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Review Article

A review of the perceptual effects of hearing loss for frequencies above 3 kHz

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Abstract

Background: Hearing loss caused by exposure to intense sounds usually has its greatest effects on audiometric thresholds at 4 and 6 kHz. However, in several countries compensation for occupational noise-induced hearing loss is calculated using the average of audiometric thresholds for selected frequencies up to 3 kHz, based on the implicit assumption that hearing loss for frequencies above 3 kHz has no material adverse consequences. This paper assesses whether this assumption is correct. *Design*: Studies are reviewed that evaluate the role of hearing for frequencies above 3 kHz. *Results*: Several studies show that frequencies above 3 kHz are important for the perception of speech, especially when background sounds are present. Hearing at high frequencies is also important for sound localization, especially for resolving front-back confusions. *Conclusions*: Hearing for frequencies above 3 kHz is important for the ability to understand speech in background sounds and for the ability to localize sounds. The audiometric threshold at 4 kHz and perhaps 6 kHz should be taken into account when assessing hearing in a medico-legal context.

Key Words: Hearing loss; noise exposure; high frequencies; speech perception; sound localization

Exposure to intense noise over a long period of time can lead to hearing loss (Borg et al, 1995). The loss usually first becomes apparent in the audiogram for frequencies close to 4 kHz, although the exact frequency where the effect is greatest can vary from 3 to 6 kHz (Passchier-Vermeer, 1974). There are many cases of noise-induced hearing loss (NIHL) where audiometric thresholds remain close to the age-expected values for frequencies up to 3 kHz, but thresholds are elevated at 4 or 6 kHz. In several countries, compensation for occupational NIHL is based on the mean estimated NIHL at 1, 2 and 3 kHz (UK, King et al, 1992) or 0.5, 1, 2 and 3 kHz (USA, American Medical Association, 2008; Dobie, 2011). Hence, people whose NIHL is restricted to frequencies above 3 kHz often receive little or no compensation. The use of the average NIHL at 1, 2 and 3 kHz or 0.5, 1, 2 and 3 kHz is based on the implicit assumption that hearing loss for frequencies above 3 kHz has no material adverse consequences. This review assesses whether that assumption is valid.

Evidence for effects of audibility at high frequencies on speech intelligibility

There are many studies showing that frequency components above 3 kHz contribute to speech intelligibility for people with normal hearing. In these studies, speech has been highpass or lowpass filtered with various cutoff frequencies, and speech intelligibility has been measured for each cutoff frequency. Such studies formed the basis for the Articulation Index (ANSI, 1969; Fletcher, 1953; French & Steinberg, 1947; Kryter, 1962) and its successor, the SII (ANSI, 1997) that is described in the next section of this paper. For example, French and Steinberg showed that decreasing the cutoff frequency of a lowpass filter from 7 to 2.85 kHz decreased the percentage of correctly identified syllables presented in quiet from 98 to 82%. Aniansson (1974) showed that lowpass filtering wideband speech with a cutoff frequency of 3.1 kHz reduced the percentage of words correctly identified from 94 to 85% for speech at a signal-to-noise ratio (SNR) of 0 dB, from 74 to 67% when a single background talker was added, and from 64 to 57% when three competing talkers were added. Studebaker et al (1987) used sharply filtered continuous speech materials presented in noise, and asked participants to estimate the percentage of words that they understood for each filtering condition. Several SNRs were used, specified as the level of the peaks in the speech relative to the root-mean-square noise level. They showed that compared to an ‘all pass’ condition (0.15–8 kHz), lowpass filtering at 3.5 kHz reduced the percentage of words understood from 57 to 41% at an SNR of

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Abbreviations

AAHL	Age-associated hearing loss
HTL	Hearing threshold level
LMHA	Limiting Master Hearing Aid
NIHL	Noise-induced hearing loss
$PTA_{2,4}$	Pure-tone average threshold at 2 and 4 kHz
SII	Speech intelligibility index
SNR	Speech-to-noise ratio
SRT	Speech reception threshold

7.5 dB, from 89 to 58% at an SNR of 8.5 dB and from 94 to 79% at an SNR of 9.5 dB. From these results, it is clear that for normal-hearing participants frequency components above 3 kHz make a sizable contribution to intelligibility, especially for speech in the presence of background sounds.

