High-Frequency Amplification: Sharpening the Pencil

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Introduction

High-frequency amplification is similar to a sharpened pencil. When amplification is extended to frequencies higher than those of today's commercially available hearing aids, the quality and clarity of the signal is perceptibly improved – much like sharpening a dull pencil to write a clearer message. Unfortunately, the benefits of improved clarity and signal quality have been difficult to demonstrate, particularly in adult listeners. This calls into question the need for commercially available hearing aids to provide amplification over the full range of speech frequencies. This paper describes the benefits of high-frequency spectral information to the speech and language development of children. Studies regarding the bandwidth of hearing aids are described, acoustic phonetic information occurring at high-frequencies are identified, the unique manner in which children with hearing loss may derive benefit from high-frequency amplification is examined, and finally, data regarding the benefits of high-frequency amplification for learning new words are presented.

How High Is High-Frequency?

To interpret the results of research regarding the relation between bandwidth and speech perception, it is important to first define the frequency range of interest. Studies regarding high-frequency amplification fall into two general categories. The first category includes commercially available devices with bandwidths ≤6 kHz. The advantage of studying the capability of commercially available devices is that the benefits or detriments of high-frequency amplification can be examined immediately, as well as over the long term. That is, the participants may use the devices for a period of time to become accustomed to the high-frequency information before returning to the clinic or lab to examine their performance under controlled conditions. One limitation, however, is that the bandwidths under investigation do not encompass the full range of speech acoustics, potentially resulting in less than optimal performance. To date, the effects of bandwidth provided by wearable devices have been examined in adults but not in children (Ching, Dillon and Byrne 1998; Horwitz, Ahlstrom and Dubno 2008; Mackersie, Crocker and Davis 2004; Plyler and Fleck 2006; Simpson, McDermott and Dowell 2005).

The second category involves amplification extending through 10 kHz. This bandwidth must be simulated in the laboratory using custom software and high-performance earphones. Studies regarding this extended bandwidth reveal the potential benefits or detriments of high-frequency amplification under highly controlled conditions; however, the long-term benefits are unknown due to the lack of a wearable device. This approach has been used in several studies both in adults (Hogan and Turner 1998; Ricketts, Dittberner and Johnson 2008; Turner and Cummings 1999) and in children (Pittman, Lewis, Hoover and Stelmachowicz 2005; Pittman 2008; Stelmachowicz, Pittman, Hoover and Lewis 2001, 2002; Stelmachowicz, Lewis, Choi and Hoover 2007; Stelmachowicz et al. 2008). Given that the speech and language skills of children develop over the long term, evidence indicating a benefit of high-frequency amplification in the laboratory would support further examination with a wearable device. For the

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purpose of this review, high-frequency amplification is defined as bandwidths extending to 9 or 10 kHz with attention to studies in which the 4 to 10 kHz frequency region was examined in detail.

What Acoustic-Phonetic Information Occurs Between 4 and 10 kHz?

Although significant improvement in speech perception has been observed with increases in bandwidth through 6 kHz (Gustafson and Pittman 2010; Horwitz et al. 2008), little or no improvement has been reported in adults for bandwidths extending to 10 kHz (Moore, Fullgrabe and Stone 2010) with reports of decreased performance for a few adult listeners in the widest bandwidths (Hogan and Turner 1998; Turner and Cummings 1999). Even so, adults report a preference for high-frequency amplification when listening to speech and music in quiet (Ricketts and Hornsby, 2005) suggesting that they perceive a benefit that is not apparent with traditional speech perception measures.

The equivocal effects of high-frequency amplification may be due, in part, to the acoustic-phonetic information occurring at high frequencies. Our knowledge of the acoustic content of speech at frequencies >6 kHz comes primarily from the long-term average spectrum of speech (Olsen, Hawkins and Van Tassell 1987; Pearsons, Bennet and Fidel 1976). The intensity range around that average is on the order of 30 dB and reflects the short-term intensity variations of strong vowels and weak voiceless consonants. Although acoustic energy resides in the 4 to 10 kHz frequency region, specific phonemes cannot be ascertained from the long-term average (Boothroyd, Erickson and Medwetsky 1994). Several studies have shown that some phonemes in the fricative class (e.g., /s/, /sh/, /f/, and /th/) contain substantial energy above 6 kHz, whereas the remaining classes of consonants and vowels do not (Boothroyd et al. 1994; Pittman, Stelmachowicz, Lewis and Hoover 2003; Stelmachowicz et al. 2001).

