Background Story

SoundRecover

The importance of wide perceptual bandwidth

Summary

It is particularly important for people with hearing impairment to be able to perceive and discriminate high-frequency sounds easily and accurately. These signals contain information about speech that benefits intelligibility, especially in some common noisy listening conditions. Clear perception of such sounds can also provide valuable localization cues and specific benefits for speech production. Recently, some advanced digital hearing instruments have been introduced that are claimed to provide extended bandwidth, and therefore improved amplification of high-frequency sounds. However, the bandwidth, measured using electroacoustic techniques, is not necessarily representative of the perceptual bandwidth obtained with real fittings. When the perceptual bandwidth is estimated taking into account the audiogram configuration of each hearing-impaired listener, it can be demonstrated that the greater amplification of high frequencies expected with extended-bandwidth devices is difficult to achieve in practice. In contrast, the Phonak proprietary non-linear frequency-compression scheme, SoundRecover, can effectively extend perceptual bandwidth by improving audibility and discrimination of high-frequency signals.

Introduction

A critical parameter of any communications system is **bandwidth**, which characterizes its information-carrying capacity. Access to the Internet, for example, is much faster via a broadband than a dial-up connection. This is mainly because a broadband connection utilizes higher frequencies to convey digital data. In general, bandwidth is defined in terms of the range of frequencies that can be carried by a communication channel. Widening the bandwidth means increasing the frequency range, and thereby enabling more information to be delivered through that channel.

The same concept can be applied to hearing. It is commonly accepted that the normal human auditory bandwidth encompasses the range of frequencies from 20 Hz to 20 kHz. However, the audibility of a sound such as a pure tone depends not only on its frequency but also on its level.

Consequently, a more useful practical definition of bandwidth would specify the range of frequencies at which tones can easily be made comfortably loud. This is illustrated in Figure 1 (Robinson & Dadson, 1957), which shows the level in dB SPL (vertical axis) required to produce the same loudness for tones heard across a wide range of frequencies (solid curve).

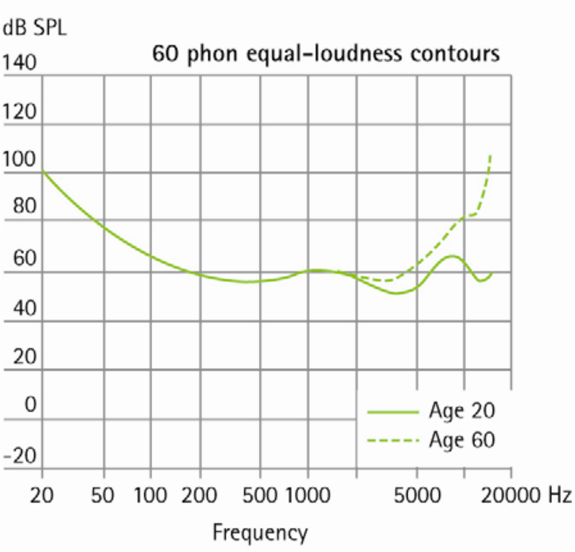

Figure 1 Equal loudness contours for young (solid curve) and older (dashed curve) listeners with normal hearing. The vertical axis shows a moderate level that is perceived as equally loud across frequency (horizontal axis).

In this graph, a tone at 1 kHz is shown as having a level of 60 dB SPL, which would be comfortably loud for an average listener with normal hearing. To maintain the same loudness as the frequency is changed, the level of the tone would need to be adjusted by less than about 10 dB across a frequency range from approximately 80 Hz up to nearly 20 kHz. At frequencies below 80 Hz, the level would need to be increased for the same perceived loudness. For example, a tone at 20 Hz would have to be presented at about 100 dB SPL to be heard as equal in loudness to the 1 kHz tone at 60 dB SPL. This demonstrates that audible bandwidth depends strongly on the sound level, even for normally hearing listeners. Generally, the effective perceptual bandwidth can be increased by raising the level of sounds.

