Do Children Require More High-Frequency Audibility than Adults with Similar Hearing Losses?

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Introduction

Speech cannot be understood if it cannot be heard. Therefore, audibility is undoubtedly a major goal of amplification for children and adults with hearing loss. In restoring audibility, it is often assumed that the listener can extract speech cues over the entire range of speech frequencies. This assumption is true for a person with mild to moderate hearing losses, but is not true when hearing loss is severe at the high frequencies. In addressing whether severely hearing-impaired children require more high-frequency audibility than adults with similar hearing losses, we will firstly examine how audibility affects judgments of speech intelligibility and measured speech intelligibility for severely hearing-impaired adults and children. Secondly, we will attempt to identify the factors that affect the usefulness of audibility for speech intelligibility. Finally, we will discuss the implications of the relationship between audibility and speech intelligibility for prescribing gain-frequency response for adults and children.

Does More Audibility Lead to Better Speech Intelligibility?

Adults

In an evaluation of the NAL-R prescription (Byrne and Dillon 1986), Byrne, Parkinson and Newall (1990) determined the gain-frequency response requirements of a group of 46 severely hearing-impaired adults using a combination of judgments and measurements of speech intelligibility, and home trials with different frequency responses. It was found that the listeners with the poorest hearing at the high frequencies required more gain in the low frequencies than was necessary to amplify these frequencies to the same loudness as other frequencies. These results led to the incorporation of a profound correction that prescribed less high-frequency emphasis than that required to achieve equal loudness across frequencies when hearing loss is severe in the high frequencies (Byrne, Parkinson and Newall 1991). For people who had relatively normal low-frequency hearing but severe high-frequency losses, Murray and Byrne (1986) found that out of the five listeners tested, one performed significantly better when the amplification bandwidth was limited to 2500 Hz, three preferred a bandwidth of 3500 Hz, and only one benefited from an extension of bandwidth to 4500 Hz.

Hogan and Turner (1998) investigated the degree of benefit obtained by hearing-impaired people from high-frequency amplification of speech. They tested 9 listeners and concluded that for hearing losses of 40 dB HL and less, adding audible speech provided as much benefit to a hearing-impaired person as it did to a normally hearing person. However, when hearing loss was about 60 dB or worse around 4000 Hz, the average benefit of adding audible speech was close to zero. Similar results were obtained for a group of 10 listeners with sloping losses (Turner and Cummings 1999).

Ching, Dillon and Byrne (1998) examined the factors affecting the amount of information that hearing-impaired listeners can extract from an audible signal. They tested a group of 40 listeners with different degrees of hearing losses, and found that severely hearing-impaired listeners were less proficient than

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Table 1. Mean hearing threshold level (HTL) in dB HL, standard deviations (SD), and Range of HTL for 21 subjects.

		Frequency (Hz)				
		250	500	1000	2000	4000
Severe Flat						
(n = 12)	HTL	75.4	79.6	82.9	80.8	80.4
	SD	12.8	12.7	9.8	11.0	13.4
	Range	45–75	65–80	70–83	55–81	60–81
Severe Sloping						
(n = 9)	HTL	69.4	75	86.1	94.4	107.8
	SD	20.4	15.6	10.8	8.1	17.7
	Range	30–90	45–90	70–100	80–105	75–125

normally hearing listeners in using the speech information contained in an audible signal. Amplifying high frequencies to high sensation levels for people with severe losses at these frequencies could even be detrimental for speech intelligibility. The authors concluded that apart from reduced audibility, a severely hearing-impaired individual's proficiency at extracting information from an audible signal was reduced by the need to listen at high sound pressure levels, and was further reduced when the individual had to listen at high sensation levels.

In our recent research, we measured speech recognition of a group of 21 severely hearing-impaired people using narrow and broad bands of speech. Twelve of the listeners had flat audiometric configurations and nine had sloping configurations. Table 1 shows the mean hearing threshold levels of the two groups. We presented the listeners with BKB sentences (Bench and Doyle 1979) that were low-pass filtered with cut-off frequencies at 1400 Hz, 2800 Hz, and 5600 Hz respectively using a Kemo filter (48 dB/octave). The overall long-term average rms levels of individual sentences were equalized. The sentences were played back using a digital cassette tape-recorder, shaped with a rising frequency response corresponding to the inverse of the international long-term average one-third octave band speech spectrum (Byrne et al. 1994), and presented monaurally via a TDH-49 earphone. For each set of filtered stimuli, the sound pressure level for detection by each listener was first established by asking him/her to adjust a remotely controlled attenuator with 1 dB steps until the sound was just audible. The speech stimuli were then presented at 6, 12, 18, 24, 30, and 36 dB above the detection level for each individual, and the listener was required to repeat as much of each sentence as possible.