Although these fricatives are members of the largest class of consonant phonemes, their relative contribution to speech perception varies widely. That contribution is reflected in their frequency of occurrence in speech and their grammatical function. Denes (1963) reported that, for the 24 English consonants, the fricative /s/ occurs more often than all other phonemes except /t/ and /n/, whereas the fricatives /sh/, /f/, and /th/ are ranked 15th, 20th and 21st, respectively. The more frequent occurrence of /s/ is due in large part to its morphological function in English denoting plurals (cat versus cats), possession (The book is Tom's), and verb tense (keep versus keeps); a function that none of the other fricatives share with the exception of /z/ which is the voiced compliment of /s/. In summary, acoustic-phonetic information does occur at frequencies >4 kHz, but the contribution of that information to speech perception is relatively small. The fricative /s/ however, is comprised largely of energy >4 kHz and conveys considerable grammatical information.

Do Children Need High-Frequency Information for Speech and Language Development?

For adults who are familiar with the English language, the absence of high-frequency information is likely to have little effect on perception because their experience with communication and the context of the message may allow them to recover the missing spectral information with little effort. Adults with hearing loss have the same advantage because they typically acquire their hearing impairment after many decades of normal hearing and communication. For these adults, amplification restores hearing sensitivity over much of the frequency range with the exception of energy ≤6 kHz. Children, on the other hand, typically acquire hearing loss early in life before speech and language are fully developed. They may have little or no experience with high-frequency information beyond that which is provided by their hearing aids and may react differently than adults when that information is presented to them. An early study in this area demonstrated this effect by comparing fricative perception in children with congenital hearing loss to that of their normal-hearing and hearing-impaired counterparts (Stelmachowicz et al. 2001). Listeners were asked to perceive three voiceless fricatives (/s/, /sh/, /f/) produced by a man, a woman, and a child. The stimuli were low-pass filtered at six cut-off frequencies between 2 and 9 kHz. The results showed significant improvement in perception as a function of bandwidth, as well as significant effects of hearing status (normal hearing > hearing loss) and age (adults > children). Further examination of the data revealed that the performance of each group was similar through 6 kHz but then differed most at 9 kHz. At that bandwidth, the performance of the children with hearing loss (HL) fell well below that of the other groups. This suggests that the children with HL were able to interpret the acoustic information as well as their normal-hearing and hearing-impaired counterparts up to the bandwidth of their personal hearing aids but not beyond.

Similar effects of experience may be observed from the results of another study regarding the perception of nine fricatives and affricates presented in noise to children with normal hearing (NH) and children with HL (Stelmachowicz et al. 2007). The phonemes were low-pass filtered at 5 and 10 kHz and presented in speech-shaped noise at a 10 dB signal-to-noise ratio. Overall, there was no difference in performance between the two bandwidth conditions for either group. However, closer examination of the data revealed that the perception of /s/ and /z/ improved with bandwidth for both groups but perception of /f/ and /v/ decreased with bandwidth for the children with HL only. Unlike the children with NH, the children with HL were unable to interpret the high-frequency energy of /f/ and /v/ and erred toward the more frequently occurring /s/ and /z/ morphemes. The fact that they may have never heard acoustic information at frequencies >6 kHz prior to the study likely contributed to their miscategorization. These results suggest that the performance of the children with NH reflects the benefits of providing high-frequency information, whereas the performance of children with HL is likely complicated by their lack of experience with that information.

Are Other Areas of Speech and Language Development Affected by High-Frequency Amplification?