Figure 1 also shows equal-loudness data for older listeners who were assumed to have normal hearing (dashed curve). Although those listeners had no signs of ear disease, their average sensitivity to high-frequency tones was much poorer than that of younger listeners (solid curve). At 10 kHz, for instance, the level difference between these two groups was almost 20 dB for the same loudness. Even larger differences are evident at higher frequencies. In contrast, the listeners' age had no effect on the equal-loudness data for frequencies lower than about 2 kHz. These measurements are consistent with the findings of many research studies which have shown that high-frequency hearing sensitivity tends to decline as a person ages, even in the absence of any specific pathology. Thus, when the bandwidth of hearing becomes narrower as a result of age-related hearing loss, the usual reason is a change in sensitivity at high frequencies rather than low frequencies. Furthermore, a similar type of bandwidth reduction can result from many common causes of hearing impairment, including exposure to excessive amounts of noise, various diseases, side-effects of ototoxic drugs, and other etiologies.

How do these considerations apply to a person who uses a hearing instrument (HI)? The answer is complicated by the presence of two interacting factors. First, there is the particular configuration of each HI user's hearing impairment, as characterized by the audiogram. The second factor is the effective bandwidth of the HI, which depends on its gain and maximum output level, parameters that inevitably vary as a function of frequency. In addition, certain sound-processing techniques such as frequency lowering can affect the perceptual bandwidth. As discussed below, to realistically determine the bandwidth of sounds available to a given HI user it is essential to consider the **combined** effect of these factors.

Perceptual importance of high frequencies

Many sounds that contribute to speech intelligibility contain or are dominated by high-frequency components. As just one familiar example, the presence or absence of the phoneme /s/ at the end of almost any English noun indicates whether the speaker means several items or only one item. Depending on the age and gender of the speaker, that phoneme typically has a spectral peak between 4 – 6 kHz, and often contains intense components up to beyond 10 kHz. There are numerous other speech sounds in every language that can be discriminated more readily when high-frequency parts of the signal are clearly audible. When a listener is attempting to understand speech in a noisy environment, these acoustic signals are particularly important because they are less susceptible to masking by the relatively intense low-frequency components of many common types of noise. Furthermore, young children with a hearing impairment who are learning a language for the first time benefit from being able to hear the high-frequency speech sounds that they are trying to produce (Stelmachowicz et al, 2002).

In addition to these well-established benefits for speech perception (Simpson et al, 2005) and production, ensuring the audibility of high-frequency sounds provides other advantages. For example, some valuable information about the source of sounds, such as birdsong and various important environmental noises, is conveyed principally by high-frequency components. The subjective quality of these sounds tends to be judged as relatively poor if the high frequencies are too soft or inaudible (Moore & Tan, 2003). The ability of people with a hearing impairment to localize sounds that contain high frequencies may also be improved with extended HI bandwidth, because the difference in level of sounds between ears can provide a strong cue to the direction of a sound source. As the level difference must be perceived as a loudness difference between ears for this cue to be reliable, the HI requires adequate bandwidth to ensure high-frequency signals are heard at appropriate levels (Dubno et al, 2002).

Hearing-instrument bandwidth

In the past, the high-frequency bandwidth limit of analog hearing aids usually resulted mainly from the electroacoustic performance. With high-powered aids in particular, it was often difficult to obtain adequate sound output levels at frequencies above about 4 kHz. In recent years, however, receiver technology has improved to the extent that bandwidth limitations are imposed instead by other factors.

In all digital hearing instruments, there is an absolute limit on bandwidth resulting directly from the sampling process. Sampling is required to convert the sound signals at the input of the HI into a stream of separate digital representations. The sampling rate has to be high enough to ensure that the continuously varying acoustic signal is represented in the digital processor with adequate fidelity. The selection of sampling rate is based on a fundamental principle of digital signal processing which states that the highest frequency that can be represented adequately after sampling is slightly less than half the sampling rate. For normal hearing listeners, the upper frequency limit is generally assumed to be 20 kHz, so the required sampling rate is more than 40 kHz. In fact, digital sound recorded using the standard compact disc (CD) format is sampled at a rate of 44.1 kHz.

Unfortunately, the use of relatively high sampling rates can have undesirable side-effects. The digital signal processor inside any modern hearing instrument is programmed to modify the sound signals at a rate that is equal or proportional to the sampling rate. One practical effect of this relationship is that higher sampling rates cause higher power consumption, and therefore poorer battery lifetime. Designers of digital HIs are faced with a difficult trade-off: widening the acoustic bandwidth of the device means shortening the battery lifetime. Consequently, it is common for the sampling rate in hearing instruments to be approximately 20 kHz. This choice means that the upper limit of the bandwidth in terms of sound produced by the HI must be about 10 kHz. In some devices, the sampling rate may be as low as 16 kHz resulting in an acoustic bandwidth of less than 8 kHz.