There are also several research studies showing that, for people with mild-to-moderate high-frequency hearing loss, speech intelligibility is improved when amplification is provided for frequencies above 3 kHz (Baer et al, 2002; Hornsby & Ricketts, 2006; Skinner et al, 1982; Skinner & Miller, 1983; Vickers et al, 2001), although hearing loss does seem to reduce the ability to make use of audible speech information (Turner & Henry, 2002). For example, Skinner and Miller (1983) measured the intelligibility of speech in quiet and mixed with noise at +6 dB SNR as a function of its audible bandwidth for seven participants with moderate sensorineural hearing loss. Words were presented at three levels (50, 60 and 70 dB SPL) and amplified with a Limiting Master Hearing Aid (LMHA). The LMHA was set for four frequency ranges: (1) 0.266–6 kHz, (2) 0.375–4.2 kHz, (3) 0.53–3 kHz, and (4) 0.75–2.12 kHz. All participants obtained the highest mean score with the LMHA set for the widest frequency range. Averaged across levels and across quiet and noise conditions, the mean correct word identification scores were 50, 45, 31 and 17% for conditions 1, 2, 3, and 4, respectively. These results suggest that increasing the audible upper frequency limit from 3 to 4 and 6 kHz leads to progressive improvements in intelligibility, although some of the benefit may have come from decreasing the low-frequency cutoff.

Baer et al (2002) measured the intelligibility of nonsense syllables presented in noise (with SNRs ranging from 0 to +6 dB) for participants with severe to profound high-frequency loss, without and with high-frequency dead regions in the cochlea (these are regions with very few or no functioning inner hair cells, synapses or neurons; see Moore et al, 2000). The stimuli were subjected to linear amplification using the Cambridge formula (Moore & Glasberg, 1998) and then lowpass filtered with various cutoff frequencies. For the participants without dead regions the mean score increased from about 70% to 80% when the cutoff frequency was increased from 3 to 7.5 kHz. For the participants with dead regions, there was no benefit of increasing the cutoff frequency from 3 to 7.5 kHz, presumably because the presence of the dead regions limited the ability to process the information conveyed by the high-frequency components.

Hornsby and Ricketts (2006) assessed the effect of highpass and lowpass filtering on the intelligibility of sentences in noise at +6 dB SNR for 10 participants with normal hearing and 10 participants with sloping high-frequency loss. When the lowpass cutoff frequency was increased from 3.2 to 7 kHz, the percent correct scores increased from about 92 to 98% for the normal-hearing participants and from about 85 to 92% for the hearing-impaired participants.

Overall, the results clearly indicate that speech intelligibility is influenced by the audibility of frequency components above 3 kHz. It follows that reduced audibility of frequencies above 3 kHz, produced by NIHL, has adverse effects on the ability to understand speech in background noise.

The studies referred to above all used speech and noise that were spatially coincident. Under conditions where the target speech and interfering sounds are spatially separated, frequencies above 3 kHz may be relatively more important, and there may be a greater advantage of extending the audible frequency range provided by bilaterally fitted hearing aids (Hamacher et al, 2006). This may happen for at least two reasons:

(1) For medium and high-frequency sounds, the head casts a kind of acoustic shadow. For example, a sound to the right of the head produces a greater intensity at the right ear than at the left (Kuhn, 1979). As a result, whenever the target speech is on the opposite side of the head to the most prominent interfering sound, there is a better signal-to-interference ratio at one ear than the other. The listener can attend selectively to the ear with the better signal-to-interference ratio, and can even switch rapidly from attending to one ear to attending to the other under conditions where the ear with the better signal-to-interference ratio fluctuates from moment to moment (Brungart & Iyer, 2012). The magnitude of head-shadow effects increases progressively with increasing frequency (Shaw, 1974; Bronkhorst & Plomp, 1988; 1989), so the advantage of listening with the 'better' ear would be expected to increase as the audible high-frequency bandwidth increases.

