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Review article:
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EXTENDING HEARING AID BANDWIDTH: **EFFECTS, CHALLENGES** AND **SOLUTIONS**

Boothroyd and Medwetsky (1992) were the first to suggest that the bandwidth of hearing aids is narrower than that of the acoustic speech signal. Earlier studies related to telephone communication (French and Steinberg, 1947; Fletcher, 1953) had found that an upper limit of 3000 Hz was sufficient to support speech perception for adults with normal hearing. This information, as well as the many technical challenges associated with bandwidth extension, has contributed to the slow progress in this area. In their 1992 study, Boothroyd and Medwetsky focused on the acoustic characteristics of /s/ spoken by adult male and female talkers in an effort to determine the optimal upper bandwidth for hearing aids. Their results revealed that the lowest frequency prominent spectral peak of /s/ varies both within and across talkers and ranges from 2.9 kHz to 8.9 kHz. They concluded that an upper frequency limit of 10 kHz would be needed to ensure the audibility of /s/ for most talkers.

Since the majority of hearing-aid users are adults who acquired hearing loss later in life, lexical, syntactic, and semantic information can be used to “fill in the blanks” when processing speech with a restricted bandwidth. This may be one reason why the acoustic needs of children with hearing loss were not readily considered in the design of hearing instruments for many years.

EFFECT OF BANDWIDTH ON SPEECH PERCEPTION

It has been demonstrated that children with hearing loss often omit /s/ in final position in speech production (Elfenbein, Hardin-Jones, and Davis, 1994). Kortekaas and Stelmachowicz (2000) examined developmental effects in the perception of /s/ and /z/ when used as an inflectional morpheme (denoting tense, plurality, possession). Participants were 5, 7, and 10-year old children and adults with normal hearing. The upper bandwidth was varied adaptively to construct psychometric functions. Results revealed significant differences between the adults and each of the younger age groups, but no differences among the three groups of children. Clarity ratings for target words in low-pass filtered sentences revealed increased clarity as a function of bandwidth for all groups.

In 2001, Stelmachowicz et al. evaluated the effects of stimulus bandwidth on the perception of /s/ by normal-hearing (NH) and hearing-impaired (HI) adults and children (5-8 year olds). Fig. 1 shows the low-pass filter frequency at which performance plateaus as a function of talker for the four groups of participants. When listening to a male talker, NH adults reach maximum performance with a bandwidth of 4 kHz, but the remaining three groups required a bandwidth of 5 kHz. A bandwidth of 9 kHz was needed to reach maximum

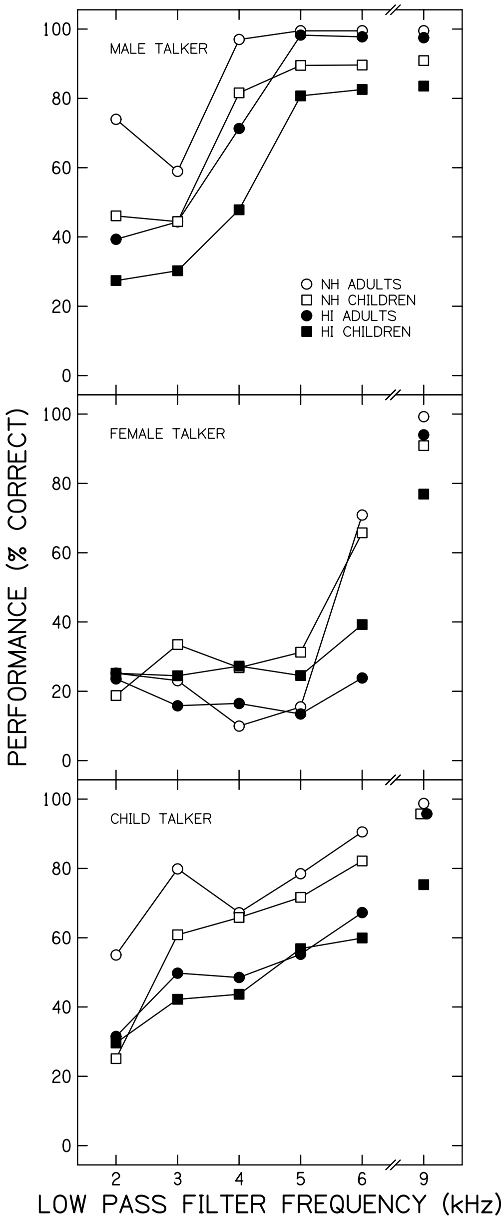

Fig. 1. Low-pass filter frequency for maximum performance as a function of talker. Data are shown for four groups of listeners (Reproduced with permission, Stelmachowicz et al., 2001).