There is both direct and indirect evidence to suggest that the limited bandwidth of commercial devices may impact other processes specific to language development in children. Indirect evidence can be found in longitudinal studies of the speech and language development of young children with HL. Moeller and colleagues (2007) monitored the spoken language of twelve children with HL for 14 months (10 to 24 months of age) and compared their early development to outcomes measured at 35 months. Extensive analyses of the children's early vocalization, babble, syllable structure, and phonetic inventory were compared to a control group of 21 children with NH at the same age or stage of development. No significant differences were reported for onset of vocalization; however, significant main affects of group and age were observed for all other measures (babble, syllable structure, phonetic inventory). The lack of significant group-by-age interactions indicated that the differences between groups were due to delayed, rather than impaired, speech and language development in the children with HL. However, the fricative production of the children with HL was found to be impaired compared to that of the children with NH. Specifically, a significant group-by-age interaction indicated that the children with HL produced significantly fewer fricatives than the children with NH and that the difference between the groups increased with age. Similar results were reported in a follow-up study of five children with HL who were identified after the age of 2 years (Moeller et al. 2010). These children were followed until 7 years of age, and their language development was compared to that of children with NH. Errors and omissions in fricative production were prevalent throughout the observation period (5 years) suggesting that the production of this class of phonemes is particularly vulnerable in children using hearing aids. The authors argue that the nature of these production errors is consistent with those that might occur due to the bandwidth limitations of commercially available hearing aids and that the morpho-syntactic development of children with HL may be adversely affected if /s/ is not represented well via amplification (Moeller et al. 2010).

Direct evidence regarding the effects of high-frequency information on speech and language development can be found in the literature regarding children's ability to learn new words. Word learning is a particularly important process because children cannot speak effectively, read comprehensively, or write meaningfully without a broad and deep vocabulary. Despite adequate amplification, word learning in children with HL has been shown to be poorer than that of children with NH (Gilbertson and Kamhi 1995; Lederberg, Prezbindowski and Spencer 2000) and is consistent with the two to three year delay in receptive vocabulary observed in these children (Moeller 2000; Yoshinaga-Itano, Sedey, Coulter and Mehl 1998; Pittman et al. 2005).

Currently, two paradigms exist to examine the process of word learning in children. The first is based on a type of word learning referred to as quick incidental learning (or novel mapping), which requires children to associate a novel word with a novel object without directions to do so. Quick incidental learning reveals children's ability to identify and map novel words to novel objects as they might when overhearing the conversations of others (Akhtar, Jipson and Callanan 2001; Akhtar 2005). However, performance can be evaluated only for a small, fixed number of exposures to the novel words, and the testing itself can add to the number of exposures

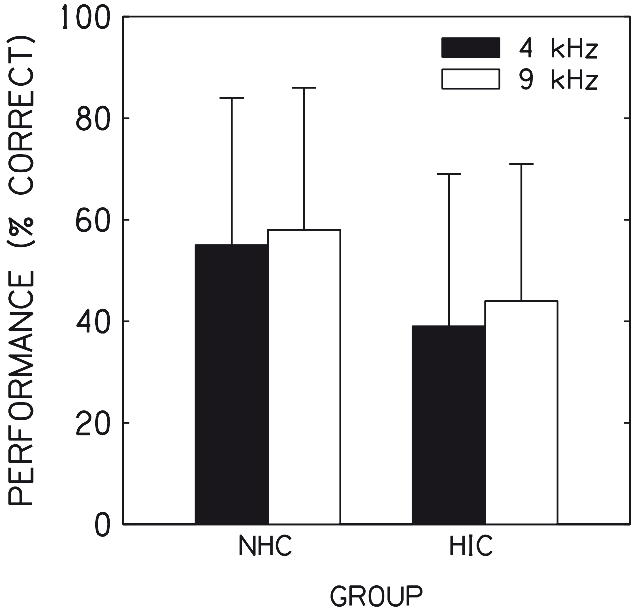

Figure 1. Average (+1SD) word learning performance as a function of group for the normal-hearing children (NHC) and the hearing-impaired children (HIC). The parameter is bandwidth.

to the new words. Also, differences between groups may not be apparent after only a few exposures when performance is poorest whereas larger differences may be revealed after more exposures. For example, Pittman and colleagues (2005) examined word learning in children with NH and children with HL for words presented in two bandwidth conditions. Eight novel words were embedded in an animated story containing novel objects referred to by the narrator. Each word was repeated three times within the story, and the children watched the story twice. Half of the words were low-pass filtered at 4 kHz and half at 9 kHz. After the child listened to the story twice, their ability to identity each object by name was examined using a conventional perception task that provided delayed feedback for correct responses.

Figure 1 shows the results for the children in each group and bandwidth condition. The performance of the children with NH was better than that of the children with HL in both the 4- and 9-kHz bandwidth conditions. Additionally, there was no difference between the bandwidth conditions for either group. Similar results were reported by Stelmachowicz and colleagues (2007) using the same word-learning paradigm presented in noise. At face value, the results suggest that high-frequency amplification had no impact on word learning. Although this may be true, a more accurate interpretation might be that bandwidth effects are not apparent after only six exposures to each novel word.