(2) Sometimes, when several people are talking at once, the listener may hear many speech sounds but may have difficulty in deciding which sounds come from which talker (Brungart & Simpson, 2007). This is called 'informational masking' (Brungart et al, 2001). A perceived spatial separation of the target speech and interfering speech can reduce informational masking and hence lead to improved intelligibility of the target talker (Freyman et al, 1999; 2001). High-frequency speech sounds are used for sound localization, and especially for resolving front-back confusions (Best et al, 2005); this is described in more detail later on. Hence, when high frequencies are audible, this can improve sound localization and this in turn reduces informational masking.

Consistent with these ideas, recent research has shown that, for people with mild-to-moderate high-frequency hearing loss, the intelligibility of target speech in the presence of a background talker in a different location from the target is improved when amplification is provided even for frequencies above 5 kHz (Moore et al, 2010a; Levy et al, 2015). This indicates that frequencies well above 3 kHz contribute to speech intelligibility when the target speech and interfering sounds are spatially separated.

A recent paper (Besser et al, 2015) has shown that the ability to take advantage of spatial separation between a target speech sound and interfering speech sounds (the 'spatial advantage') depends on audiometric thresholds at high frequencies, in the range 6–10 kHz. Elevated audiometric thresholds in the frequency range 6–10 kHz are associated with a decrease in the spatial advantage. Another recent paper (Silberer et al, 2015) has shown that for speech in noise and in the absence of visual cues (i.e. without lipreading) an audible frequency range extending up to about 7 kHz is required for optimal intelligibility.

Overall, the evidence is strong that the audibility of frequencies above 3 kHz is important for speech intelligibility and that NIHL for frequencies above 3 kHz has adverse effects on the ability to understand soft speech and on the ability to understand speech in background sounds, especially when the background sounds come from a different spatial location to the target sounds. This is recognized by manufacturers of hearing aids, since almost all hearing aids on the market today are designed with the goal of amplifying frequencies up to at least 5 kHz, and some manufacturers are developing hearing aids that amplify over an even wider frequency range (Fay et al, 2013; Levy et al, 2015). For people whose high-frequency hearing loss is too severe for them to benefit from amplification of frequencies above 3 kHz, frequency-lowing is often used to provide information about those components (Alexander, 2013). Also, prescriptive methods for fitting hearing aids based on the audiogram all prescribe gain for frequencies up to at least 6 kHz (Keidser et al, 2011; Moore et al, 2010b; Scollie et al, 2005).

Effects on speech intelligibility expected from the Speech Intelligibility Index

A standard method for predicting speech intelligibility is the Speech Intelligibility Index (SII; ANSI, 1997). The method is based mainly on the audibility of the speech and does not take into account the adverse effects of hearing loss on the ability to discriminate sounds that are well above the detection threshold (Moore, 2007; Plomp, 1978); such effects are discussed later in this paper. The SII does not explicitly take into account the fact that the information in speech (for example the envelope fluctuations) is correlated across frequency bands: the closer the centre frequencies of the bands, the higher is the correlation (Crouzet & Ainsworth, 2001). Hence the SII does not give accurate predictions of intelligibility for speech that is filtered into very narrow frequency bands whose separation is varied (Warren et al, 2005). Also, the SII does not give accurate predictions of intelligibility for speech in fluctuating background sounds (Rhebergen & Versfeld, 2005). However, for lowpass or highpass filtered speech presented in quiet or in a steady background sound, the SII generally gives accurate predictions.

The SII method incorporates a weighting function whereby the information at different frequencies is assigned a weight according to its relative importance. The overall weight assigned to frequencies above 3 kHz depends on the speech material. For 'average speech' the total weight assigned to frequencies above 3 kHz is approximately 23%. For some specific speech tests, using nonsense syllables where each English phoneme occurs equally often, CID words, NU6 nonsense syllables, the diagnostic rhyme test, short passages of easy materials, and SPIN test monosyllables, the corresponding percentages are 26, 16, 17, 17, 18, and 20%, respectively. When the face of the talker is visible, so lip-reading is possible, the high-frequency components in the acoustic signal become relatively less important (Kryter, 1962; Sumby & Pollack, 1954). However, there are many situations when lip-reading is not possible, for example, when listening to a companion at dinner while cutting up food or when listening to the radio.