performance for the perception of /s/ spoken by female and child talkers for all listeners.
In a follow-up study, Stelmachowicz et al. (2002) examined perception of /s/ and /z/ spoken by male and female talkers for 36 NH children (3-5 years) and 40 HI children (5-13 years). The latter group wore their personal hearing aids. By age 5 years, 3 months mean scores for both the female and male talkers were > 95% for the children with NH. Results for the HI children revealed an improvement in performance as a function of age, with greater variability for the youngest children. Collapsed across age, slightly better mean scores were observed for the male talker (90%) compared to the female talker (85%). Additional analyses of the HI data revealed that audibility in the frequency region from 2-4 kHz was most important for the perception of these phonemes spoken by a male talker, but that a wider frequency range (2-8 kHz) was needed for the female talker.

Pittman et al. (2003) examined the spectral characteristics of speech produced by adults and 2-4 year old children measured at both 0 degrees azimuth and at the hearing-aid microphone. The goal was to quantify the audibility of specific phonemes for the purpose of monitoring one's own speech. Fig. 2 illustrates the mean short-term spectra of /s/ and /ʃ/ (produced by adult males, adult females, and 2-4 year old children) measured at the hearing-aid microphone. For both phonemes, stimulus amplitude is similar for the male and female talkers, but greater mid-frequency energy is apparent for the male talker. Overall amplitude is markedly reduced for the child talkers; this result may be due to reduced vocal effort by young children and suggests that the ability to adequately monitor one's own productions may be compromised in this group.

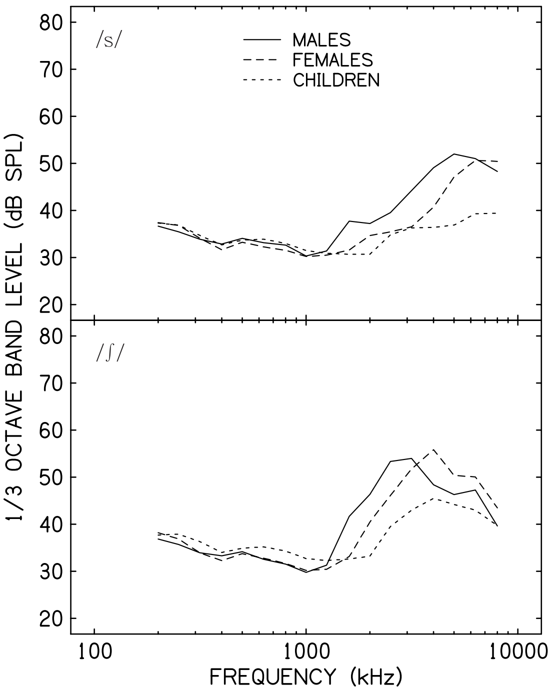

Fig. 2. Spectrum level as a function of frequency for /s/ and /ʃ/ produced by a male, female, and child talker (Reproduced with permission, Pittman et al., 2003).

Early work in the area of hearing-aid bandwidth focused on the perception and production of fricatives. To determine if a restricted bandwidth might also influence more complex auditory skills, Stelmachowicz et al. (2007) examined the effects of bandwidth on word and fricative perception, novel-word learning, and listening effort in both NH and HI children. Results revealed significant effects of bandwidth on perception of the fricatives /s/, /z/, and /ð/ (Fig. 3) and monosyllabic words (Fig. 4). However, no significant effects of bandwidth were found for either novel word learning or listening effort.