Figure 1 shows the mean speech scores for the three filtered conditions for the two groups of listeners. Speech scores improved with increases in sensation level. It is worth noting that the first 24 dB of sensation level provided most of the information for speech intelligibility. Further increases in sensation level resulted in little improvement in speech scores or even a small decrement in performance in the case of wide-band speech presented to the group with severe sloping loss.

Speech scores also increased when the bandwidth was extended from 1400 to 2800 Hz, but there was no further increment with a further extension of bandwidth to 5600 Hz. For the severe sloping group, speech scores deteriorated with increased bandwidth at high sensation levels. The reduced performance with the broadest bandwidth and highest sensation level is consistent with our previous report on the limited efficacy of high-frequency amplification for severe losses. These results also agree with those reported by Amos and Humes (2001) showing that for a group of adults with moderate to severe high-frequency loss, word recognition improved when amplification bandwidth was extended from 1600 Hz to 3200 Hz, but no further increases were obtained when the bandwidth was extended to 6400 Hz. All of the above results support the proposition that when hearing loss is extreme at the high frequencies, it is not beneficial to attempt to provide audible signal at those frequencies.
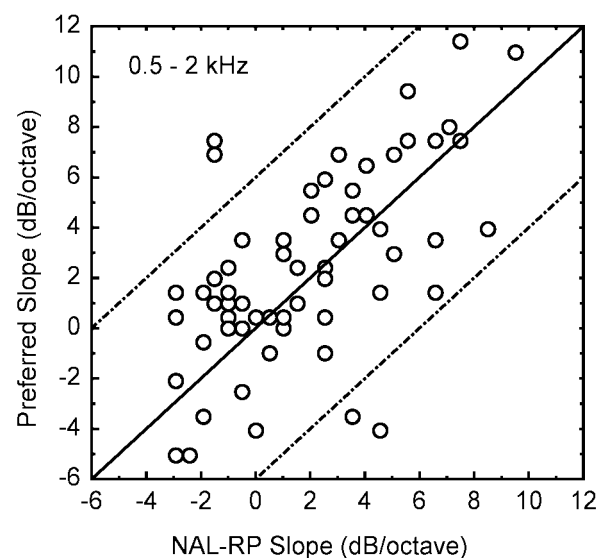
Children

Are the findings with adults applicable to children? The amplification needs of children have been investigated directly using judgments and measurements of speech intelligibility. Snik, van den Borne,

Sentence perception
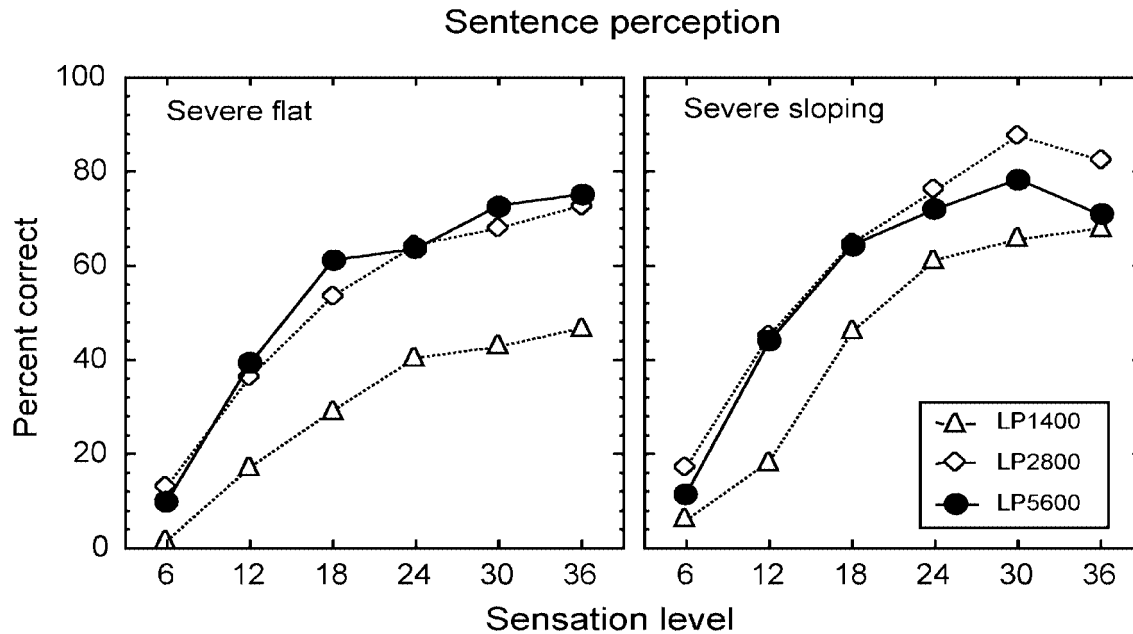
Figure 1. Mean percent correct for BKB sentences low-pass filtered at 1400 Hz (triangles), 2800 Hz (diamondss), and 5600 Hz (circles) at six sensation levels. The left panel shows scores for 12 adults with severe flat losses, and the right panel shows scores for 9 adults with severe sloping losses.