The value of the SII varies from 0 to 1. A value of 0 indicates that no usable information is conveyed (this is an approximation). A value of 1 indicates that all of the important information in the speech is audible. A value of 0.75 is high enough for good communication with a clear talker and in the absence of reverberation. The SII for a telephone signal with a frequency range from 0.5 to 3.2 kHz, which was to designed to give just-adequate intelligibility for people with normal hearing, is 0.71. A value of 0.5 indicates that there would be some difficulty in understanding speech, with significant errors being made, and a value of 0.3 indicates considerable difficulty in understanding speech, with many errors of understanding.

To calculate the expected effect of NIHL for a given individual, the first stage is to estimate the expected hearing loss for a non-noise-exposed individual of that age and gender. In the UK this is usually done by using the audiometric thresholds at 1 and 8 kHz as anchor points, and selecting appropriate values from tables of hearing loss as a function of age and gender for non-noise-exposed individuals (Coles et al, 2000), although this approach has been criticized (Ali et al, 2014). An alternative 'two-pass' method has recently been proposed by Lutman et al (2016). This method takes into account the fact that while noise exposure typically has its greatest effects on audiometric thresholds for frequencies close to 4 kHz, the effects can spread to lower and higher frequencies as the loss becomes more severe (Passchier-Vermeer, 1974). Other approaches are used in other countries. Once the age-expected hearing loss is estimated, it is subtracted from the actual hearing loss. This gives an estimate of the noise-induced component of the hearing loss.

An example of a typical case for a man aged 55 years is shown in Table 1, using the method of Lutman et al (2016). Note that the exact method used to estimate the noise-induced component of the hearing loss is not critical for the present purpose. Row 3 of the table shows the hearing threshold levels (HTL) for frequencies from 1 to 8 kHz. The thresholds are within the normal range for frequencies up to 3 kHz, but are elevated at higher frequencies. Row 4 shows the HTLs at the anchor points of 1 and 8 kHz, and row 5 shows the age-associated hearing loss (AAHL) for a man aged 55 at the 50th percentile, taken from Table 2 of Coles et al (2000). The actual audiometric threshold is 3 dB worse than for the AAHL at the 1-kHz anchor point and 3 dB better than for the AAHL at the 8-kHz anchor point. These 'misfit' values are shown in row 6. Row 7 shows interpolated misfit values, and row 8 shows the first-pass estimate of the AAHL. Row 9 shows the 'bulge', which is the first-pass estimate of the noise-induced component of the hearing loss. Row 11 shows the modified HTL at the anchor points, which is what the HTL would be expected to be if there had been no noise exposure; the modifications are based on the first-pass estimate of the noise-induced loss at 4 kHz. Row 12 shows the AAHL values used for the second pass. Here, they are the same as the values in row 5, although they can be selected to be different. Row 13 shows the misfit values at the anchor points and row 14 shows the interpolated misfit values. The final estimate of the AAHL is shown in row 15, and the estimated noise-induced loss is shown in row 16. The mean estimate of the NIHL at 1, 2 and 3 kHz is only 2.4 dB, which would usually be considered as of no importance. The mean estimate of the NIHL at 1, 2 and 4 kHz is more substantial, at 11.7 dB.

SII values were calculated for the example illustrated in Table 1 using the band-importance function for everyday speech and for three listening situations. For each listening situation the SII was calculated for two cases: (1) For a hearing loss based on the estimated AAHL (row 15 in Table 1), and (2) For a hearing loss based on the actual audiogram. The difference between the two cases represents the extra effect of the NIHL. The outcome is shown in Table 2.

For speech presented at a typical conversational level of 65 dB SPL without any background noise, the difference in SII

Table 1. Illustration of the two-pass method of Lutman et al (2016) for estimating the noise-induced component of hearing loss for a hypothetical case of a 55-year-old man.