The second paradigm used to examine word learning is based on a process called fast mapping in which children are given an explicit reference (e.g., "This is a blag") and expected to remember the reference for later recall. This approach can be used to determine the number of exposures a child needs to learn new words (learning rate) at a specific level of performance, for example, 70% correct. Pittman (2008) examined the effects of bandwidth on learning rate for 36 children with NH and 14 children with moderate hearing loss. Five CVCVC nonsense words were created and paired with five pictures of nonsense toys. The words were spoken by a female talker and low-pass filtered at 4 and at 9 kHz. Figure 2 shows the long-term average spectrum for the five novel words. The shaded area represents the subtle difference between the 4- and 9-kHz bandwidth conditions. The children in each group were subdivided to form two groups of seven children with HL and two groups of 18 children with NH. One subgroup from each group learned the words in the 4 kHz bandwidth and the other subgroup learned the words in the 9 kHz bandwidth. The receptive vocabulary and short-term memory of the children in each subgroup condition were measured prior to testing and found to be equivalent. Finally, the stimuli were amplified and frequency-shaped for each child with hearing loss.

During testing, the children played a computer game to learn the names of five novel toys through a process of trial and error. Figure 3 shows one of the games used. After each novel word was presented, the

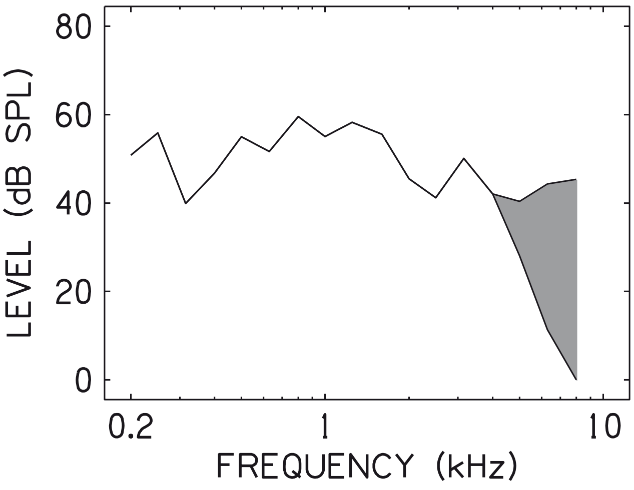

Figure 2. Long-term average spectrum of the five nonsense words. The shaded area represents the difference between the 4 and 9 kHz bandwidth conditions.

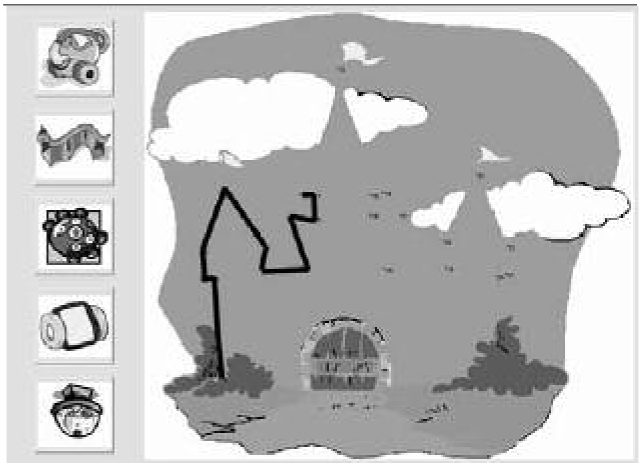

Figure 3. Screen image of the dynamic learning game showing a partially completed dot-to-dot game.