There are several conventional methods of measuring the bandwidth of hearing aids. One widely used technique is specified by the American National Standards Institute (ANSI). In ANSI S3.22, the HI is adjusted to provide amplification in a predetermined reference condition (reference test gain), and the resulting response is measured as a function of frequency. Figure 2 shows a typical measurement, using two hearing instruments with broad bandwidth as an example. For an input at 60 dB, the output is averaged at three specific frequencies (usually 1.0, 1.6, and 2.5 kHz). Subsequently two frequencies are identified at which the output is 20 dB below the calculated average. Those two frequencies are taken to define the lower and upper limits of the bandwidth. For the response curve shown in Figure 2, the bandwidth of Instrument A, estimated according to the ANSI method, is from below 100 Hz to approximately 7.5 kHz.

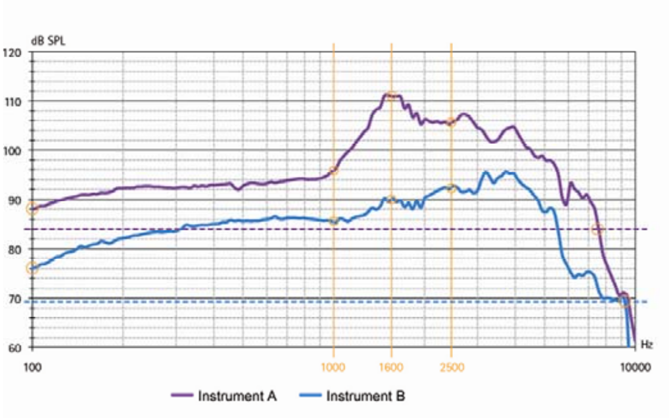

Figure 2 Example of ANSI standard bandwidth calculation for two current hearing instruments. Each curve shows the output versus frequency for the reference test gain condition with an input of 60 dB. The response is averaged at three frequencies (vertical yellow lines), and then reduced by 20 dB (horizontal dashed lines). The bandwidth is delimited by the two frequencies at which these lines intersect the curve. Thus, Instrument A has an upper bandwidth limit of approximately 7.5 kHz, whereas Instrument B has an upper limit of 9.2 kHz.

Figure 2 additionally shows the same measurement for Instrument B. In this case, the bandwidth, determined using the ANSI method, has an upper limit of approximately 9.2 kHz. However, it is also clear that the calculated average output of Instrument A is higher than that of Instrument B at every frequency. In fact, if absolute output level rather than the output relative to the reference condition is used to estimate the bandwidth, these two HIs have upper frequency limits that are almost identical. These observations demonstrate that bandwidth measurements conducted in accordance with a technical standard do not necessarily provide useful information about the effective bandwidth of a HI when it is fitted to a user. In contrast, a determination of **perceptual bandwidth**, taking into account not only the electroacoustic characteristics of the HI but also the user's configuration and degree of hearing impairment, is much more informative.

Perceptual bandwidth

A conventional audiogram records a person's threshold of hearing at a number of discrete frequencies. The lowest frequency is usually 125 or 250 Hz, while the highest frequency may be up to 8 kHz. For several technical and practical reasons, it can be difficult to obtain reliable thresholds for very high frequencies (e.g., above 8 kHz). Even when threshold levels are available beyond the typical frequencies measured in routine clinical practice, prescriptive fitting rules that specify suitable gain and amplitude compression characteristics for a HI generally do not provide targets at those frequencies. Nevertheless, it would be necessary to know the high-frequency thresholds in order to assess the full range of frequencies that a particular HI is able to make audible when fitted to each individual.