Brokx and Hoekstra (1995) optimized the hearing aid fittings of a group of 16 profoundly hearing-impaired children by a refitting and evaluation procedure, and compared the resultant fittings to several prescriptions. The authors concluded that the NAL-RP proved to be the most adequate rule for obtaining the desired insertion gain. Byrne et al. (1991) compared the best gain-frequency response determined using judgments and performance of speech intelligibility for a group of 14 children with those for 46 adults determined in the same way, and found that the requirements were similar between the two groups. Like adults, children who had severe to profound hearing losses in the high frequencies required less high-frequency emphasis and more low-frequency audibility for better speech intelligibility.

In an evaluation of the NAL-RP prescription for children, Ching, Newall and Wigney (1996), and Ching, Hill, Birtles and Beecham (1999) determined the best frequency response for understanding speech for 43 children with severe and profound hearing losses using speech intelligibility judgments. The children compared the NAL-RP prescription with alternative frequency responses that provided either more or less high-frequency emphasis while they listened to a story, and selected the frequency response

Figure 2. Preferred frequency response slope from 500 to 2000 Hz expressed in terms of dB/octave in relation to the NAL-RP prescribed slope.

that was best for understanding speech. Figure 2 shows the children's preferences in relation to the NAL-RP prescription. On average, the children's preferred frequency response was not significantly

different from the NAL-RP prescription. When the children's preferences were compared to the DSL prescription which was developed with children in mind (Seewald, Ross and Spiro 1985), about half agreed with the prescription, with the remaining children all preferring less high-frequency emphasis than that prescribed by the DSL formula. Although the NAL-RP has been derived mainly on the basis of adult data, the good agreement between the frequency response judged to be best for speech intelligibility by children and the NAL-RP prescription suggests that children's amplification needs are the same as adults with similar hearing losses. However, the extent to which the preferences and performance of children were affected by the amplification characteristics that they were familiar with is not known. The amplification characteristics would have been constrained by the conventional hearing aids the children were wearing, and perhaps also the prescription used for fitting in circumstances where one was applied.

Can we expect children who are provided with similar levels of audibility as adults to recognise speech as well as adults? Not really, as it has long been known that age has an effect on a range of auditory and speech perceptual tasks. Byrne (1983) demonstrated that five-year-old children with normal hearing required about 15 dB more gain than adults to recognise words as well as adults. More recent evidence on detecting and discriminating speech in noise (Nozza, Rossman, Bond and Miller 1990; Nozza, Rossman and Bond 1991; Nozza 2000) and recognition of sentences (Stelmachowicz, Hoover, Lewis, Kortekaas and Pittman 2000) all indicated that younger children who have normal hearing required greater audibility than older children or adults to achieve similar levels of performance. Hnath-Chisolm, Laipply and Boothroyd (1998) concluded that developmental changes in speech perception capacity appeared to be related to cognitive and possibly, to phonological and linguistic developments rather than to sensory capability. It cannot be inferred from these studies that younger hearing-impaired children required greater high-frequency audibility than adults for speech understanding. Indeed, Pittman and Stelmachowicz (2000) showed that on average, 10-year-old children with moderate hearing losses perceived the fricatives /f/, /θ/, /s/, /ʃ/ as well as adults with similar hearing losses at an equivalent audibility level. There is no doubt that the development of speech skills continues over the first ten years of life for normally hearing children, but

there is no research guiding how amplification could be varied systematically with auditory training and experience to encourage the development of speech processing skills of hearing-impaired children, or indeed whether it is desirable to do so.

Factors That Affect the Usefulness of Audibility

If the goal of amplification is to maximise speech intelligibility, it is necessary to consider the relative usefulness of an audible signal at different frequencies so that optimal sensation levels can be provided in each region. The factors affecting the usefulness of an audible signal for children and adults with severe hearing losses are not well understood. For adults with acquired extreme hearing losses at the high frequencies, it is clear that many of them could no longer make effective use of the audible signal presented in that region although they had the ability to do so prior to the onset of severe hearing loss.

The usefulness of audibility for speech intelligibility can be examined using a theoretical model called the Articulation Index or AI (ANSI 1969). The calculation method has been revised and is now known as the Speech Intelligibility Index or SII (ANSI 1997). The AI is calculated by adding how much the speech peaks exceeds hearing thresholds (or how much is audible) at each frequency. The maximum contribution is limited to 30 dB. The amount of audible signal at different frequencies is weighted by the relative importance attached to those frequencies. For average speech, the importance for critical bands from 450 to 4000 Hz is equal (Pavlovic 1987). The sum of the weighted audibility across all frequencies gives the AI, which can be related to speech scores by a transfer function. Speech performance can be accurately predicted from the AI for people with normal hearing, and those with mild and moderate hearing losses (Dirks, Bell, Rossman and Kincaid 1986; Dubno, Dirks and Schaefer 1989), but the AI overestimates performance of people with severe hearing losses (Dugal, Braida and Durlach 1978; Pavlovic, Studebaker and Sherbecoe 1986). This implies that the contribution of a certain amount of audibility is reduced when hearing loss is severe.