Lutman et al 2016 method		*Frequency*						
Pass 1		1.0	2	3	4	6	8	
Hearing threshold level (HTL), dB HL		10.0	10.0	15.0	50.0	45.0	35.0	
HTL at selected anchor points		10.0					35.0	
Selected age-associated hearing loss (AAHL)		7	13	19	28	32	38	55at50
Misfit values (dB)		3.0					−3.0	
Interpolated misfit values (dB)		3.0	1.0	0.0	−1.0	−2.0	−3.0	
Age adjusted AAHL		10.0	14.0	19.0	27.0	30.0	35.0	
Bulge (dB)		0.0	4.0	4.0	23.0	15.0	0.0	
Pass 2								
Modified HTL at anchor points (dB)		6.5					25.8	
Selected age-associated hearing loss (AAHL)		7	13	19	28	32	38	55at50
Misfit values (dB)		−0.5					−12.2	
Interpolated misfit values (dB)		−0.5	−4.3	−6.3	−8.3	−10.2	−12.2	
Modified AAHL (dB)		6.5	8.7	12.7	19.7	21.8	25.8	
Modified bulge = noise-induced loss (dB)		3.5	1.3	2.3	30.3	23.2	9.2	
Mean noise-induced loss 1, 2 and 3 kHz	2.4							
Mean noise-induced loss 1, 2 and 4 kHz	11.7							

Table 2. Calculated values of the SII for a hypothetical case, based on the estimated age-associated hearing loss (AAHL) and the actual hearing loss for three listening situations. The difference between the two SII values for a given situation represents the decrease in SII resulting from the noise-induced component of the hearing loss.

		Situation	
	Speech in quiet at 65 dB SPL	*Speech in quiet at 50 dB SPL*	*Speech at 65 dB SPL in noise at 0 dB SNR*
SII for AAHL	0.95	0.81	0.39
SII for actual hearing loss	0.81	0.71	0.31
Difference	0.14	0.10	0.08
Difference in percent	15%	12%	21%

was 0.14 (a decrease of 15%). Since both SII values were high, the noise-induced component of the loss would not prevent good communication with a talker who spoke clearly in a non-reverberant room but might lead to slight difficulty with a talker who did not speak clearly, had a foreign accent, or was heard in a reverberant room.

Consider next the situation for soft speech at 50 dB SPL, such as might occur when a person talks in an adjacent room or when sitting close to the back of a lecture room. The difference for this situation was 0.10 (a decrease of 12%). The decrease in SII value produced by the noise-induced component of the hearing loss would lead to some difficulty in understanding clearly spoken speech and marked difficulty for a talker who did not speak clearly or was heard in a reverberant room.

The primary problem experienced by people with hearing loss, at least when the hearing loss is mild or moderate, is difficulty in understanding speech in noisy situations (Kochkin, 2010; Moore, 2007; Plomp, 1978; 1986). To quantify the likely magnitude of this difficulty, the SII was calculated for speech presented at a level of 65 dB SPL in a background noise of the same overall level. This is representative of a moderately noisy situation. The background noise was assumed to have a similar average spectrum to the target speech, but with slightly less energy for high frequencies, to allow for the fact that reflection of noise from the walls, floor and ceiling of a typical room is reduced at high frequencies. The difference for this situation was 0.08 (a decrease of 21%). The decrease in SII would lead to a clearly noticeable increase in difficulty in understanding speech in noisy situations.

This example illustrates how the noise-induced component of the hearing loss at frequencies above 3 kHz can lead to some increase in difficulty in understanding soft speech in quiet and a marked increase in difficulty in understanding speech in background noise.

As noted above, the SII is based mainly on the proportion of the speech that is audible. The SII does not take into account effects of NIHL other than elevation of the audiometric threshold. Such effects include reduced frequency selectivity (the ability to 'hear out' or separate the different frequencies that are present in complex sounds like speech) (Glasberg & Moore, 1986; Moore, 2007), and degeneration of neurons in the auditory nerve (Kujawa & Liberman, 2009; Wan & Corfas, 2015). Thus calculations based on the SII probably underestimate the effects of NIHL.

Other deleterious effects of high-frequency hearing loss

The voices of small children have a higher frequency spectrum than for adults and their speech may be less clear than that of adults. Certain speech sounds (such as 's') produced by women and children may contain energy largely above 4 kHz. Hence, hearing loss at 4 kHz and above may compromise the ability to hear such sounds (Stelmachowicz et al, 2001). Certain bird songs are composed mainly of frequencies above 3 kHz (see, for example, the spectra for songs of two species of sparrow in Figures 3 and 4 of Hoese et al, 2000). It follows that hearing loss at frequencies around 4–6 kHz is likely to have an impact on the ability to hear such sounds. Of course, the importance of this is likely to vary markedly across individuals.

