Psychoacoustics of normal and impaired hearing

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Recent developments in the field of psychoacoustics are presented, focusing on areas which have application in the diagnosis and understanding of impaired hearing. Cochlear hearing loss often results in a loss of the compressive non-linearity that operates in normal ears; this loss is probably the main cause of loudness recruitment. Forward masking can be used as a tool to assess the strength of cochlear compression in human listeners. Hearing impairment can sometimes be associated with complete loss of function of inner hair cells over a certain region of the cochlea, resulting in a 'dead region'. Two psychoacoustic methods for detecting dead regions and defining their limits are described. The implications of the results for fitting hearing aids are discussed. Finally, the effect of cochlear hearing loss on the perception of rapid sequences of sounds (stream segregation) is described.

This chapter presents a selective review of recent developments in the field of psychoacoustics. It focuses on areas which have application in the diagnosis and understanding of impaired hearing. It does not repeat topics covered in my earlier *British Medical Bulletin* review[1]. For more comprehensive coverage of the psychoacoustics of impaired hearing, the reader is referred to reviews elsewhere[2,3].

Using forward masking to assess cochlear compression

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Recent physiological studies of the mechanics of the basilar membrane within the cochlea indicate that the response to sinusoidal tones can be highly compressive[4,5]. The compression can be quantified by plotting the magnitude of the response as a function of the magnitude of the input, giving an input–output function. A schematic example is given in Figure 1. The solid line shows what would be observed for a tone at the characteristic frequency (CF) of the place being studied (the CF is the frequency giving maximal response at that place for a low-level input). For mid-range sound levels, the output grows by only 2.5 dB for each 10-dB increase in input level, indicating compression. The function becomes

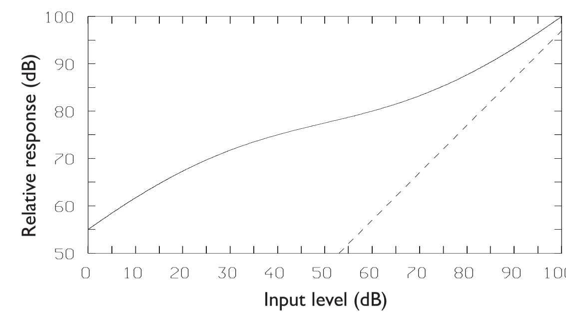

Fig. 1 The solid line shows a schematic illustration of an input–output function on the basilar membrane for a tone with frequency close to CF. The dashed line shows a linear input-output function. This is typical of what might be observed for a tone with frequency well below CF.

more linear (steeper) for very low and very high sound levels. The long-dashed line shows the type of function that would be observed for a tone with frequency well below CF. In this case, the response grows in a linear manner; each 10-dB increase in input level gives rise to a 10-dB increase in response.

The compression on the basilar membrane is believed to arise from the operation of an 'active' physiological mechanism which depends on the motile behaviour of the outer hair cells (see chapters by Ashmore and by Kemp in this volume). The compression is very fast-acting[6] and it allows the normal auditory system to operate over a wide range of sound levels, *i.e.* it provides the large dynamic range of about 120 dB. It also plays a role in many other aspects of auditory perception, including intensity discrimination, masking, loudness, and timbre perception[7]. Hearing loss is often caused by loss of function of the outer hair cells (see chapters by Forge & Wright and by Raphael in this volume). This leads to the loss of compression, which is probably the main cause of the reduced dynamic range and loudness recruitment that are typically associated with cochlear hearing loss[3,8].

Compression in the cochlea can be quantified in human listeners using forward masking. The listener is required to detect a brief signal presented just after the end of a masker that typically lasts 100–300 ms. It is assumed that the threshold for detecting the signal is monotonically related to the 'internal' effect produced by the masker at the place in the cochlea where the signal is detected. This place will have a CF close to the signal frequency. The advantage of forward masking is that the signal and the masker are separated in time, so the masker and the signal are processed independently on the basilar membrane, and non-linear interactions between them are minimal.

In forward masking, a given increment in masker level often does not produce an equal increment in amount of forward masking. For example, if the masker level is increased by 10 dB, the masked threshold may only increase by 3 dB[9,10]. This effect can be quantified by plotting the signal threshold (in dB) as a function of the masker level (in dB). The resulting function is called a growth-of-masking function. In simultaneous masking, such functions often have slopes close to one, when a broad-band noise masker is used. In forward masking, the slopes are usually less than one.