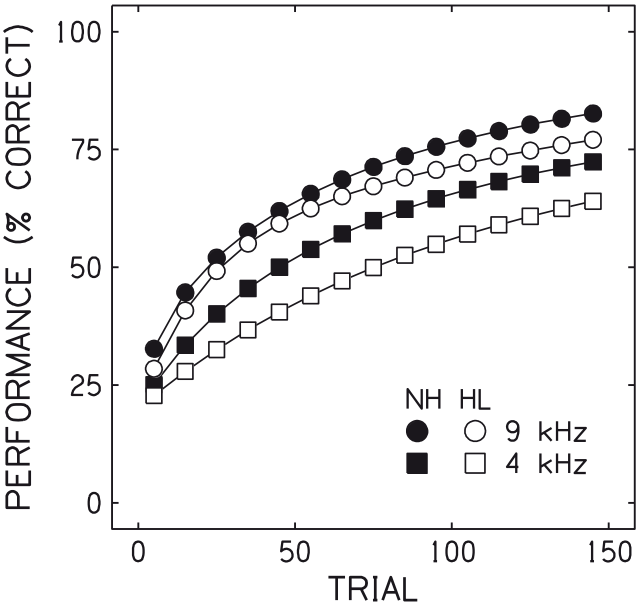

Figure 4. Average word learning performance as a function of trial in 15 bins of 10 trials each. The parameter is group (normal hearing and hearing loss) and bandwidth condition (4 and 9 kHz).

	Bandwidth	
Group	4 kHz	9 kHz
Normal Hearing	40	20
Hearing Loss	121	72

Table 1. Learning rate (number of trials to criterion) for each groups and bandwidth condition.

children selected one of the toys on the left side of the computer screen. If the correct toy was selected, the game (displayed on the right) advanced one step. In this example, a line was drawn to the next position in the dot-to-dot game. If an incorrect toy was selected, the game did not advance. Each of the five novel words was presented 30 times in random order for a total of 150 trials requiring ≤15 minutes to complete the testing.

The trial-by-trial data were then binned into groups of ten trials each in order of occurrence. Average performance within each bin was calculated and then fitted with a function to determine the number of trials necessary to learn the words at a level of 70% correct. Figure 4 shows the average learning functions for the children with NH (filled symbols) and the children with HL (open symbols). The squares and circles represent performance in the 4- and 9-kHz conditions, respectively. Overall, performance in the 9-kHz bandwidth condition was higher than in the 4-kHz condition and the performance of the children with NH was better than that of the children with HL. For the purposes of this study, the harmonic mean was used to calculate the number of trials necessary to reach the criterion performance of 70%, rather than the geometric or arithmetic mean because it is more appropriate for calculating an average of rates. Table 1 shows the number of trials required by each group to learn all 5 words in each bandwidth condition. On average, both groups required more trials to learn the words in the narrower bandwidth condition, and the children with HL required more trials to learn the words than the children with NH. Statistical analyses revealed a significant main effect of bandwidth but not an effect of group, indicating that limited high-frequency information significantly slowed word learning for both groups.

Two additional results should be noted. First, the learning rate of the children with HL in the 4-kHz bandwidth (121 trials to criterion) was 6 times greater than that of the children with NH in the 9-kHz bandwidth (20 trials to criterion). These conditions best represent the bandwidths that both groups experience in everyday life. The difference in learning rate is consistent with the differences in standardized measures of receptive vocabulary observed in children with HL compared to children with NH (Blamey et al. 2001; Briscoe, Bishop and Norbury 2001; Gilbertson and Kamhi 1995; Pittman et al. 2005). Second, the learning rates for the 9-kHz bandwidth condition were similar for both the children with NH and the children with HL. Although the children with HL had little or no experience with high-frequency information, they were able to learn the new words nearly as well as their normal-hearing counterparts in this condition. This suggests that if children with HL are provided with high-frequency amplification, they may experience immediate benefits as they learn new words.

Summary

The evidence indicates that extending the bandwidth of commercially available hearing aids to 10 kHz may significantly improve children's ability to perceive fricatives (Stelmachowicz et al. 2007), produce fricatives (Moeller et al. 2007), use morphemes consistently and correctly (Moeller et al. 2010), and learn new words (Pittman 2008). Taken together, these results suggest that subtle increases in signal quality may produce a quantitative improvement in children's communication. Therefore, the development of a commercial device offering extended high-frequency amplification is supported. Such a device would allow for the confirmation of these benefits in children over the long term. There are, however, challenges that would accompany the development of such a device. For example, a reliable method for measuring real-ear amplification at frequencies >4 kHz would need to be developed and implemented clinically. Without real-ear confirmation of high-frequency audibility, benefits to speech and language development cannot be determined with any certainty. Also, prescriptive targets for frequencies >6 kHz do not currently exist, again making it difficult to prescribe accurately high-frequency amplification. However, the existing evidence suggests that children with HL would substantially benefit from the effort required to overcome these and other obstacles.

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