Audibility and speech intelligibility revisited: implications for amplification

TERESA YC CHING[1,2] , HARVEY DILLON, FRANCES LOCKHART, EMMA VAN WANROOY AND MATT FLAX

[1] *National Acoustic Laboratories, Australian Hearing, 126 Greville Street, Chatswood, NSW 2067, Australia*

[2] *HEARing CRC, Australia*

A major goal of amplification is to restore audibility to people with hearing loss in as wide a range of frequencies as possible for maximising speech intelligibility. The usefulness of audibility for speech intelligibility, however, decreases as hearing loss increases. This reduced effectiveness of audibility may be related to the presence of cochlear dead regions or just to reduced frequency and temporal resolution. In this paper, the current literature that relates the presence of dead regions to usefulness of high-frequency audibility is examined. This is followed by a brief description of an empirical study that investigated f

potential benefits of providing ample high-frequency audibility in hearing-aid fitting have received much attention. There exists a body of literature suggesting that high-frequency audibility might have minimal value for certain individuals with high-frequency impairment (e.g. Murray and Byrne, 1986; Rankovic, 1991; Hogan and Turner, 1998; Ching *et al*, 1998; Turner and Cummings, 1999). Ching *et al*. (1998) studied speech recognition abilities of hearing impaired listeners as a function of hearing threshold levels, frequency region of speech cues and sensation levels, using filtered sentences presented in quiet as stimuli. The results showed wide variability across subjects in their abilities to extract information from amplified speech at high frequencies. The SII overestimated performance, especially for listeners with severe to profound hearing levels at these frequencies. On average, when hearing loss reached about 60 dB HL, the listeners were able to extract only about half of the information that can be extracted by normal-hearing listeners (Ching *et al*., 2001). Hogan and Turner (1998) reported data indicating that when high-frequency hearing exceeded about 55 dB HL, most listeners could not benefit from increased audibility in that frequency region. The evidence suggests that there is much variability in what is optimal high-frequency amplification for speech intelligibility in quiet, at least for people with moderate loss or greater. Subsequent studies by Turner and Henry (2002) and Hornsby and Ricketts (2003) investigated speech recognition in noise. They suggested that high-frequency audibility may be more useful when listening in noise than in quiet. Recent findings from Hornsby *et al*. (2011) indicated that extending high-frequency gains from 3.5 kHz to 8.9 kHz for people with flat or gently sloping hearing loss was not detrimental to speech intelligibility in noise and might even be beneficial for some individuals. These data imply that the effective audibility model developed previously on the basis of data from speech intelligibility in quiet (Ching *et al*., 2001) may need to be modified after speech intelligibility in noise is considered.

The mechanisms underlying hearing loss desensitization are likely to include hair cell dysfunction associated with hearing loss, which is manifested as a reduction in frequency resolution and/or temporal resolution (Ching *et al*., 2002), or in the presence of a region with non-functioning inner hair cells in the cochlea, commonly referred to as a cochlear dead region (CDR). Moore (2000, 2004) developed a clinical test, known as the Threshold Equalizing (TEN) test, for effective diagnosis of CDR. Explanations of the principles and procedure for the TEN test as well as the empirical basis of the test are detailed in Moore (2001). Briefly, this test is based on the assumption that detection of a tone that falls within a region where there are no functioning inner hair cells actually occurs as a result of the spread of excitation from a location on the basilar membrane that has functioning inner hair cells and neurons. In such cases of off-frequency listening, the masking effect of a broad-band noise on a tone would be greater than if the tone were detected via excitation at the location that is maximally sensitive in an undamaged cochlea. The current literature on the impact of the presence of CDRs on potential benefits from high-frequency audibility is mixed. If the presence or absence of CDRs alters the effectiveness of high-frequency audibility beyond that accounted for by hearing thresholds, then hearing-aid prescription procedures need to incorporate dead region data in their derivation. Clinical practice would also need to include identification of dead regions prior to hearing-aid fitting.