Oxenham and Moore[11] have suggested that the shallow slopes of the growth-of-masking functions can be explained in terms of the compressive input–output function of the basilar membrane. Such an input–output function is shown schematically in Figure 2. It has a shallow slope for medium input levels, but a steeper slope at very low input levels. Assume that, for a given time delay of the signal relative to the masker, the response evoked by the signal at threshold is directly proportional to the response evoked by the masker. Assume, as an example, that a masker with a level of 50 dB produces a signal threshold of 12 dB. Consider now what happens when the masker level is increased by 20 dB. The increase in masker level, denoted by ΔM in Figure 2, produces a relatively small

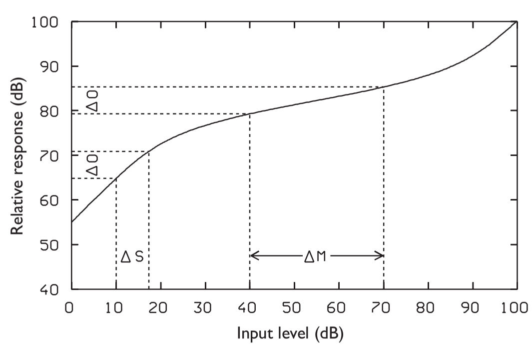

Fig. 2 The curve shows a schematic input-output function on the basilar membrane. When the masker is increased in level by ΔM, this produces an increase in response of ΔO. To restore signal threshold, the response to the signal also has to be increased by ΔO. This requires an increase in signal level, ΔS, which is markedly smaller than ΔM.

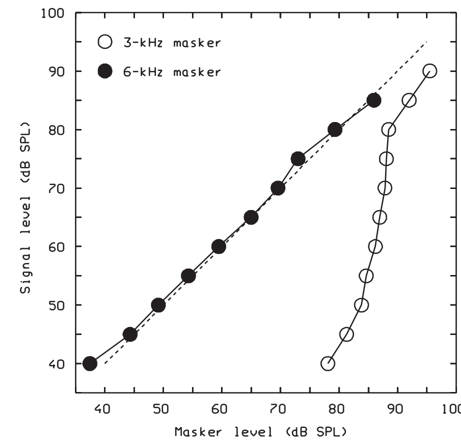

Fig. 3 Data from Oxenham and Plack[12] for normally hearing subjects. Thresholds for detecting a 6-kHz signal following a 3-kHz or 6-kHz masker are shown. The signal level was fixed, and the masker level was varied to determine the threshold. Symbols represent the mean thresholds of three normally hearing subjects. Error bars represent ± 1 SEM. They are omitted where they would be smaller than the relevant data point.

increase in response, ΔO. To restore the signal to threshold, the signal has to be increased in level so that the response to it increases by ΔO. However, this requires a relatively small increase in signal level, ΔS, as the signal level falls in the range where the input–output function is relatively steep. Thus, the growth-of-masking function has a shallow slope.

Oxenham and Plack[12] have investigated forward masking for a 6-kHz sinusoidal masker and a signal of the same frequency. They showed that if the signal is made very brief and the time delay between the masker and signal is very short, the level of the signal at threshold is approximately equal to the masker level. Under these conditions, the signal and the masker are compressed by a similar amount on the basilar membrane, and the growth-of-masking function has a slope of unity. This is illustrated in Figure 3 (filled symbols). When a masker frequency well **below** the signal frequency was used (3 kHz instead of 6 kHz), the growth-of-masking function had a slope much **greater** than unity; a 10-dB increase in masker level was accompanied by a 40-dB increase in signal level, as shown by the open symbols in Figure 3. This can be explained as follows: the signal

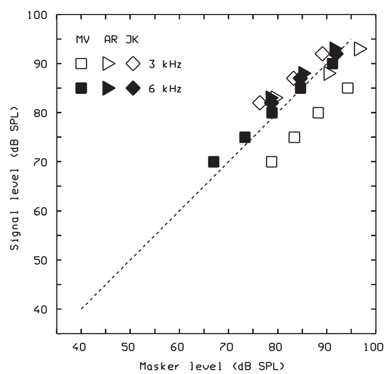

Fig. 4 Data from Oxenham and Plack[12] for three subjects with cochlear hearing loss. Individual data from subjects MV, AR and JK are plotted.

threshold depends on the response evoked by the masker at the place with CF close to the signal frequency. The growth of response on the basilar membrane for tones with frequency well below CF is linear (see the long-dashed line in Fig. 1). Thus, the signal is subject to compression while the masker is not (essentially the opposite of the situation illustrated in Fig. 2). This gives rise to the steep growth-of-masking function.

