The role of temporal fine structure in normal and impaired hearing

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Any complex sound that enters the normal ear is decomposed by the auditory filters into a series of relatively narrowband signals. Each of these signals can be considered as a slowly varying envelope (E) superimposed on a more rapid temporal fine structure (TFS). In this chapter, I consider the role played by TFS in a variety of psychoacoustic tasks; the role of TFS in speech perception is considered in a companion chapter (Lorenzi and Moore, this volume). I argue that cues derived from TFS play an important role in the ability to "listen in the dips" of a fluctuating background sound, and that TFS cues influence effects such as comodulation masking release. I argue further that TFS cues also play a role in pitch perception and sound localisation. Evidence is reviewed suggesting that cochlear hearing loss reduces the ability to use TFS cues. The perceptual consequences of this, and reasons why it may happen, are discussed.

INTRODUCTION

When a complex broadband sound such as speech is analysed in the cochlea, the result is a series of bandpass-filtered signals, each corresponding to one position on the basilar membrane. Each of these signals contains two forms of information; fluctuations in the envelope (the relatively slow variations in amplitude over time) and fluctuations in the temporal fine structure (TFS, the rapid oscillations with rate close to the center frequency of the band). This is illustrated in Figure 1, which shows the outputs of 1-ERB-wide (Glasberg and Moore, 1990; Moore, 2003) bandpass filters centred at 369, 1499 and 4803 Hz in response to the sound "en" in "sense". Information about the envelope is carried by changes in firing rate of the auditory nerve over time, while information about the TFS is carried in the pattern of phase locking, especially the inter-spike intervals. In most mammals, phase locking breaks down for frequencies above 4 - 5 kHz, so TFS information is presumably not conveyed to the brain for frequencies above 4 - 5 kHz.

According to this conceptual framework, the ranges of rates that are classified as envelope or TFS are not fixed in Hz, but increase as the centre frequency of the auditory filter increases. For example, the mean TFS rate in the bottom panel of Figure 1 corresponds roughly with the centre frequency of the simulated auditory filter used for that panel (369 Hz), while the mean envelope rate (number of maxima per second) is much lower, at about 100 Hz. For the top panel, the mean TFS rate is again close to the centre frequency of the simulated auditory filter used for that panel (4803 Hz). The mean envelope rate depends on exactly how the envelope is extracted, but it is markedly higher than for the bottom panel. In fact, some envelope fluctuations in the top panel are comparable in rate to the TFS in the bottom panel.

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The transmission of envelope fluctuations by an auditory filter requires that the sidebands associated with the modulation are passed by the filter at the centre frequency of interest, fc. It seems reasonable to assume that negligible modulation is passed when the sidebands are attenuated by 20 dB or more. This means that, for *normal* auditory filters, the limiting AM rate is about 1.66 ERB_N. The maximum envelope rate that can be passed by the auditory filters in a normal auditory system is shown in Table 1 for selected values of *fc*.

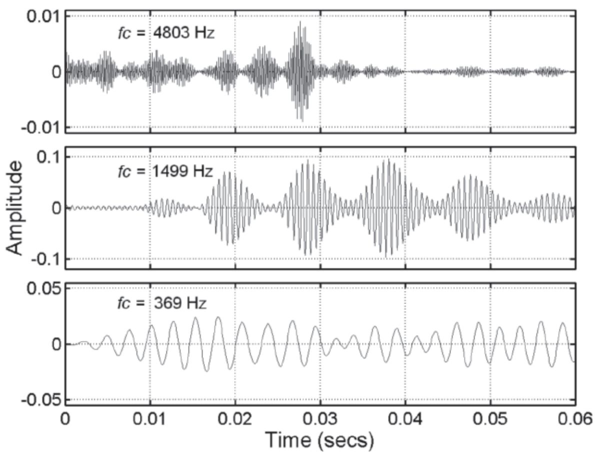

Fig. 1: Waveforms at the outputs of simulated auditory filters centred at 369, 1499 and 4803 Hz in response to the sound "en" in "sense".

fc, Hz	500	1000	2000	4000	8000
Maximum rate, Hz	130	220	339	757	1473

Table 1: Maximum modulation rates passed by normal auditory filters with various centre frequencies, *fc*.