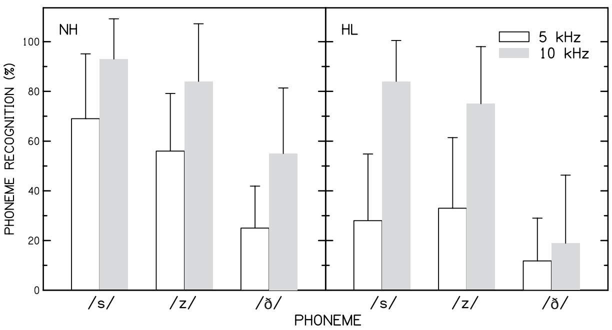

Fig. 3. Percent correct phoneme recognition for /s/, /z/, and /ð/ for listeners with normal hearing and hearing loss. (Reproduced with permission, Stelmachowicz et al., 2007).

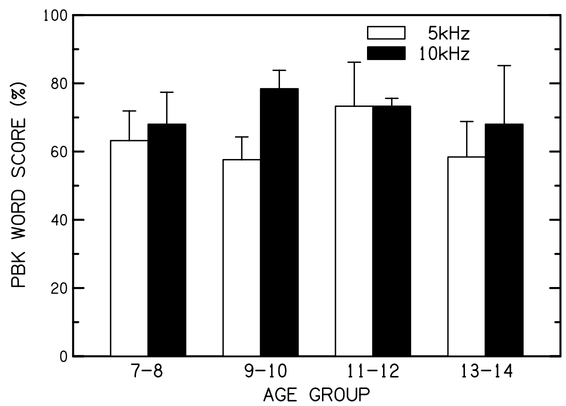

Fig. 4. Percent correct word scores for listeners with hearing loss. (Reproduced with permission, Stelmachowicz et al., 2007).

EFFECT OF BANDWIDTH ON SPEECH DEVELOPMENT

Interestingly, the results of a longitudinal study of phonetic development in infants with hearing loss who were identified early and fitted with hearing aids by 4.7 months (on average) and age-matched infants with normal hearing revealed a significant delay in fricative and affricate development in the children with hearing loss (Moeller et al., 2007). The left panel of Fig. 5 illustrates that the non-fricative sounds are delayed in the HI group relative to the NH children, but that the pattern of development over time is similar for the two groups. For fricatives and affricates (right panel), however, the gap between the two groups increases as a function of age. It is likely that reduced audibility of these speech sounds due to a restricted hearing-aid bandwidth, as well as the common occurrence of reverberation and noise, may be contributing factors to these delays in phonological development. Fig.6 illustrates the development of three classes of speech sounds for the HI children in relation to the NH group. For example, at 16 months of age, the HI children are at 80% of the NH group in terms of vowel acquisition and by 24 months, they have narrowed the gap to 90%. A similar developmental trend is observed for the stops, nasals, glides, and liquids. Consistent with the data reported above, a very different pattern emerges for the fricative class where overall performance is at 40% of the NH group at 16 months and has actually decreased to 30% of normal by 24 months.

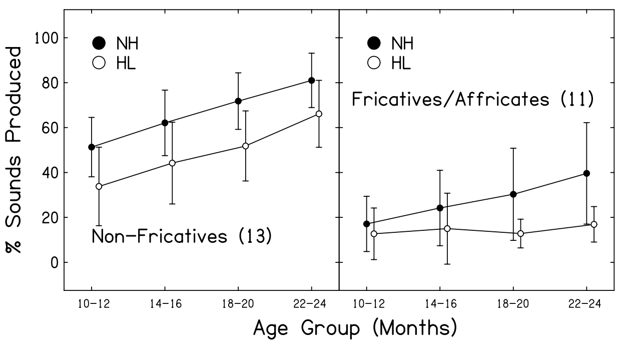

Fig 5. Percent sounds produced as a function of age group for non-fricatives and fricatives/affricates. Data are shown for listeners with and without hearing loss. (Reproduced with permission, Moeller et al., 2007).