The SII method includes a level distortion factor in the calculation of the audibility function. This factor stipulates that the contribution of audibility starts to decrease when the overall sound pressure level

exceeds 73 dB SPL. Many severely hearing-impaired listeners require sound pressure levels much higher than this for sounds to be audible, and are therefore susceptible to the effects of level distortion. Recent research indicates, however, that level distortion cannot adequately account for the reduced performance of people with severe losses. Ching et al. (1998) proposed a method of quantifying the proficiency of each individual in extracting information from an audible signal at each frequency region (equation 9). For the octave band centered at 4000 Hz, an audible signal made zero contribution to intelligibility for many of the severely hearing-impaired listeners. This effect can be visualised in figure 2, which shows that extending the speech bandwidth from 2800 to 5600 Hz or increasing audibility at frequencies where the hearing is most impaired does not necessarily lead to increased speech scores.

The reasons underlying degraded proficiency are as yet undefined. It is generally accepted that hearing thresholds more than 60 dB higher than normal are likely to involve both outer hair cell and inner hair cell dysfunction (Van Tasell 1993). When thresholds exceed 90 dB in the high frequencies, Moore (2001) suggested that the hearing loss is likely to be associated with a dead region or a region with a population of non-functioning inner hair cells in the cochlea. A major manifestation of hair cell dysfunction is reduced frequency resolution. We have therefore sought to find a physiological explanation of the reduced proficiency by measuring frequency resolution of the 21 listeners whose speech scores are shown in figure 2. We used a notched-noise method as described in detail in Ching, Dillon and Byrne (1997, p 442). Briefly, we derived a frequency resolution index by measuring the difference in the levels between a continuous noise masker and a notched-noise masker necessary to mask a probe tone presented at 10 dB sensation level. Proficiency factors for the same listeners at 0.35, 1, 2, and 4 kHz were derived using the method reported in Ching et al. (1998). Correlation analysis was performed between proficiency and frequency resolution index at the same frequency regions. Significant correlations ($p < 0.05$) were obtained between frequency resolution at 2 kHz and proficiency at 2 kHz; and also between frequency resolution at 1 and 2 kHz and proficiency at 4 kHz. Figure 3 shows the relation between frequency resolution at 2 kHz and the proficiency at 2 and 4 kHz.

Because both frequency resolution and proficiency were related to hearing threshold levels ($p < 0.05$), the effects of hearing threshold on resolution and proficiency were partialled out before fur-
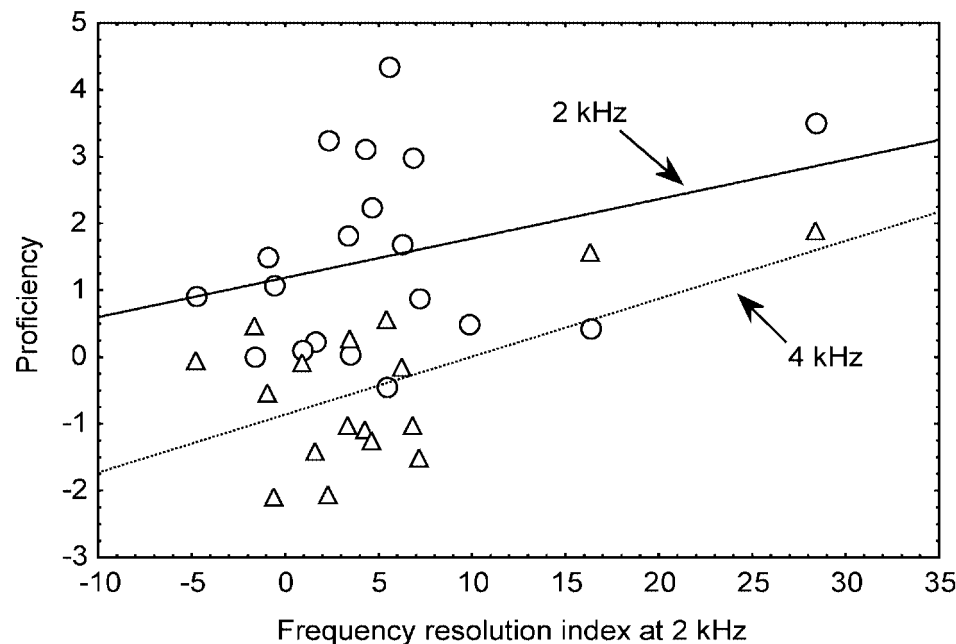
Figure 3. Individual proficiency at 2000 Hz (circles) and 4000 Hz (triangles) in relation to frequency resolution at 2000 Hz.

