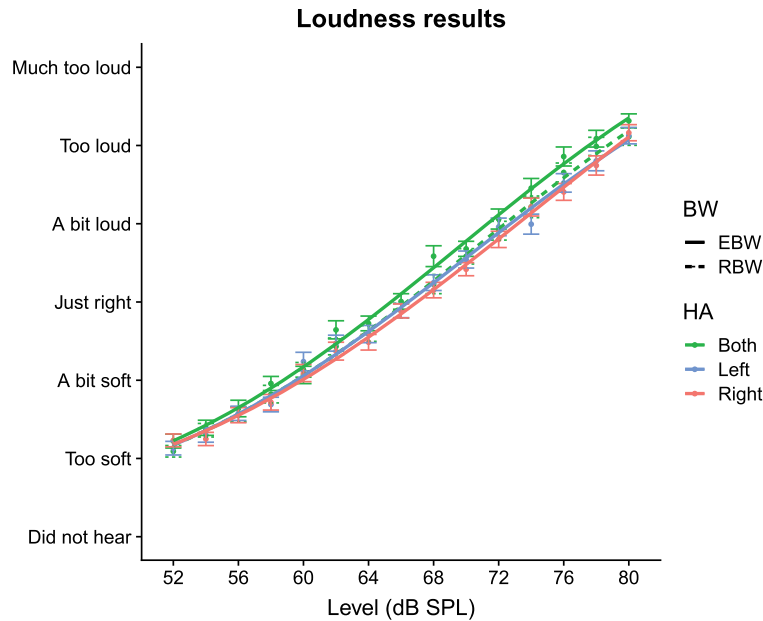
### PLLs

For the PLL data, the Up and Down track of the procedure provided slightly different PLL estimates, consistent with a bias toward the starting level (see Figure 7). The values shown are the gain values from the hearing aid fitting software for the right ear, according to moderate input sounds (G65) for the “mid” frequency handle when displaying three frequency handles, to demonstrate the difference in PLL when measuring the Up and Down track. Paired  $t$  tests indicated significant differences between the tracks of both conditions, with  $p$  values of  $< .001$  after Holm correction. The results indicate that the use of both the Up and Down tracks may help to balance the response bias from the final PLL measure by approximately 2 dB.

The software values associated with average PLL from the Up and Down tracks were used when measuring the hearing aid output for the ISTS signal at 60 dB SPL, at PLL and at RLL settings (see Figure 8). For both the EBW

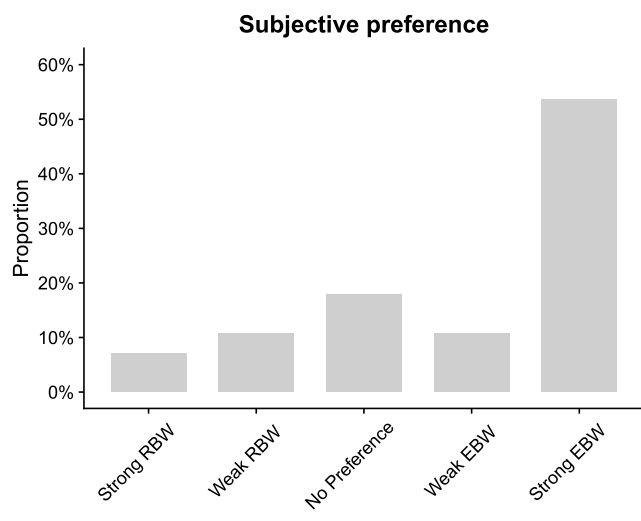


**Figure 5.** The sigmoidal fits of the aided loudness growth conditions as well as the mean  $\pm 1$  SEM are shown. EBW = extended bandwidth; RBW = restricted bandwidth; HA = hearing aid (color in the online version).