If the compression on the basilar membrane is lost as a consequence of cochlear hearing loss, then the growth-of-masking functions in forward masking (in dB per dB) should have slopes close to unity, except when the signal is very close to its absolute threshold. Furthermore, the slope should remain close to unity, regardless of the relative frequencies of the masker and signal, as all frequencies should be processed linearly. Empirical data have confirmed these predictions[11–13]. This is illustrated in Figure 4, which shows individual data from three subjects with moderate cochlear hearing loss in the same conditions as those used for the normally hearing subjects in Figure 3. In contrast to Figure 3, all three hearing-impaired subjects in Figure 4 show linear growth-of-masking functions for both the 6-kHz and the 3-kHz masker. This is consistent with the view that cochlear damage results in a loss of basilar membrane compression.

While forward masking is a useful laboratory tool for quantifying cochlear compression, it is probably not suitable as a clinical tool, because quite a lot of practice is required before stable results are obtained. However, a simple measure of frequency selectivity, based on the measure-

ment of thresholds for detecting a sinusoidal signal in a noise with a spectral notch[14–16] gives results that are quite highly correlated with measures of cochlear compression obtained using forward masking[17]. This correlation probably occurs because both cochlear compression, and the sharpness of tuning (selectivity) of the cochlea are strongly dependent on the active mechanism. Thus, the strength of cochlear compression can be estimated indirectly from the detection threshold of a tone in a noise with a spectral notch.

Diagnosis of dead regions in the cochlea

Cochlear hearing loss is sometimes associated with complete destruction of the inner hair cells (IHCs)[18]. Sometimes the IHCs may still be present, but may be sufficiently abnormal that they no longer function. The IHCs are the transducers of the cochlea, responsible for converting the vibration patterns on the basilar membrane into action potentials in the auditory nerve[19]. When the IHCs are non-functioning over a certain region of the cochlea, no transduction will occur in that region. Hence, such a region is called a dead region[8,20,21].

A dead region can be defined in terms of the CFs of the IHCs and/or neurones immediately adjacent to the dead region[21]. For example, if there is a dead region at the basal end of the cochlea, and the CF of the IHCs/neurones immediately adjacent to the dead region is 2 kHz, this is described as a dead region extending from 2 kHz upwards. A tone with frequency falling in a dead region is detected via the apical or basal spread of the vibration pattern to places where there are surviving IHCs and neurones[22]. Thus, the 'true' hearing loss at a given frequency may be greater than suggested by the audiometric threshold at that frequency.

The audiogram cannot be used to determine whether or not a dead region is present in a given individual, although a large low-frequency loss or a loss that increases rapidly with increasing frequency is often associated with a dead region[21]. In the laboratory, dead regions have been diagnosed by using simultaneous masking to measure psychophysical tuning curves (PTCs)[22,23]. The signal is fixed in frequency and in level, usually at a level just above the absolute threshold. The masker is usually a narrow band of noise. For each of several masker centre frequencies, the level of the masker needed just to mask the signal is determined. For normally hearing subjects, the tip of the PTC (*i.e.* the frequency at which the masker level is lowest) always lies close to the signal frequency; the masker is most effective when its frequency is close to that of the signal.

When hearing-impaired listeners are tested, PTCs have sometimes been found whose tips are shifted well away from the signal frequency[20,23]. This happens when the signal frequency falls in a dead region. For example, when there is a low-frequency dead region, the detection of low-frequency tones is mediated by neurones with high CFs, so a high-frequency masker is more effective than a masker close to the signal frequency.