ther analysis. Forward stepwise regression using proficiency at 4 kHz as a dependent variable and frequency resolution at the four frequencies as independent variables showed that frequency resolution at 2 kHz accounted for about 50% of the variance of proficiency at 4 kHz at best. This regression result applied only to data from people with severe hearing losses. Our previous analysis that included listeners with a range of hearing losses showed that reduced frequency resolution could not explain variations in proficiency adequately. Even in the current analysis, about half of the variance remains unexplained.

There is no doubt that a listener's proficiency in extracting useful information from an audible signal decreases as hearing loss increases. We refer to this as 'desensitization', after Studebaker, Sherbecoe, McDaniel and Gray (1997). Using data reported in an earlier paper (Ching et al. 1998), we derived the relationship between hearing thresholds and desensitisation at different frequencies (Ching, Dillon, Katsch and Byrne 2001). Figure 4 shows desensitised audibility in relation to audibility at 2 and 4 kHz. For a 60 dB hearing loss at 2 kHz (or lower in frequency), a listener could be expected to extract information from an audible signal almost as effectively as a normally hearing person, but a listener with the same degree of hearing loss at 4 kHz could extract only about half of the information contained in an audible signal for speech perception. This relative difference in effectiveness of audibility at low and high frequencies

for the same degree of hearing loss may be explained by the relative importance of time and place cues for extracting information in the respective frequency regions. It is known that people, even those with normal hearing, can use fine timing information to extract information in the low and mid frequencies, but have to rely on spectral (or place) cues in the high frequencies (Fletcher 1995). Because cochlear impairment appears to degrade frequency resolution more than temporal resolution (Moore 1995), greater desensitisation would be expected to occur at the high frequencies than the lower frequencies for the same degree of audiometric loss.

Implications for Prescribing High-Frequency Gain

Adults

Can we decide when a hearing loss at a certain frequency is so severe that it is not aidable, and therefore ignore it in calculating the optimal frequency response? No, even on average, we cannot set a definite cut-off point because how much an audible signal in a frequency region is worth having depends on the input level as well as the hearing loss at other frequencies. When prescribing amplification for people with severe hearing losses, sounds must be amplified to be both audible and comfortable in a typically small dynamic range. For low input levels, the
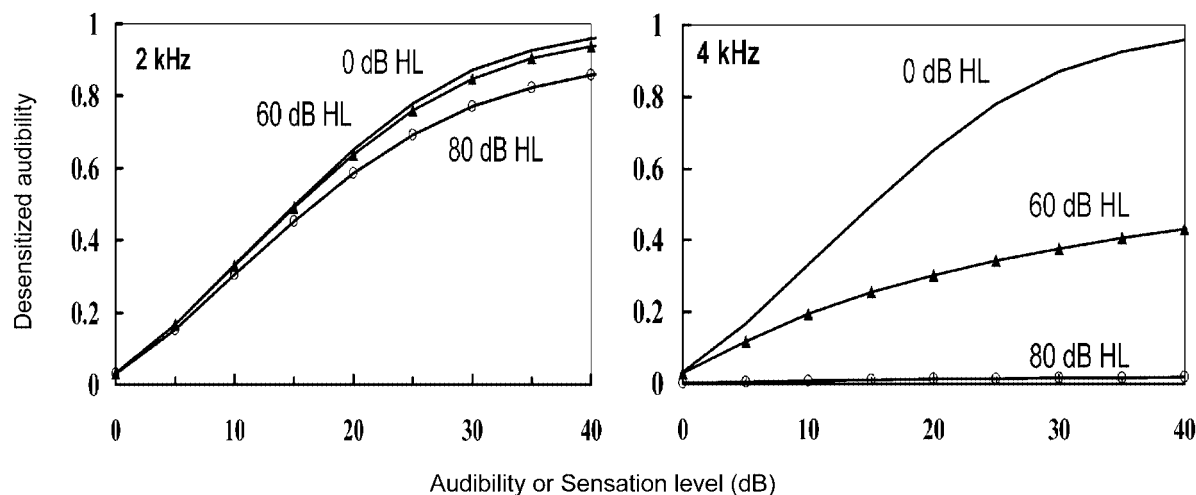
Figure 4. Averaged desensitised audibility in relation to audibility for 0 dB HL (solid line), 60 dB HL (line with triangles), and 80 dB HL (line with circles) at 2000 Hz and 4000 Hz.
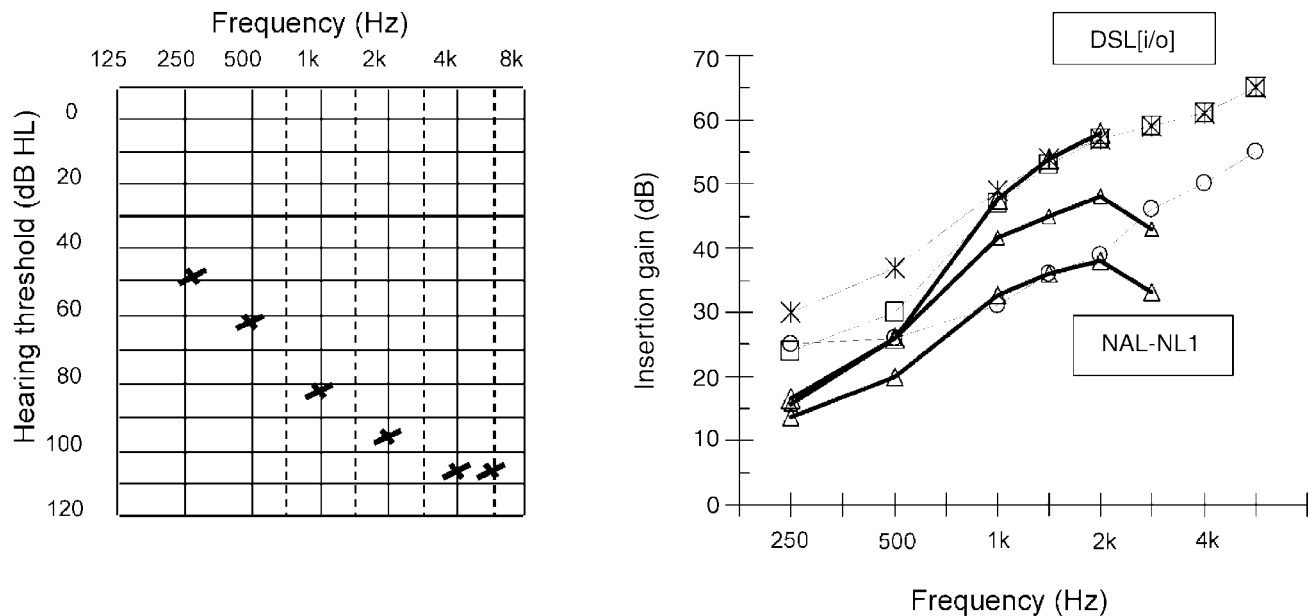
Figure 5. The left panel shows a severely sloping audiogram, and the right panel shows the insertion gain prescriptions for NAL-NL1 (bold) and DSL[i/o].