The ability to determine whether a sound is coming from in front or behind, and above or below, depends on information provided by reflections of sound from the pinna (the outer ear); these reflections change the spectrum of the sound reaching the eardrum (Blauert, 1997). The changes in spectrum are most marked and are most useful for frequencies above 3 kHz (Gardner & Gardner, 1973; Best et al, 2005). Hearing loss for frequencies of 4 kHz and above is likely to reduce the ability to use pinna cues and hence decrease the ability to determine whether sounds are coming from in front or behind, and above or below. This happens partly because of reduced audibility of high-frequency sounds, but mainly because hearing loss is usually associated with reduced frequency selectivity, and this decreases the ability to discriminate the spectral changes (Jin et al, 2002). The extra component of hearing loss at 4 and 6 kHz produced by noise exposure reduces the ability to judge whether sounds are coming from in front or behind, and above or below, and increases the smallest detectable change in location of a sound (Rønne et al, 2016).

Effects of noise exposure not revealed by the audiogram

There is evidence from both animal studies (Kujawa & Liberman, 2009) and human studies (Epstein et al, 2016; Stamper & Johnson, 2015) that noise exposure can lead to loss of synapses between the inner hair cells in the cochlea and the neurons in the auditory nerve, even when the audiogram remains normal or near-normal (Gourevitch et al, 2014; Wan & Corfas, 2015). Following the loss of synapses, the neurons in the auditory nerve degenerate, but this can take a considerable time, up to several years (Kujawa & Liberman, 2015). The degeneration tends to be greatest in neurons tuned to high frequencies (Kujawa & Liberman, 2009). When effects of NIHL are apparent in the audiogram, the loss of synapses and neurons is probably even greater than when the audiogram remains within normal limits. The loss of synapses and neurons results in a reduced flow of information from the cochlea to the brain, and to a less precise neural representation of the properties of sounds. Consistent with this, noise exposure is associated with greater self-reported hearing difficulty (Tremblay et al, 2015) and with a poorer-than-normal ability to detect envelope fluctuations in sounds (Stone & Moore, 2014), even when the audiogram remains within normal limits. Loss of neurons in the auditory nerve probably contributes to the difficulties experienced by people with NIHL when trying to understand speech in the presence of background sounds (Epstein et al, 2016; Plack et al, 2014). The effects of loss of neurons are not taken into account in the SII calculations described above. Hence, these calculations probably under-estimate the degree of difficulty experienced by people with NIHL.

Predicting self-reported hearing difficulty based on audiometric thresholds

It has been argued that self-assessment should be the ‘gold standard’ for determining the effects of hearing impairment in everyday life since ‘No one can assess the effects of hearing loss on daily life better than the affected person (assuming that this is a competent, cooperative adult who is not claiming compensation)’ (Dobie & Sakai, 2001). However, since a person claiming compensation for hearing loss might give an exaggerated report of the adverse effect of their hearing loss, self-report is not considered appropriate when assessing individual claims for compensation. Hence, surrogate measures must be used. Two possible surrogate measures are performance on objective measures of the intelligibility of speech in quiet or in noise and some sort of average of the audiometric thresholds at selected frequencies.

A widely used approach to assessing the relative importance of hearing loss at different audiometric frequencies is to obtain self-report assessments of hearing difficulty from a large number of hearing-impaired people and to determine the extent to which these assessments are predicted by the audiometric thresholds at specific frequencies or combinations of frequencies (Dobie, 2011; Dobie & Sakai, 2001; King et al, 1992). This approach has been reviewed by Dobie and Sakai (2001) and Dobie (2011) and it is the one that is most widely used in the medico-legal context. Generally, the audiometric thresholds showing the highest correlation with self-reported hearing difficulty are 0.5, 1 and 2 kHz. When combinations of the audiometric thresholds at different audiometric frequencies are used, the combinations including the frequencies 0.5, 1 and 2 kHz generally lead to the highest correlations. When a combination of four frequencies is used, the correlations are almost the same for the combination 0.5, 1, 2, and 3 kHz and the combination 0.5, 1, 2, and 4 kHz (Dobie, 2011). These results have been taken as indicating that hearing loss for frequencies up to 3 kHz is the major determinant of self-reported hearing difficulty, with the usual caveat that correlation does not imply causation.