Channels with low *fc* do not convey high-rate modulation in the normal auditory system. However, the limitations imposed by peripheral filtering are different for hearing-impaired (HI) subjects, who have broader filters than normal (Pick *et al.*, 1977; Glasberg and Moore, 1986; Moore, 2007), and for people with cochlear implants (for whom modulation rates are limited by the filters used in the processor). It might be thought, therefore, that hearing-impaired people would perform better than normally hearing subjects when trying to detect high-rate amplitude modulation imposed on carriers at medium to low centre frequencies. Similarly, people with cochlear implants should show superior performance for high-rate modulation imposed on sinusoidal or pulsatile carriers and delivered directly to a single electrode of a cochlear implant. However, the empirical data show that this is not the case, except for very low centre frequencies (Shannon, 1992; Moore and Glasberg, 2001). This leads to the conclusion that the ability to detect amplitude modulation at high rates (above about 130 Hz) is at least partly limited by central processes. Only for low centre frequencies does the filtering in the normal auditory system play a limiting role (Kohlrausch *et al.*, 2000).

The speed with which the TFS changes over time and the complexity of the TFS also tend to increase with increasing bandwidth of the auditory filters. This happens largely because broader filters pass a wider range of frequency components, and this, in itself, lead to more complex and more rapidly varying TFS.

THE ROLE OF TFS IN PITCH PERCEPTION: SLUGGISHNESS

Evidence accrued over many years suggests that TFS plays a role in the perception of pitch for both pure and complex tones; for reviews, see Moore (2003) and Plack and Oxenham (2005). Of particular relevance here is the role of TFS in the detection of frequency modulation (FM), since changes in TFS over time may play a crucial role in the use of TFS information in speech. Moore and Sek have shown that a "place" model based on excitation patterns (i.e., a model that does not assume the use of TFS) can account for the detection of FM, or mixtures of FM and amplitude modulation (AM) when the FM rate is medium or high (10 Hz and above) (Moore and Sek, 1992; Moore and Sek, 1994). However, when the FM rate is low (5 Hz or less), the model fails to predict the data (Moore and Sek, 1995; Sek and Moore, 1995). Moore and Sek proposed that, for very low FM rates, FM is detected by virtue of the changes in phase locking to the carrier that occur over time. In other words, TFS is used to detect FM at very low rates. They suggested further that the mechanism for decoding the phase-locking information was "sluggish" and could not follow rapid oscillations in frequency. Hence, it played little role for high modulation rates. The concept of "sluggishness" has also been used to explain the pitch of musical tones with vibrato (Gockel *et al.*, 2001). This sluggishness may be similar to that observed for binaural processing of interaural phase differences or interaural correlation, which also depends on sensitivity to TFS (Blauert, 1972; Grantham and Wightman, 1978; 1979).

In response to complex sounds, the broadened auditory filters associated with cochlear hearing loss would allow the TFS to be more complex and to fluctuate more rapidly than would be the case for normally hearing listeners. If sluggishness is a general feature of the processing of TFS information, this might contribute to the difficulty of hearing-impaired listeners in using TFS information, as described elsewhere in this volume (chapter by Lorenzi and Moore) and later in this chapter.

THE ROLE OF TFS IN DIP LISTENING

It has been known for many years that it is often easier to detect a signal in a background sound that is fluctuating than in a background sound that is steady, especially when the frequency of the signal is different from the centre frequency of the masker (Fastl, 1975; Buus, 1985; Mott and Feth, 1986; Moore, 1988). This effect has usually been ascribed to the ability to "listen in the dips" of the fluctuating background sound. The question considered here is: how does the auditory system determine whether there is a signal of interest in the dips? Two possible cues are illustrated in Figure 2. The left panel shows the waveform of an AM tone that is considered as a masker. The right panel shows the waveform produced by adding a signal to the masker; the signal frequency is 1.8 times the masker carrier frequency.