overall loudness has to be kept low, and amplification of frequencies with effective hearing to optimal levels should take precedence over other frequencies where audibility is less effective. For high input levels, audibility can be provided across a wider frequency range. The usefulness of an audible signal at one frequency region also depends on the hearing losses at other frequencies. For example, if the hearing threshold level were 100 dB HL at the higher frequencies, then it might be desirable to amplify these frequencies if the hearing loss were also profound or very severe at the low frequencies, whereas this might not be so if hearing threshold levels at the low frequencies were greatly better than at the high frequencies. The general point is that the decision for how much gain to provide at different frequencies must depend on an evaluation of the relative effectiveness of audibility at different frequencies. Such considerations will need to include the hearing loss at the specific frequency, the hearing loss at other frequencies, and the overall speech input level. The NAL-NL1 prescriptive procedure (Dillon 1999) attempts to take these general recommendations into account. For any individual, the optimal response will presumably also depend on whether the person has better-than-average or worse-than-average frequency selectivity for that degree of hearing loss.

Figure 5 illustrates the differences in gain-frequency response prescribed for a hypothetical listener who has severe sloping hearing losses when effectiveness of audibility was (NAL-NL1) and was not considered (DSL[i/o]; Cornelisse, Seewald and Jamieson 1994; Seewald et al. 1997) respectively. The left panel shows the audiogram, and the right panel shows the insertion gains for 50, 65, and 80 dB input levels for each prescription.

The two gain-frequency responses for an average input of 65 dB are shown in figure 6.