One justification for the use of self-report assessments rather than objective measures of the ability to understand speech in quiet or in background sounds is that it avoids any arbitrary decision about which of the many available objective speech tests should be used. However, the selection of the test(s) used to obtain self-report measures from the many tests available is also somewhat arbitrary. An argument in favour of the use of audiometric thresholds rather than objective measures of speech intelligibility is that the former are generally more highly correlated than the latter with self-report measures of hearing difficulty (Dobie & Sakai, 2001). However, this partly reflects the fact that the objective measures of speech intelligibility used in most large-scale clinical studies are based on a relatively small number of test items, and hence have high variability. Measures of speech intelligibility based on more data, and with lower variability, such as the study of Smoorenburg (1992) described in the next section, might show a higher correlation with self-reported hearing difficulties; this remains to be determined.

The argument that self-report measures should be regarded as the gold standard can be questioned. For a hearing loss that develops slowly and progressively, as is usually the case, the affected person may not notice the change in their hearing until it becomes rather severe. Consistent with this, many people who judge their own hearing to be ‘normal’ nevertheless have hearing loss that presumably leads to some hearing difficulty (see the supplementary material in Füllgrabe et al, 2015). Furthermore, self-report measures are affected by factors other than hearing ability, such as age and intelligence (Gatehouse, 1990). Perhaps for these reasons, self-report measures often show only a modest correlation with audiometric thresholds. For example, the ‘‘Communication Profile’’ scores from the CPHI self-assessment inventory (Demorest & Erdman, 1987) had a correlation of −0.4 with the mean audiometric threshold at 0.25, 0.5, 1, 2 and 4 kHz in the analysis reported by Dobie (2011). This was the highest (negative) correlation obtained among the various combinations of audiometric frequencies that were evaluated.

Most of the studies that have reported correlations between self-reported hearing difficulty and audiometric thresholds have been based on participants with a wide range of ages and types of hearing loss. The best combination of frequencies for predicting hearing difficulties among people with NIHL (or a combination of NIHL and age) might differ from that for the general population of hearing-impaired people. For example, low-frequency hearing loss is often associated with hearing disorders such as Ménière's syndrome that lead to severe speech perception and other difficulties (Soderman et al, 2002). The inclusion of such people in the sample population will increase the correlation between self-reported hearing difficulty and audiometric thresholds at low frequencies. Indeed, Dobie (2011) pointed out that '... the best set of audiometric frequencies for predicting self-reported disability will include relatively higher frequencies for a sample of people with only mild to moderate loss and relatively lower frequencies for a sample of people with profound impairments'. Many people with NIHL fall into the former category. Gomez et al (2001) examined the relationship between audiometric thresholds and self-reported hearing difficulty for 376 farmers who were known to be exposed to potentially damaging levels of noise. The agreement between self-report scores of hearing difficulty and audiometric thresholds was higher for the average across 1, 2, 3, and 4 kHz than for the average across 0.5, 1, and 2 kHz or across 3, 4, 6 and 8 kHz. This finding suggests that for people with NIHL, audiometric thresholds at higher frequencies (3 and 4 kHz) are related to self-reported hearing difficulty.

In summary, while for the hearing-impaired population in general self-reported hearing difficulties are predictable to some extent from audiometric thresholds for frequencies up to 3 kHz, this does not necessarily mean that hearing loss for frequencies above 3 kHz is unimportant. Furthermore, for a population restricted to those with significant noise exposure, the average of 1, 2, 3, and 4 kHz as a predictor led to better agreement with self-reported difficulties than the average of 0.5, 1, and 2 kHz.

Predicting measured speech intelligibility from the audiogram: the study of Smoorenburg (1992)

Smoorenburg (1992) published a study of the effects of NIHL on the ability to understand speech in quiet and in noise and of the relationship of that ability to the audiogram, using 200 participants. This study had three strengths for the purposes of the present review. Firstly, all participants were selected because they were exposed to relatively intense noise at work, so the population was representative of those seeking compensation for NIHL. Second, the participants in the study were not actually seeking compensation for their hearing loss and had no motivation for exaggerating the extent of their hearing difficulties. Thirdly, the ability to understand speech in noise was measured for three background noise levels, so that an accurate composite estimate of that ability was obtained. All participants were younger than 55 years to minimize the effects of age.