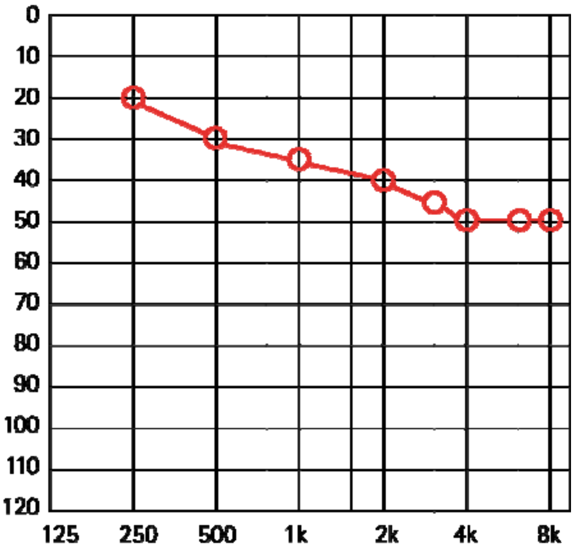

Figure 3 Audiogram for a typical sloping mild to moderate hearing loss

Figure 3 is an example of a typical sloping hearing loss of mild to moderate severity, with thresholds at and above 4 kHz of 50 dB HL. After conversion to equivalent levels at the eardrum, this audiogram is shown as the red curve in Figure 4. Also shown in the latter figure is a fitting of a Phonak HI with wide bandwidth. The proprietary frequency-shifiting algorithm **SoundRecover** is disabled (green curve). The HI was adjusted to approximate as closely as possible the target recommended by the DSL Adult v5.0a formula.

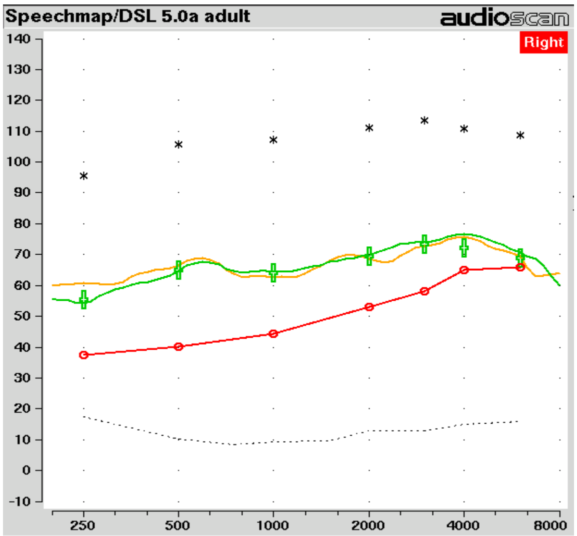

Figure 4 The results of fitting two HIs according to the DSL v5.0a formula (green crosses) for the audiogram (red curve) shown in Figure 3. The Phonak HI (green curve) had SoundRecover disabled. The yellow curve shows comparable results from a different manufacturer's HI which is claimed to provide extended bandwidth.

It is evident that the Phonak HI without SoundRecover was able to provide useful audibility of the test signal (speech at an average level of 65 dB SPL) up to at least 6 kHz. The yellow curve in the same figure shows, for comparison, results for a premium-level competitive product which claims extended bandwidth to 10 kHz. The measurements plotted in Figure 4 demonstrate clearly that these two HIs result in almost identical perceptual bandwidths when fitted to suit a common audiogram configuration. However, neither HI would provide useful audibility for frequencies higher than about 6 kHz, in spite of the fact that the maximum available gain for those frequencies was selected in each device. It is noteworthy that this restriction on audibility above 6 kHz is present even for a mild to moderate hearing loss with thresholds in this region of only 50 dB HL. This limitation on perceptual bandwidth is a consequence of particular characteristics of both the audiogram *and* the technical performance of the HIs when fitted for that audiogram.

What can be done to overcome this limitation? Currently, the only practical solution is the use of a sophisticated frequency shifting algorithm, which can improve the audibility of high-frequency sound signals without affecting signals at lower frequencies. Unique to Phonak, SoundRecover expands the perceptual bandwidth available to HI users by compressing and shifting a selected input band restricted to high frequencies. The effect of SoundRecover on bandwidth is illustrated in Figure 5, which shows how the maximum input frequency is reduced to fall within the useful bandwidth of the HI when it is fitted appropriately to a person with hearing impairment. Only frequencies above a specified cut-off frequency are compressed in this way. As lower-frequency signals do not pass through the frequency-compression processing, the quality of sounds delivered to the HI user is preserved.