PTCs are rather time consuming to determine, and have rarely been used in clinical practice. Recently, Moore *et al*[20] described a test for the identification of dead regions which is intended to be short and simple enough for use in clinical practice. The test is based upon the detection of sinusoids in the presence of a broad-band noise, designed to produce almost equal masked thresholds (in dB SPL) over a wide frequency range, for normally hearing listeners and for listeners with hearing impairment but without dead regions. This noise is called threshold equalizing noise (TEN). The detection threshold is approximately equal to the level of the noise in a one-ERB wide band centred at 1 kHz; ERB stands for equivalent rectangular band-width of the auditory filter, and its normal value at 1000 Hz is about 132 Hz[15]. For example, a noise level of 70 dB/ERB usually leads to a masked threshold of about 70 dB SPL.

When a tone has a frequency that falls well within a dead region, the tone is detected using neurones with CFs remote from the signal frequency. The amplitude of basilar membrane vibration at the remote place will generally be less than the amplitude in the dead region. Therefore, the broad-band noise masks the tone much more effectively than would normally be the case, as the noise only has to mask the reduced response at the remote place. Thus, if the threshold for detecting a tone in the TEN is **markedly** higher than normal, this indicates a lack of functioning IHCs/neurones with CFs corresponding to the frequency of the tone (*i.e.* a dead region).

To validate the TEN test, Moore *et al*[20] measured PTCs and applied the TEN test in the same hearing-impaired listeners. The hypothesis tested was that higher-than-normal thresholds in the TEN would be associated with PTCs with shifted tips. Results for a hearing-impaired person who does not appear to have a dead region are shown in Figure 5. The lower panel shows results obtained with the TEN, except that filled squares indicate absolute thresholds (in dB SPL). Over the frequency range where the TEN produces masking, the masked thresholds are only slightly higher than normal, being around 71–75 dB for the TEN level of 70 dB/ERB. For frequencies of 3000 Hz and above, the TEN level of 70 dB/ERB is not sufficient to produce masking, so the masked thresholds are close to the absolute thresholds.

The upper panel of Figure 5 shows PTCs determined for three signal frequencies. In each case, the signal level and frequency are indicated by a filled symbol. The corresponding PTC is indicated by an open symbol of the same shape. For each PTC, the tip is close to the signal frequency. The PTCs are consistent with the results using the TEN, indicating that each signal was detected via IHCs/neurones with CFs close to the signal frequency.

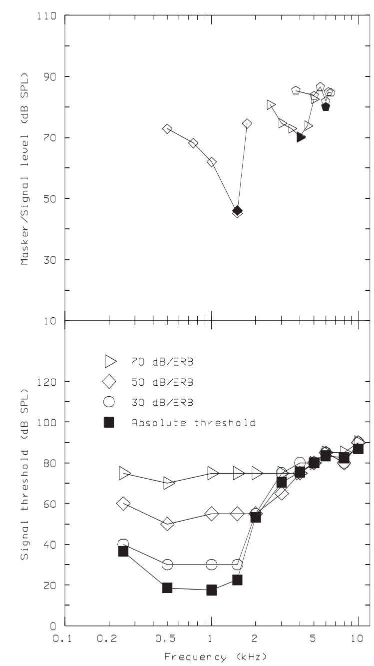

Fig. 5 Results for a hearing-impaired person who does not have a dead region. The lower panel shows results obtained with the TEN, except that filled squares indicate absolute thresholds. The upper panel shows PTCs determined for three signal frequencies. In each case, the signal level and frequency are indicated by a filled symbol. The corresponding PTCs are indicated by open symbols of the same shape.

Figure 6 shows results for a hearing-impaired person who probably does have a dead region. This person has near-normal hearing for frequencies up to 1000 Hz, but a severe-to-profound loss at higher frequencies. For signal frequencies of 1500 Hz and above, masked thresholds in the 70 dB/ERB noise were 10 dB or more higher than the mean normal value. For signal frequencies from 3000–5000 Hz, the masked thresholds in the 30 dB/ERB noise were elevated above the absolute thresholds and were at

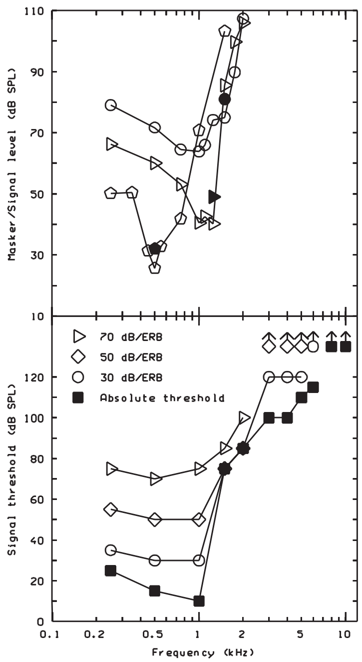

Fig. 6 Results for a person with a dead region at high frequencies. Otherwise, as Figure 5. Symbols with up-pointing arrows indicate cases where the threshold was too high to be measured; the highest measurable threshold (determined by equipment limitations) was 120 dB SPL. The specific symbol used with the arrow indicates the lowest TEN level for which a threshold could not be measured.