In this paper, we first review research on the impact of cochlear dead regions on benefits from high-frequency cues. Secondly, we present findings of a study that investigated speech intelligibility in quiet and in noise by people with hearing impairment together with a model for predicting speech intelligibility for people with different degrees of hearing loss. The clinical implications for hearing-aid amplification are discussed.

IS AUDIBILITY AT HIGH FREQUENCIES BENEFICIAL FOR SPEECH INTELLIGIBILITY?

Speech and environmental sounds contain energy over a very wide range of frequencies. Research has shown that speech sounds such as [f v θ ð s z ʃ ʒ tʃ dʒ] are among the most frequently misperceived (Parkinson *et al*., 1996; Ching *et al*., in preparation) and mispronounced phonemes, and are the latest to be acquired by children with hearing loss (Moeller *et al*., 2007; Ching *et al*., 2011). These observed deficits have been attributed to inadequate audibility of the high-frequency sounds and the limited bandwidth of hearing aids. Manufacturers of hearing aids generally report that the upper bandwidth of devices exceeds 6 kHz, with the upper frequency range defined as the 20-dB down point relative to the average gain at 1.0, 1.6 and 2.5 kHz (ANSI, 2009). Thus, a hearing aid with an average used gain of 40 dB would only have 20 dB of gain at the upper frequency limit. In many cases, this may be inadequate to ensure audibility of low-level high-frequency components of speech that contains important linguistic information (Boothroyd and Medwetsky, 1992). For instance, the peak energy of [s] spoken by female and child talkers occurs in the 6 to 9 kHz region, and so hearing aids may require an upper limit of 10 kHz to ensure audibility of [s]. Previous research that investigated whether provision of high-frequency speech cues was helpful to listeners with and without CDR is mixed, as shown in Table 1.

	Source	Design	Hearing level	Stimuli	Maximum Bandwidth	Presentation method	Test condition	Impact of CDR	Findings
1.	Vickers *et al.*, 2001	Between groups comparison. 10 subjects: 12 ears with CDR, 6 ears without.	High-frequency hearing loss: moderate to severe or profound. The group without CDR had better hearing.	Vowel-Consonant-Vowel (VCV) syllables, Low-pass filters customised for CDR location for each subject; or spanned the range 800 to 7500 Hz for subjects without a CDR.	7.5 kHz	Via HD580 earphones, shaped according to the Cambridge formula. Nominal input level for the broadband stimuli was 65 dB SPL.	Quiet	Yes	Amplifying frequencies above 70% of the estimated edge frequency of the CDR was not beneficial, and might be detrimental.
2.	Baer *et al.*, 2002	Between-group comparison. 10 subjects: 6 ears with CDR, 10 ears without (8 subjects had previously participated in the Vickers *et al*. study).	High-frequency hearing loss: moderate to severe or profound. The group without CDR had better hearing.	VCV, customised for CDR location for each subject; or spanned the range 800 to 7500 Hz for subjects without a CDR.	7.5 kHz	Via HD580 earphones, shaped according to the Cambridge formula. Nominal input level for the broadband stimuli was 65 dB SPL.	Noise	Yes	Amplifying frequencies above 50 -100% of the estimated edge frequency of the CDR was not beneficial.
3.	Mackersie *et al.*, 2004	Matched-pairs design. 14 subjects: 8 ears with suspected CDR and 8 ears without.	Steeply sloping high-frequency loss.	VCV in quiet; Monosyllabic words in spectrally matched noise. Low-pass filters customized for CDR location for each subject. Threshold-matched controls had the same low-pass filters.	4.5 kHz	Via behind-the-ear hearing aids, set according to DSL[i/o] formula. Presentation level at 65 dB SPL.	Quiet,	No	Provision of high frequencies were equally helpful for subjects with and without CDR.
							Low noise (15 and 10 dB signal-to-noise ratio)	No	Provision of high frequencies were equally helpful for subjects with and without CDR.
							High noise (5 and 0 dB signal-to-noise ratio)	Yes	Subjects with CDR did not improve when frequencies more than 100% above the edge of the CDR were presented.
4.	Preminger *et al.*, 2005	Compared users of hearing aids (HA) with and without CDR. 49 subjects: 22 ears with CDR, 76 without.	At least 2 pure-tone thresholds greater than 50 dB and no thresholds greater than 80 dB. Better hearing for group without CDR.	Quick Speech-in-noise sentences: standard lists and high-frequency lists (lists with high-frequency emphasis)	4.5 kHz	Via insert earphones, presentation level at 70 dB HL for subjects with averaged hearing loss < 45 dB HL, and presentation level adjusted to "loud but OK" as judged by each subject who had greater hearing loss.	Noise	No	Benefit from high-frequency cues did not differ between the group with CDR and the group without CDR.
5.	Cox *et al.*, 2011	Compared HA candidates with and without CDR	Flat or sloping hearing loss, with thresholds of 60 - 90 dB HL in the 1-3 kHz region, and ≥ 25 dB HL below 1 kHz. Group without CDR had better hearing.	Quick Speech in noise sentences: High- frequency lists and the same lists low-pass filtered at 2 kHz.	4.5 kHz	Insert earphones. Presentation level adjusted to "loud but OK" as judged by each subject.	Noise	No	Provision of high-frequency gains was helpful for both groups, but the improvement was very small.