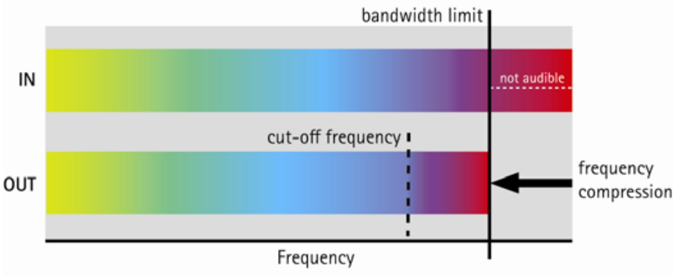

Figure 5 How SoundRecover can extend the perceptual bandwidth. The upper bar shows the full frequency spectrum of sounds at the input of a hearing instrument. Signals with frequencies above the bandwidth limit, shown to the right of the solid vertical line, are not audible to the HI user. With SoundRecover enabled, however, signals above the cut-off frequency (vertical dashed line) are compressed in frequency so that they fall within the available bandwidth (lower bar).

A number of research studies have confirmed that speech intelligibility is often improved, both in quiet and in noise, with use of SoundRecover, and that the sound quality of the processing is readily accepted (Glista et al, 2009, Wolfe et al, 2009). These benefits have not been found to be limited to any specific age group, degree of hearing loss or range of audiometric configurations.

Figure 6 shows the expected perceptual effects of SoundRecover when enabled in the Phonak hearing instrument. In contrast to Figure 4, this figure shows the output of each HI for a test signal consisting of a noise band centred on 6.3 kHz. (This is a synthetic signal, recently made available for clinical use in the Verifit verification system, with characteristics similar to that of the phoneme /s/).

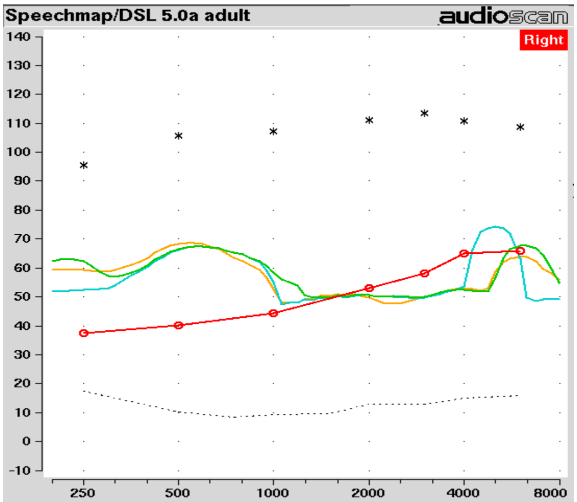

Figure 6 As for Figure 4, but for an input signal consisting of a narrow-band noise centred on 6.3 kHz. The blue curve shows the effect of enabling SoundRecover in the Phonak HI.

Without SoundRecover (green curve), only marginal audibility for this signal can be achieved, and the competitive device (yellow curve) peaks below the hearing threshold and thus does not provide audibility at all. Note that the fitting parameters of each HI remained as described for figure 5, fine-tuned with maximum high frequency gain. With SoundRecover enabled, the test signal is amplified by the Phonak HI to clearly audible levels (blue curve). For further

details on how to conduct and interpret this Verifit procedure designed to verify the performance of hearing instruments with frequency shifting technology, please refer to the document "Guidelines for fitting hearing instruments with SoundRecover" available at
www.phonakpro.com/soundrecover

In summary, advances in signal processing and receiver design have made it possible to design hearing instruments with an electroacoustic frequency response out to about 10 kHz, when measured in a coupler. However, usable "real world" gain above 6 kHz is often not practically achievable even when such devices are fit for a mild to moderate hearing loss. In many actual fittings, the wide bandwidth of the HI itself is not sufficient to extend the perceptual bandwidth and thereby make high-frequency signals audible. Research has shown that the perception of these signals is very important. SoundRecover can provide otherwise unachievable high frequency audibility by extending the perceptual bandwidth of Phonak HIs in addition to the comparatively wide bandwidth already provided by their fundamental electroacoustic design. The benefits of this technology have been scientifically proven by a series of studies published in both peer reviewed and non-peer reviewed journal (see additional publications on SoundRecover at the end of this document).

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