120 dB SPL, *i.e.* 90 dB higher than for normal-hearing subjects! This strongly suggests that tones with frequencies of 1500 Hz and above were being detected via IHCs/neurones with CFs below 1500 Hz.

The PTC for this subject for a signal frequency of 500 Hz has a tip at 500 Hz. However, the PTCs for signal frequencies of 1200 and 1500 Hz are shifted downwards to about 1000–1200 Hz. This suggests that the dead region starts at 1000–1200 Hz, and extends upwards from there,

which is consistent with the finding that thresholds in the TEN were near normal for frequencies up to 1000 Hz, but were higher than normal for frequencies of 1500 Hz and above.

In total, Moore *et al*[20] tested 20 ears of 14 subjects with sensorineural hearing loss. Generally, there was a very good correspondence between the results obtained using the TEN and the PTCs; if, for a given signal frequency, the masked threshold in the TEN was 10 dB or more higher than normal **and** the TEN produced at least 10 dB of masking (*i.e.* the masked threshold was 10 dB or more above the absolute threshold), then the tip of the PTC determined using that signal frequency was shifted. If the masked threshold in the TEN was not 10 dB or more higher than normal, the tip of the PTC was not shifted. Hence, the following 'rule' was formulated: if the threshold in the TEN is 10 dB or more above the TEN level/ERB, and the TEN produces at least 10 dB of masking, this is indicative of a dead region at the signal frequency. It should be noted, however, that if the TEN does not produce at least 10 dB of masking, the result must be regarded as inconclusive; a dead region may or may not be present.

The presence or absence of dead regions can have important implications for the fitting of hearing aids. People with moderate-to-severe high-frequency hearing loss often do not benefit from amplification of high frequencies[24–26]. In several of these studies, it was suspected that there were dead regions at high frequencies, although there was little direct evidence to support this idea. Recently, Vickers *et al*[27] measured the identification of nonsense syllables by people with high-frequency hearing loss. One group of subjects was diagnosed as having high-frequency dead regions, using the tests described above. The other group did not have dead regions. For both groups, the stimuli were subjected to frequency-dependent linear amplification according to the 'Cambridge' formula[28], which is intended to restore the audibility of speech presented at a moderate level (about 65 dB SPL). Then, the stimuli were low-pass filtered with various cut-off frequencies. For subjects without dead regions, performance generally improved progressively with increasing cut-off frequency. For most subjects with dead regions, performance improved with increasing cut-off frequency until the cut-off frequency was somewhat above the estimated edge frequency of the dead region, but hardly changed with further increases. For a few subjects, performance initially improved with increasing cut-off frequency and then worsened with further increases. The cut-off frequency giving optimum performance was estimated to be 1.5–2 times the estimated edge frequency of the dead region. Baer *et al*[29] found similar results for speech presented in background noise.

The practical implications of these results are as follows. Firstly, for a person with an extensive high-frequency dead region, the ability to understand speech will probably be rather poor, and a hearing aid may be of limited benefit. However, as noted above, amplification should be applied for frequencies up to about 1 octave above the estimated edge frequency of the dead region. There may be several benefits of reducing the gain for frequencies above this. Firstly, this may actually lead to improved speech intelligibility, as described above. Secondly, it may reduce problems associated with acoustic feedback (whistling). Thirdly, it may reduce distortion in the hearing aid. Finally, it allows the dispenser to concentrate efforts on providing appropriate amplification over the frequency range where there is useful residual hearing.