The top right graph shows overall loudness of amplified speech for each response using a loudness model proposed by Moore and Glasberg (1997). The bottom right graph shows SII that included level distortion and hearing loss desensitisation calculated using a modified SII method (Ching et al. 2001). The graph shows that the gain-frequency response prescribed by DSL[i/o] is better (higher SII) than NAL-NL1 for speech intelligibility, but the former is also twice as loud as the latter. In practice, a hearing-aid user would adjust the volume to achieve a preferred loudness level. Therefore, a valid comparison of two prescribed frequency response needs to be made at equated loudness levels (Studebaker 1992). Figure 7 shows that the frequency response prescribed by NAL-NL1 is better for speech intelligibility (higher
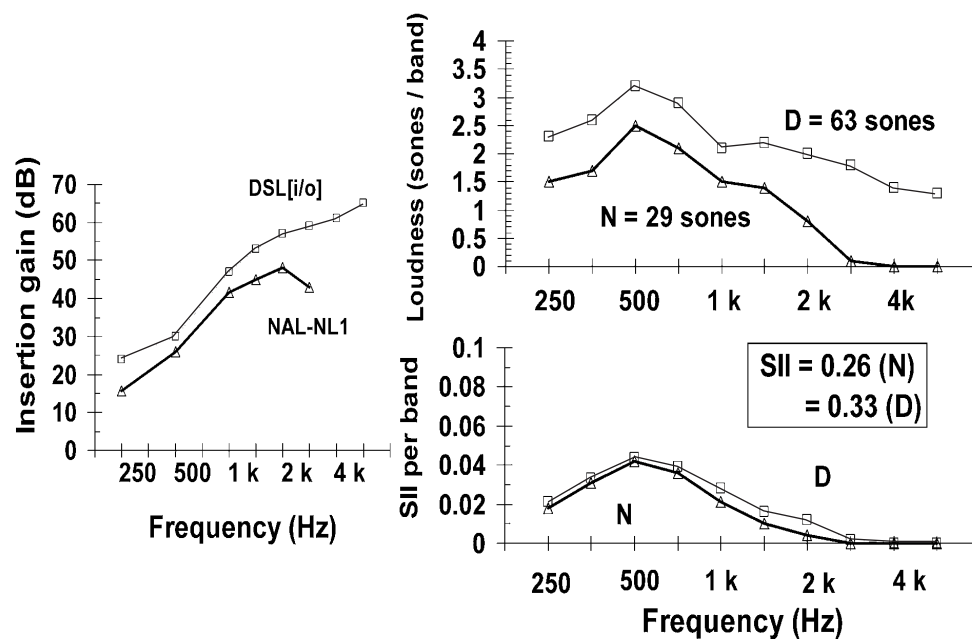
Figure 6. The left panel shows the NAL-NL1 (triangles) and DSL[i/o] (squares) for speech input level of 65 dB SPL. The top right panel shows loudness in sones per band for the two prescriptions, and the bottom right panel shows SII per band. SII = Speech Intelligibility Index, N = NAL-NL1, D = DSL[i/o].
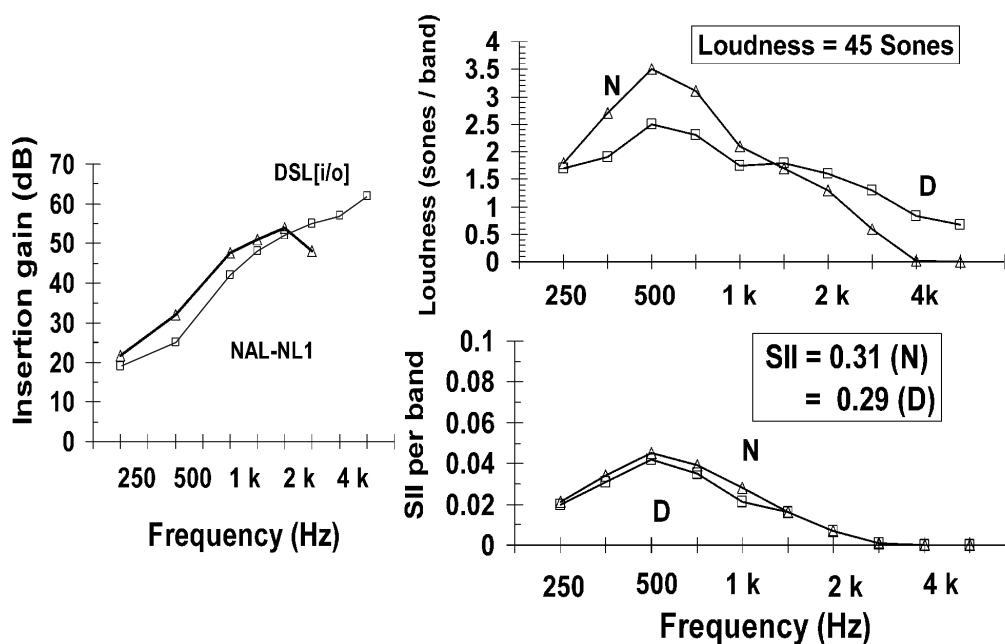
Figure 7. As in figure 6, but with the two prescriptions equated in loudness.

SII) than the frequency response prescribed by DSL [i/o]. The same is true for input levels at 50 dB and 80 dB when the two prescriptions are compared at equated loudness levels.