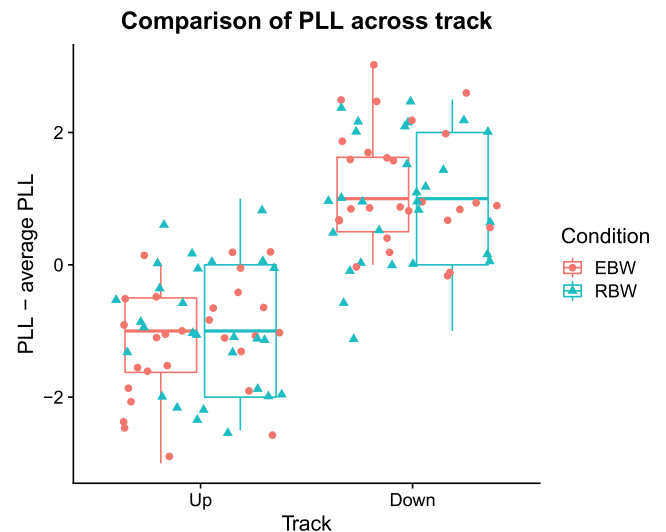
and RBW conditions, the PLLs and RLLs were compared using the better ear. The aided 1/3 octave band levels of speech were power sum averaged over the range of 0.2–4 kHz to represent the bandwidth present in both conditions. The differences between the PLLs and RLLs were calculated between the EBW and RBW condition to determine if aided bandwidth changes resulted in different PLLs. The PLLs differed from RLLs by  $-0.9$  and  $-0.7$  dB on

**Figure 6.** The subjective preference of the children as measured by an unforced-choice paired comparisons task. RBW = restricted bandwidth; EBW = extended bandwidth.

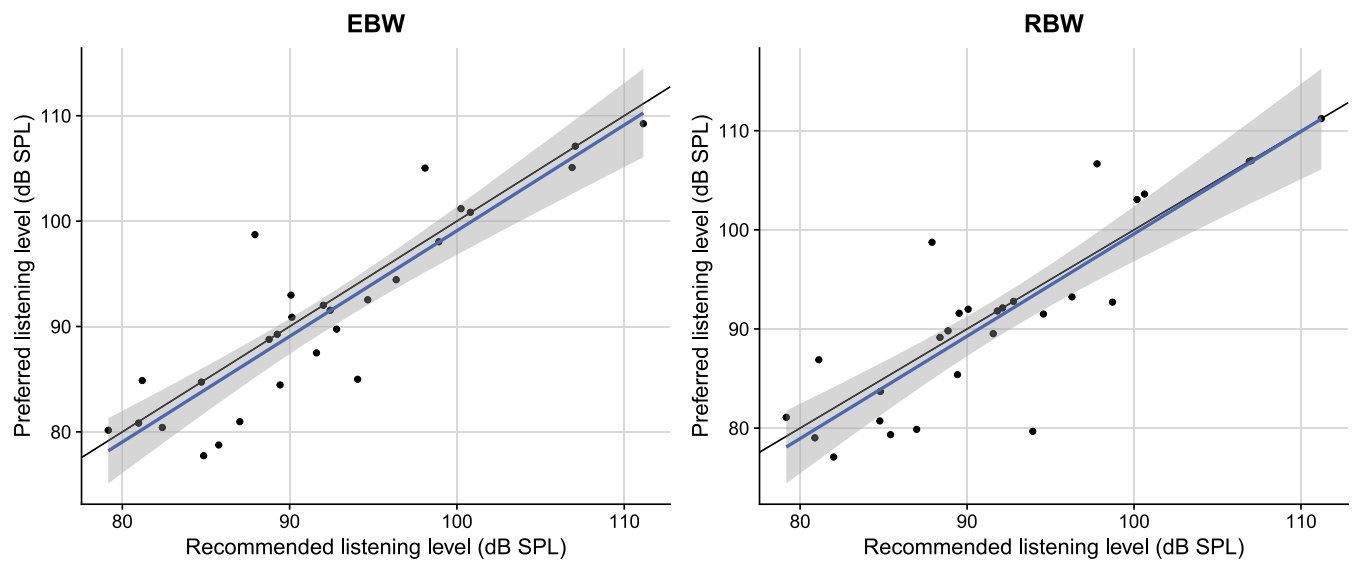


average in the EBW and RBW conditions and ranged between  $-14.3$  and  $10.8$  dB. The PLL and RLL differences for both bandwidth conditions were not significantly different from each other,  $t(27) = 0.64$ ,  $p = .527$ . No significant

**Figure 7.** Comparison of the procedural tracks to measure the preferred listening levels (PLLs). Each dot on the y-axis shows the average PLL of the Up and Down track subtracted from the found PLL value (software value, see text) for each participant. The individual results for each condition are shown on top of the box plots with jitter (color in the online version). EBW = extended bandwidth; RBW = restricted bandwidth.