Perceptual streaming

A rapid sequence of sounds may perceived as coming from a single source (called fusion), or as coming from more than one source (called fission or stream segregation)[30,31]. The term 'streaming' is used to denote the processes determining whether one stream or multiple streams are heard. Streaming has often been studied using sequences of the form ABA–ABA–..., where A and B represent brief sinusoidal tone bursts and – represents a silent interval[30]. When the frequency separation of A and B is large, two streams are heard, one (A tones) going twice as fast as the other (B tones). When the frequency separation is small, fusion occurs and a characteristic 'gallop' rhythm is heard. For intermediate frequency separations of A and B, the subject may either hear two streams or one. The frequency separation at which the subject cannot perceive two streams, but only hears the gallop rhythm, is called the fission boundary.

It has been proposed[32,33] that streaming depends primarily upon the filtering that takes place in the cochlea. For example, the computer model of Beauvois and Meddis[33] is based on the idea that streaming depends upon the overlap of the excitation patterns evoked by successive sounds in the cochlea; a large degree of overlap leads to fusion while a small degree leads to fission. People with cochlear hearing loss usually have reduced frequency selectivity, which leads to broader excitation patterns[3]. If the model of Beauvois and Meddis is correct, the fission boundary should be larger than normal in people with cochlear hearing loss.

This prediction was tested by Rose and Moore[34]. They measured fission boundaries for the ABA–ABA– sequence described above, using both normally hearing subjects and subjects with unilateral and bilateral cochlear hearing loss. For the unilaterally hearing-impaired listeners, there was no consistent difference in the fission boundary across ears. The bilaterally hearing-impaired listeners sometimes showed fission boundaries within the normal range, and sometimes showed larger than

normal fission boundaries. These results indicate that factors other than overlap of excitation patterns must influence streaming for sequences of pure tones. It may be that the pitches of successive tones need to be clearly different for fission to be heard. If the pitches of the tones are unclear, this may lead to larger-than-normal fission boundaries. It is known that the frequency discrimination of sinusoids is worse than normal in people with cochlear hearing loss[2], and this may indicate that the pitch sensation is less clear.

Grimault *et al*[35] studied streaming for sequences of harmonic complex tones, comparing the results for young, normally hearing subjects and elderly subjects having either impaired or normal hearing for their age. They used the ABA–ABA– sequence. The tones A and B differed in fundamental frequency (F0), but were band-pass filtered so as to contain harmonics in the same frequency region (1375–1875 Hz). When the F0s of the A and B tones were low (around 88 Hz), the harmonics would not have been resolved by the auditory system[36], and excitation patterns would have been very similar for the A and B tones. In this condition, performance was similar for the young and for the elderly hearing-impaired subjects. Thus, consistent with earlier results using similar stimuli, the results indicate that streaming can occur in the absence of differences in the excitation patterns[37–39]. Presumably, the streaming depends on differences in the time pattern (F0) of the successive tones.

When the F0s of the tones were higher (around 250 Hz), some of the harmonics would have been resolved in the auditory periphery of the normally hearing subjects, but the harmonics probably were not resolved by the elderly subjects, owing to their reduced frequency selectivity. In this condition, the former showed significantly more stream segregation than the latter.

The results of Rose and Moore[34] and of Grimault *et al*[35] suggest that the stream segregation of both pure and complex tones can be adversely affected by cochlear hearing loss. This may contribute to the difficulties experienced by hearing-impaired people in understanding speech in situations where there are competing sounds such as other speakers and music.

Key points for clinical practice

- Cochlear hearing loss is usually associated with damage to the active mechanism in the cochlea. This results in reduced frequency selectivity, which contributes to difficulty in understanding speech in noise, and reduced cochlear compression, which is probably the main cause of loudness recruitment. Cochlear compression can be assessed in the laboratory using forward masking, but in the clinic it can be more easily measured by an indirect method, based on the detection of a tone in notched noise.

- Cochlear hearing loss is sometimes associated with complete loss of function of inner hair cells over a certain region of the cochlea, called a dead region. People with extensive dead regions often do not benefit much from a hearing aid, although there can be some benefit of amplifying frequencies up to an octave above the edge frequency of a high-frequency (basal) dead region.
- Dead regions can be diagnosed in the laboratory using psychophysical tuning curves. A method suitable for clinical use involves measuring detection thresholds for tones in quiet and in threshold-equalising noise (TEN).
- Cochlear hearing loss is often associated with abnormalities in the perception of rapid sequences of sounds (stream segregation). This may be a side-effect of reduced frequency selectivity, and it may contribute to the difficulties experienced by hearing-impaired people in understanding speech in situations where there are competing sounds such as other speakers and music.

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