EFFECT OF HEARING-AID BANDWIDTH ON QUALITY JUDGMENTS FOR SPEECH AND MUSIC

Recent studies also have examined the effects of stimulus bandwidth on the perceived quality of speech and/or music by adults with hearing loss. Moore and Tan (2003) investigated the perceived naturalness of speech (spoken by male and female talkers). They re-

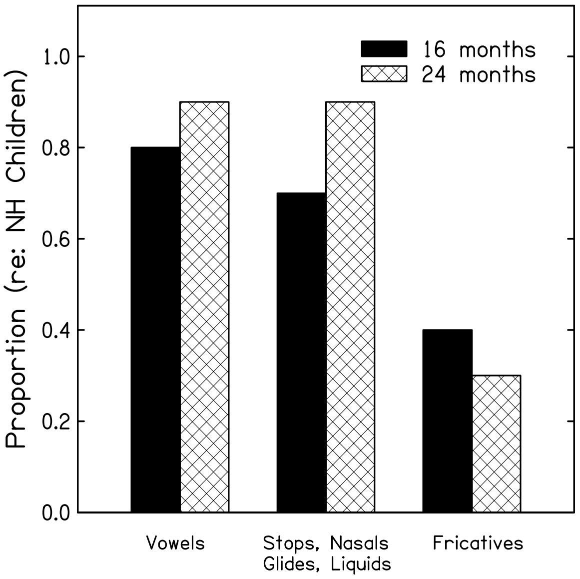

Fig. 6. Proportion of vowels, stops, nasals, glides and liquids and fricatives produced correctly by children with hearing loss at 16 and 24 months of age. (Reproduced with permission, Moeller et al., 2007).

ported a marked degradation in performance when the upper cutoff frequency was decreased below 10,869 Hz. For music, the highest quality ratings occurred at an upper cutoff of 16,854 Hz. More recently, Ricketts et al., (2008) studied the effects of bandwidth on sound quality for adults with hearing loss. Paired comparisons were used to determine preferred sound quality for music and for a movie sound track. Results revealed that preferences were related to the slope of hearing loss in the 4-12 kHz region. Specifically, individuals with steeply-sloping hearing losses showed a preference for narrower bandwidths. To date, no similar studies have been conducted in children with hearing loss.

EXPANDING THE BANDWIDTH OF HEARING AIDS: TECHNOLOGICAL CHALLENGES

Despite major advances in hearing-aid technology over the past decade, the effective bandwidth of current devices typically is narrower than that of the acoustic speech signal. The current ANSI standard for determination of the frequency range (bandwidth) of hearing aid can tend to overestimate the usable bandwidth of hearing aids. Specifically, even in cases where the upper cutoff frequency is relatively high (e.g., 6-7 kHz), the actual use gain may be insufficient to provide audibility for the high-frequency components of speech. This should also be seen in conjunction with the dynamic capabilities of the hearing aid receiver in this frequency region.

There are multiple reasons why an expansion of bandwidth is technologically challenging. It is difficult to build wideband transducers that can provide both high gain and low distortion. In addition, the acoustic coupling for BTE instruments (i.e., tubing and earmold) essentially behaves like a low-pass filter. While the bandwidth of ITE and receiver-in-the-ear-canal devices can be wider than BTE instruments, ear canal size and concerns for hearing-aid retention typically prohibit the use of these devices with infants and young children. Finally, acoustic feedback is likely to increase with an expansion of the upper frequency limit of hearing instruments. This is especially an issue with the pediatric population, where the fast growth of the outer ear makes frequent ear impressions necessary, to ensure a tight fitting earmould. Solutions need to be developed to address the above mentioned challenges.

POTENTIAL SOLUTIONS

The most obvious solution to the limited bandwidth problem is to develop methods to extend the bandwidth of hearing aids without incurring new complications. An alternative approach, however, is the use of frequency-lowering schemes. Several forms of this technology are currently available in wearable hearing instruments. With these devices, real-time digital analysis is used to “shift” or “compress” high frequency sounds to lower frequencies to improve auditory access. In cases where hearing loss in the high frequencies is severe and/or “dead regions” exist, a widened bandwidth will be unlikely to provide sufficient audibility of speech. Frequency-lowering provides an alternative and may be the only option in cases where extending the bandwidth does not achieve audibility.