**Figure 8.** Recommended listening levels (fit to target) were compared to the measured preferred listening levels for the extended bandwidth (EBW) and restricted bandwidth (RBW) condition. The black thin line of perfect correspondence is shown, as well as the blue regression line, and the 95% confidence interval in gray (color in the online version).



correlations were found between the PTA of the better ear and the PLL–RLL differences, in either the EBW condition ( $r = -.01$ ,  $p = .957$ ) or the RBW condition ( $r = .11$ ,  $p = .552$ ).

## Discussion

### Main Findings

In this group of children, modern BTE devices provided average audibility of the peaks of midlevel speech to about 8 kHz. On average, these MAOF findings are close to the recommended 9 kHz of EBW in the Pediatric Amplification Guideline, for optimal audibility of high-frequency sounds, such as /s/ (AAA, 2013). High-frequency audibility limits exceeded 4.5 kHz for all children and yielded a high consonant discrimination in noise score of 82%, on average. Many previous laboratory studies have used RBW conditions with filtering to about 4 or 5 kHz to represent the achievable bandwidth of older hearing aids (e.g., Cox et al., 2011; Füllgrabe et al., 2010; Hornsby & Ricketts 2003; McCreery & Stelmachowicz 2011). In this study, we aimed to examine this difference by using wearable modern hearing aids to assess outcomes across test conditions. We provided hearing aid fittings using an EBW condition and a condition in which output was minimized above 4.5 kHz, or the RBW condition. Consonant discrimination in noise scores dropped, on average, by 5.4% in the RBW condition, which is attributed to the improved perception of high-frequency phonemes in the EBW condition. However, no significant difference between bandwidth conditions was found for aided loudness perception, nor was there a significant difference in PLLs when comparing results for the bandwidth conditions. Furthermore, measures of

subjective preference indicated that 65% of the children preferred the EBW condition over the RBW condition, with 54% of all children indicating a strong preference. The results suggest that providing the full bandwidth available in modern devices had beneficial effects for children who use hearing aids, fitted to the DSL v5.0 child prescription, without causing significant increases in their loudness perception. This EBW is equal to providing audibility up to 8 kHz, when considering average MAOF results reported for peak levels of speech.

### Comparison to Adults

In a previous study, a group of adults were evaluated using a similar outcome measure battery (Van Eeckhoutte et al., 2020). The group of adult listeners had mild-to-moderate high-frequency sloping sensorineural hearing loss. The current study shows that the children in this study, who had a large range of degrees and configurations of hearing loss, also benefitted from the full bandwidth available from modern hearing aids. Furthermore, we did not observe a significant difference in aided loudness perception or a significant difference in PLLs with EBW versus RBW. This was observed in both groups, despite several differences between the two studies: (a) The DSL v5.0 targets for children provide more gain than the adult prescription for the same audiometric hearing loss (Scollie et al., 2005), and (2) different device types were used—the adult listeners were fitted with RIC devices, and children were fitted with BTE devices with custom earmolds. Overall, this may indicate that it is possible to provide improved speech sound recognition without adversely affecting loudness or requiring a different volume control setting in either

group. The magnitude of speech sound recognition improvement with EBW was similar between groups (5.4% for children, 4.1% for adults) and was mainly driven by the high-frequency phonemes /s/, /z/, and /t/ in both adults and children. However, more children (65%) indicated a preference for the EBW condition, compared to the adults (46%), which is consistent with previous studies indicating that children prefer and require more audibility to achieve similar levels of performance (see reviews by Scollie et al., 2005; Stelmachowicz et al., 2004).

### **Comparison of Outcome Measures in Other Studies**

#### **Consonant Discrimination in Noise**

The results of this study are largely consistent with lab studies that show sometimes small, but generally beneficial, effects of providing the EBW on speech discrimination in noise (Amos & Humes, 2007; Cox et al., 2011; Füllgrabe et al., 2010; Hornsby et al., 2011; Hornsby & Ricketts, 2003; Levy et al., 2015; Mackersie et al., 2004; McCreery & Stelmachowicz, 2011; Plyler & Fleck, 2006; Seeto & Searchfield, 2018; Simpson et al., 2005; Turner & Cummings, 1999; Turner & Henry, 2002). Similar to results in other studies, these confusion differences are also consistent with improved access to and use of high-frequency speech audibility (Alexander & Rallapalli, 2017; McCreery et al., 2014; Pittman, 2008; Stelmachowicz et al., 2004), with a small change in overall percent correct having a large impact on the audibility of specific, high-frequency phonemes.