Table 1: Summary of research on the impact of cochlear dead regions (CDR) on benefits of high-frequency audibility. The presence of CDR was identified using the Threshold Equalizing Noise (TEN) test.

The evidence is therefore not consistent as to whether the optimum bandwidth is different for people with CDR than for those without CDR. There are three complications in trying to reconcile these findings. First, the studies finding that the presence of CDR affected the optimum bandwidth extended amplification up to 7.5 kHz whereas the studies that found no effect extended amplification up to only 4.5 kHz. It would not be surprising if the increased benefit of wide bandwidth for those without CDR was most easily measured when the bandwidth was increased to 7.5 kHz than when it was increased only to 4.5 kHz. Second, in those studies where the optimum bandwidth was greater for those without CDR, these same subjects also had less high-frequency loss than those with CDR, so it is unclear how much of the differential is accountable for on the basis of hearing thresholds, rather than the presence or absence of CDR. Third, high-frequency amplification is not just a matter of bandwidth, but also of the sensation level achieved. It is possible that the benefit of extending bandwidth depends on what sensation level is achieved within that extended bandwidth, and within the baseline bandwidth.

In determining the optimal gain-frequency response that maximises speech intelligibility while maintaining comfortable overall loudness, it must be remembered that gain increase in one frequency region is possible only at the expense of gains provided in other frequency regions, unless the amplified signal is also made louder overall. If too much gain is applied across all frequencies, the result can be discomfort, decreased intelligibility, or both. The constraints for providing high-frequency gains include listener-related factors such as loudness discomfort, hearing sensitivity, frequency and/or temporal resolution being too poor for amplified signals to be usable, presence of dead regions in the cochlea, and subjective preferences for sound quality; as well as the device-related limitations on gain imposed by feedback oscillation and the limited maximum output of hearing aids.

SPEECH INTELLIGIBILITY OF HEARING-IMPAIRED LISTENERS: QUIET AND NOISE

To quantify the contribution of an audible signal in different frequency regions to speech intelligibilty for people with different degrees of hearing loss, and to investigate factors affecting speech intelligibility, we assessed 20 normal-hearing and 55 hearing-impaired listeners using a battery of tests. Audiological assessments included hearing threhold levels, tympanometry, and transient-evoked otoacoustic emissions. Speech perceptual tests included measurements of high-pass (cutoff frequencies at 0.7 kHz, 1.4 kHz and 2.8 kHz) and low-pass filtered (cutoff frequencies at 0.7 kHz, 1.4 kHz, 2.8 kHz and 5.6 kHz) sentences and consonants in nonsense syllables. The speech stimuli were presented in quiet at a high and a low sensation level, and also in babble noise. Further, psychoacoustic tests included the measurement of tuning curves at 0.5, 1, 2 and 4 kHz using pulsed pure tones as signals and narrow-band noise maskers; and assessments of cochlear dead regions using the TEN test (Moore, 2001). We also assessed the cognitve ability of the listeners using a visual monitoring task (Knutson ., 1991).