NEW SOLUTIONS BRING NEW CHALLENGES

As manufacturers strive to extend the upper bandwidth hearing aids, an additional challenge emerges. Specifically, for frequencies above 4 kHz, it is known that standing waves will occur in the ear canal due to an interaction between the incoming sound and reflections from the tympanic membrane. During probe-microphone measures, these minima will be observed as notches in the aided frequency response (Wiener and Ross, 1946; Khanna and Stinson, 1985). These notches are artifacts of the measurement process and are not believed to be indicative of the input to the middle ear and cochlea. In the region where aided gain appears to be insufficient, clinicians are likely to increase hearing-aid gain to compensate for what is thought to be inadequate audibility. These increases in gain may result in excessive amplification with a subsequent risk to residual hearing (Hawkins, 1982). With significant increases in hearing-aid bandwidth, valid and reliable techniques to measure sound levels in the ear canal must be developed (McCreery et al. 2008; Lewis et al., 2009).

References

Boothroyd, A. and Medwetsky, L. (1992). Spectral distribution of /s/ and the frequency response of hearing aids. *Ear and Hearing, 13*, 150-157.

Elfenbein, J.L., Hardin-Jones, M.A., and Davis, J.M. (1994). Oral communication skills of children who are hard of hearing. *J Speech Lang Hear Res, 37,* 216-226.

Fletcher, H. (1953). Speech and Hearing in Communication. New York: Van Nostrand.

French, N.R. and Steinberg, J.C. (1947). Factors governing the intelligibility of speech sounds. *J Acoust Soc Am, 19,* 90-119.

Hawkins, D. B. (1982). Overamplification: A well-documented case report. *J Speech Hear Dis. 47,* 382-384.

Khanna, S. M., & Stinson, M. R. (1985). Specification of the acoustical input to the ear at high frequencies. *J Acoust Soc Am, 77,* 577-589.

Kortekaas, R. and Stelmachowicz, P.G. (2000). Bandwidth effects on children's perception of the inflectional morpheme /s/: Acoustical measurements, auditory detection, and clarity rating. *J Speech Lang Hear Res, 43,* 645-660.

Lewis, J. et al., (2009). Comparison of in-situ calibration methods for quantifying ear-canal sound level. American Auditory Society Meeting. Scottsdale, AZ, March.

McCreery, R., et al. (2008). Use of forward pressure level (FPL) to minimize the influence of acoustic standing waves during probe-microphone hearing-aid measures. International Hearing Aid Conference. Lake Tahoe, CA, August.

Moeller, M.P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., Wood, S.L., Lewis, D.E., Pittman, A.L. & Stelmachowicz, P.G. (2007). Vocalizations of infants with hearing loss compared to infants with normal hearing - Part I: Phonetic development. *Ear and Hearing. 28:* 605-627.

Moore, B. C., & Tan, C. T. (2003). Perceived naturalness of spectrally distorted speech and music. *J Acoust Soc Am, 114*, 408-419.

Pittman, A.L., Stelmachowicz, P.G., Lewis, D.E., & Hoover, B.M. (2003). Spectral characteristics of speech at the ear: Implications for amplification in children. *J Speech Lang Hear Res, 46,* 649-657.

Ricketts, T. A., Dittberner, A. B., & Johnson, E. E. (2008). High-frequency amplification and sound quality in listeners with normal through moderate hearing loss. *J Speech Lang Hear Res, 51,* 160-172.

Stelmachowicz, P., Pittman, A., Hoover, B., and Lewis, D. (2001). The effect of stimulus bandwidth on the perception of /s/ in normal and hearing-impaired children and adults. *J Acoust Soc Am, 110,* 2183-2190.

Stelmachowicz, P.G., Pittman, A.L., Hoover, B.M., & Lewis, D.L. (2002). Aided perception of /s/ and /z/ by hearing-impaired children. *Ear and Hearing, 23*, 316-324.

Stelmachowicz, P.G., Lewis, D.E., Choi, S., Hoover, B. (2007). Effect of stimulus bandwidth on auditory skills in normal-hearing and hearing-impaired children. *Ear and Hearing, 28,* 483-494.

Weiner, F. M., & Ross, D. A. (1946). The pressure distribution in the auditory canal in a progressive sound field. *J Acoust Soc Am, 18,* 401-408.

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