In Van Eeckhoutte et al.'s (2020) study, the frequency spectra of the /s/, /t/, and /z/ stimuli that were used for the consonant discrimination in the noise task were analyzed, and the frequency of the largest spectral peak was found to exceed 4.5 kHz (min = 5.0 kHz, max = 7.6 kHz) for /s/ and /z/ stimuli and for the two female talkers for /t/. The provision of more fricative energy may lead to better perception of /s/ and /z/ (Dubno & Levitt, 1981; Pittman & Stelmachowicz, 2000, 2003). Providing access to an EBW could prevent delays in phonological development in children with hearing loss (McCreery et al., 2017; Moeller et al., 2007; Stelmachowicz et al., 2004).

#### **Subjective Preference**

Subjective preference has mainly been investigated with adult listeners (Füllgrabe et al., 2010; Moore et al., 2011; Moore & Tan, 2003; Ricketts et al., 2008; Van Eeckhoutte et al., 2020). Using a linear lab system, one study measured higher pleasantness ratings for an RBW condition (5 kHz) versus an EBW condition (7.5 or 10 kHz) in a similar group of adult listeners with hearing loss (Füllgrabe et al., 2010). However, using a multichannel compression system, no consistent preference in terms of pleasantness was associated with RBW versus EBW, except for results measured for female speech processed with fast compression (Moore et al., 2011). The indifference, in terms of subjective preference, for either bandwidth condition is similar to the adult study by Van Eeckhoutte et al. (2020). In their study,

most listeners (71%) indicated “no preference” at least once for either the RBW or EBW bandwidth condition. The largest group (33%) indicated “no preference” twice, while the remaining participants indicated preferring either the RBW (13%) or the EBW (25%) once and “no preference” once. Brennan et al. (2014) investigated subjective preference for RBW and EBW with children and adults and found that both groups did not differ in their preferences. However, based on their figures, it seemed that more children than adults preferred the EBW over the RBW condition for speech, which agrees with the results of this study.

#### **Aided Loudness Perception and PLLs**

The results from this study indicate that the loudness perception, as measured by both aided loudness growth and PLLs, did not vary significantly with bandwidth. Furthermore, the level difference needed to reach the same loudness percept for the binaural EBW loudness condition and the monaural EBW loudness conditions was only around 1 dB (0.8 and 1.1 dB SPL for “a bit soft”, and 1.4 and 1.9 dB for “a bit loud”). This small difference is thought to reflect binaural loudness constancy rather than binaural loudness summation (Fletcher & Munson, 1933), and this difference was also found in the adults study. The phenomenon was first described by Epstein and Florentine (2012), showing less binaural loudness summation in the presence of ecologically valid variables. For example, less binaural loudness summation was found for speech presented via a loudspeaker than presented via insert earphones and less with visual cues from a video screen than without. Cox and Gray (2001) and Van Eeckhoutte et al. (2020) both reported a difference of 1 dB between the binaural EBW and binaural RBW conditions, as well as between the binaural EBW and monaural EBW conditions for adults. This study with children reports the same difference (0.8 and 1.1 dB SPL for “a bit soft” and “a bit loud”). Further research could investigate whether the same conclusions, in terms of loudness perception, are measured for music stimuli.

### **Conclusions**

This study supports the recommendation to provide the full available bandwidth, whenever possible, when fitting children with modern commercially available hearing aids. An EBW can be beneficial, especially when considering speech sound recognition performance. In this clinical sample of children with different configurations and degrees of hearing loss, fitted to the DSL v5.0 child prescription, all children achieved audibility exceeding 4.5 kHz, as measured by the MAOF method. Average achieved audibility was approximately 8 kHz. Outcome measures indicated that these fittings provided considerable improvements for /s/, /z/, and /t/ perception in noise compared to a fitting with RBW to about 4.5 kHz, without any significant effects for loudness perception or PLLs. Most children (65%) had a subjective preference for the EBW condition compared to

the more RBW condition. In summary, the study suggests that modern hearing aids can achieve greater bandwidth, when compared to past studies. Clinicians should seek to verify and maximize high-frequency audibility to achieve any potential perceptual benefits in children with hearing loss who wear hearing aids.

## Acknowledgments

The study was funded by the Ontario Research Fund RE08-072 and by licensing revenues from the software that computes the DSL v5.0 targets returned to research. The authors thank Phonak AG (Sonova) for donating hearing aids for this study and acknowledge the help of Steve Beaulac, Joshua Baitz, and Paula Folkeard. The authors also wish to thank Brian B. Monson and an anonymous reviewer for their helpful comments on an earlier version of the manuscript.

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