Results

Consistent with our previous findings on speech intelligibility (Ching ., 1998), the standard SII (ANSI, 1997) overestimated performance of hearing-impaired listeners, and the magnitude increased with severity of hearing loss. In other words, the effectiveness of audibility decreased as hearing loss increased. The SII method was therefore modified to allow for a non-monotonic relationship between sensation level and effective audibility. Whereas effective audibility increases from 0 to 1 as the sensation level of the maximum short-term rms levels of speech increases from 0 to 30 dB for normal-hearing listeners, this relationship was modified for hearing-impaired listeners to curve and asymptote at a level that is below the maximum of 1. The data on sentence material were used in the initial parameter fitting process in which parameters were allowed to vary smoothly with frequency and with hearing loss. The optimal values did not vary significantly with frequency or with test condition (quiet or noise). Consequently, the model was simplified to a form that allows the asymptotic value to vary with just the hearing loss. It appears when hearing loss exceeds 65 dB HL, the contribution of audibility to speech intelligibility is only about half of that obtained by normal-hearing listeners.

The same parameter fitting process was repeated for nonsense syllable material collected from the same group of listeners. The curves derived from the sentence material and nonsense syllables were almost identical. Furthermore, the same process was applied to speech intelligibility data previously reported for a different group of listeners (Ching ., 1998). Again, similar parameter values were obtained, providing support for the robustness of the function relating effective audibility to hearing level, at least when applied to average data. The asymptotic value is shown as a function of hearing loss in Figure 1.

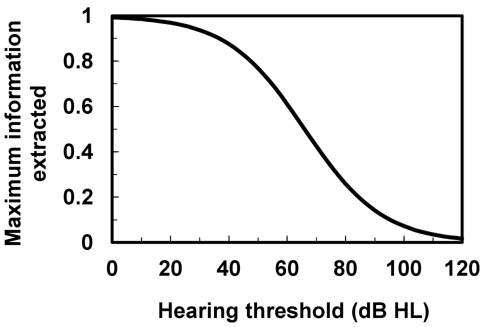

Fig. 1: The proportion of information that hearing-impaired people with different degrees of hearing loss can extract when optimal audibility has been achieved.

Our results indicate that the proficiency of hearing-impaired listeners in extracting speech information from an audible signal decreased with increased hearing loss, reduced tuning curve sharpness, increased elevation of masked thresholds in the TEN test, reduced otoacoustic emission strength, reduced cognitive ability and increased age. After allowing for the effect of hearing loss desensitization using the modified SII as described above, only cognitive ability and age were correlated with discrepancies between the predicted and observed speech intelligibility.

CONCLUSION

The effectiveness of audibility decreases with increase in hearing loss, and the degradation in noise is at least as great as in quiet. Hearing loss and its associated reduction in effective audibility appear to be the strongest predictor for speech intelligibility. It appears that information about the presence or absence of CDR does not enhance the predictability of speech intelligibility over and above what can be explained by the reduction in effective audibility with increase in hearing threshold levels (shown in Figure 1). The estimated amount of speech information that can be extracted from an audible signal for people with different degrees of hearing loss is, nonetheless, an average. Some hearing-impaired people may extract more, and others (possibly those with CDR) less than the amount shown. Although the current evidence does not lend support to the need to use information about CDR in deriving a prescription, such information may be useful in fine-tuning hearing-aid fittings away from prescriptive targets to meet individual needs.

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