Children

Would the same conclusions be applicable to prescribing amplification for children? The crux of the matter lies in what causes the hearing loss desensitisation observed for the high-frequency parts of speech. Cochlea damage undoubtedly leads to deterioration in frequency and temporal resolution ability, but for the same degree of hearing loss, greater desensitisation is observed in the high frequencies than in the lower frequencies. If the degraded ability at the high frequencies occurs because the human cochlea is inherently dependent on spectral (place) cues for extracting information in this region, whereas it can rely on both time and place cues in the lower frequencies, then it is not possible to convey substantially more high-frequency information effectively to people with severe losses at the high frequencies. Providing children with greater high-frequency emphasis than that required by adults with a similar hearing loss would result in loudness that many adults are not willing to tolerate. Simply adding 10 dB more gain at the high frequencies, for instance, would increase the overall loudness of the amplified signal, and the hearing-aid user would need to adjust the volume to re-establish a preferred loudness level. That would result in something less than 10 dB extra signal at the high frequencies and a reduction in signal at lower frequencies. The information that is lost due to sub-optimal levels of audibility at these less-impaired frequencies may be greater than what is gained by increasing audibility at the more-impaired frequencies. In circumstances where the hearing-aid user could not or was not permitted to adjust the volume (as is often the case for young children), excessive noise exposure might lead to further damage to the cochlea (Macrae 1991, 1995).

If, on the other hand, the degraded analytic ability at the high frequencies occurred because of deprivation of adequate auditory stimulation for a long time, then children should be provided with more high-frequency amplification than is currently prescribed for adults. Indeed, children should be provided with high-frequency gain adequate to achieve good audibility as soon as possible to facilitate the development of processing skills in this region. The same could be said for adults – they should be provided with good audibility at the high frequencies soon after the onset of deafness in order to preserve their processing ability. These two potential causes of hearing loss desensitization imply opposite courses of action for prescribing amplification for children.

The Prescription and the Individual

Even when an appropriate prescription is used, it is important to recognise that a prescription is a simple rule that is best for an average listener, and is unlikely to be perfect for every individual at all times. In terms of prescribing high-frequency emphasis, it can be expected that a person who has better-than-average analytic ability might require more gain in the high frequencies than is prescribed, whereas a person who has poorer-than-average analytic ability might require less high-frequency gain than is prescribed. Some researchers proposed the use of measurements such as temporal resolution (Ochs 1990), or estimations of dead regions (Moore 2001) in addition to hearing thresholds to derive the appropriate gain-frequency response for each individual. The precise link between these measurements and the resulting prescription is yet to be specified, however, and validation of this link is yet to be performed.

For infants and young children, often very little audiological information is available despite the necessity to provide timely amplification after diagnosis. Additional measurements such as those proposed are not feasible or practical. Using a prescription that is validated to be correct on average as a starting point would minimise the need and extent of adjustment required for an individual. To optimise amplification for each individual, NAL recommends that hearing aids be initially adjusted using a prescription, then fine-tuned individually using an evaluation procedure (Byrne and Cotton 1988; Byrne 1994). Currently, research efforts at NAL are directed towards the development of a range of evaluative procedures that are suitable for infants and children of different age groups. These include the use of a clinical paired-comparisons test (Ching et al. 1999), or a functional assessment method comprising structured interviews with parents and/or teachers (Ching, Hill and Psarros 2000; Ching et al. 2001). We are also investigating the use of cortical potentials as a means for evaluating or fine-tuning hearing aids. To better understand the amplification requirements of children with different degrees of hearing losses, NAL is

collaborating with the University of Western Ontario (UWO) on a joint project funded by the Oticon Foundation. Given that children in Australia would have been fitted with hearing aids according to a NAL prescription, and children in Canada would have been fitted with hearing aids according to a DSL prescription, our collaborative study will also enable us to determine the effects of previous experience on amplification requirements of children.

Summary

The question of whether children require greater high-frequency audibility than adults depends on the cause of the reduced ability of the impaired ear to extract information from an audible signal as hearing loss increases (hearing loss desensitisation). The desensitisation is more pronounced at the high than at the lower frequencies. If this is caused by deprivation of auditory stimulation at the high frequencies, than adequate gain must be provided to achieve good audibility at these frequencies. To the contrary, if it occurs because of fundamental differences in the way information is extracted at low and high frequencies by the human cochlea, providing greater high-frequency emphasis than is required by adults to children would only expose the children to excess loudness or lead to less than optimal levels of gain at lower frequencies without conveying more information at the high frequencies. The issue needs to be resolved by research. Nonetheless, it is clear that methods for predicting optimal amplification that simply rely on audibility will lead to erroneous conclusions for many hearing-impaired people, including children.

To date, there is no conclusive evidence showing that young children should be treated differently from older children or adults with respect to prescribing amplification, provided that such amplification is in real-ear terms thereby accounting for the effects of different ear-canal sizes.

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