Smoorenburg found that the speech reception threshold (SRT) for speech in quiet (the speech level required for 50% of sentences to be identified correctly) showed the highest correlation with audiometric thresholds at low frequencies. The best three-frequency predictor of the SRT for speech in quiet was the average audiometric threshold at 0.5, 1, and 2 kHz. However, most of the participants had low SRTs for speech in quiet (90% had SRTs lower than 30 dBA), indicating that they had little difficulty in understanding soft speech.

For speech in noise, the SRT (the speech-to-background ratio required for 50% of sentences to be identified correctly) showed the highest correlation with audiometric thresholds at high frequencies. Smoorenburg determined the correlation between the audiometric threshold at each frequency and the SRT for speech in noise. The correlation showed a maximum at 4 kHz, although the correlation was above 0.6 for frequencies from 3 to 6 kHz. The best three-frequency predictor of the ability to understand speech in noise was the weighted mean threshold at 4, 5, and 2 kHz (in order of importance); the correlation in this case was 0.75. The best unweighted two-frequency predictor was the average of the audiometric thresholds at 2 and 4 kHz (denoted $PTA_{2,4}$); the correlation in this case was 0.72. For $PTA_{2,4} = 0$ dB, the SRT was typically close to –5 dB, whereas for $PTA_{2,4} = 60$ dB the SRT was close to +2 dB. It is noteworthy that the value of $PTA_{2,4}$ accounted for 52% of the variance in the SRTs in noise. In contrast, the best predictor of self-reported hearing difficulty in the study of Dobie (2011) accounted for only 16% of the variance in CP scores.

Again, while correlation does not prove causality, these findings suggest that hearing loss at 4 kHz (and probably 5 kHz) is important in determining the intelligibility of speech in noise for people with NIHL: the higher the audiometric threshold at 4 and 5 kHz, the worse is the intelligibility. Based on the data in Figure 10 of Smoorenburg (1992), a 10-dB increase in $PTA_{2,4}$ is associated, on average, with a 1.2-dB increase in the SNR required to identify 50% of sentences completely correctly. Such a 1.2-dB change corresponds to a 17% decrease in the number of sentences that can be correctly understood under difficult listening conditions (Plomp & Mimpen, 1979). Thus, if the noise-induced component of the hearing loss leads to an increase in $PTA_{2,4}$ of X dB, this would be expected, on average, to decrease the number of correctly identified sentences in noise by X times 1.7%. For example, if the noise-induced component of the hearing loss averaged across 2 and 4 kHz is 12 dB, this would be expected to decrease the number of correctly identified sentences in noise by about 20%. In summary, the results of Smoorenburg (1992) indicate that even relatively small noise-induced elevations in audiometric threshold at 4 kHz are associated with a markedly reduced ability to understand speech in noise.

The results of a study of Wilson (2011) are broadly consistent with those of Smoorenburg (1992). Wilson tested 3266 veterans, many of whom had been exposed to intense noise, and had dips in their audiograms around 4 kHz, indicating NIHL. The intelligibility of speech in noise was assessed using the Words-in-Noise (WIN) test, which evaluates word recognition in multitalker babble at seven SNRs and uses the 50% correct point (in dB SNR) as the primary outcome metric. Wilson found that scores on the WIN were predicted significantly better by the average audiometric threshold at 1, 2 and 4 kHz than by the average audiometric threshold at 0.5, 1, and 2 kHz, confirming the importance of high-frequency hearing for the ability to understand speech in noise.

Conclusions and recommendations

There is very strong evidence that NIHL for frequencies above 3 kHz has adverse effects on the ability to understand speech, especially when background noise is present. Hearing loss for frequencies above 3 kHz also adversely affects the ability to localize sounds and to hear certain kinds of environmental sounds. Therefore, the audiometric threshold at 4 kHz, and possibly also at 6 kHz, should be taken into account when considering compensation for occupational NIHL in a medico-legal context. A major complaint of people with NIHL is difficulty in understanding speech in noise. A good predictor of the ability to understand speech in noise for people with NIHL is the average audiometric threshold at 2 and 4 kHz.

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