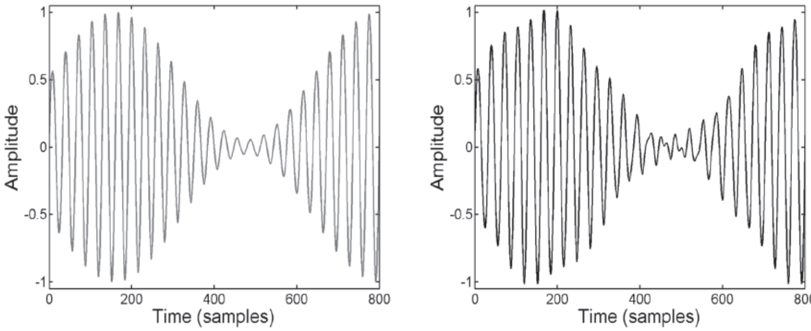

Fig. 2: The waveform of an AM tone that is considered as a masker (left) and the waveform produced by adding a signal to the masker (right). The signal frequency is 1.8 times the masker carrier frequency.

One possible detection cue is the reduction in the modulation depth produced by adding the signal to the masker. This reduction would be most marked at the output of an auditory filter centred close to the signal frequency. While the auditory system is sensitive to changes in modulation depth (Ozimek and Sek, 1988; Wakefield and Viemeister, 1990; Moore *et al.*, 1991; Moore *et al.*, 1995), sensitivity is not very high, and dip-listening thresholds often appear to be too low to be explained by the use of this cue. Also, randomly varying the modulation depth of the masker between the two halves of a forced-choice trial was shown to have no effect on thresholds for detecting a sinusoidal signal in an AM masker with a lower centre frequency (Moore and Glasberg, 1987), which strongly suggests that changes in AM depth within a channel are not used as a cue.

Another possible cue is visible in the waveform for time samples around 450-500 in the right panel of Figure 3; the TFS in the dip is altered by the presence of the signal. This potentially provides a much more effective detection cue than changes in envelope shape or modulation depth. I consider next psychoacoustic studies supporting the idea that dip listening depends partly on the use of TFS information. This interpretation of the studies depends on the assumption that phase locking, and hence sensitivity to TFS, is lost for frequencies above 4 –5 kHz in humans. While there is direct physiological evidence supporting this assumption for mammals (Palmer and Russell, 1986), there is no direct evidence supporting it for humans.

Masking release for a narrowband fluctuating masker

Moore and Glasberg (1987) conducted an experiment similar to that of Buus (1985). They measured the threshold for detecting a sinusoidal signal in a masker that consisted of either a single sinusoid or a pair of equal-amplitude sinusoids, that produced beats at a rate depending on their frequency separation. The overall level of all maskers was 80 dB SPL and the signal frequency was always 1.8 times the masker centre frequency. The masker centre frequency was either 250, 1000, 3000 or 5275 Hz, and the corresponding signal frequencies were 450, 1800, 5400 or 9495 Hz. For the beating masker, the beat rate was 4, 8, 16, 32 or 64 Hz. The mean results for three subjects are shown in Figure 3. For the masker centred at 1000 Hz, the threshold for the signal in the beating masker was considerably lower than the threshold in the steady masker. The difference, which is referred to hereafter as “masking release” was largest (mean ≈ 25 dB) for the 4-Hz beat rate, and decreased progressively as the beat rate was increased to 64 Hz (mean ≈ 10 dB). The pattern of results was similar for the masker centred at 250 Hz, although the overall magnitude of the differences was smaller. However, for the highest masker centre frequency, for which both the signal and the masker frequency fell above the range where phase locking is thought to occur, the masking release was smaller, at about 10 dB, and did not show a clear trend to decrease with increasing beat rate of the masker. The results for the masker centre frequency of 3000 Hz were intermediate in form between those for the 1000-Hz and 5275-Hz masker centre frequencies.

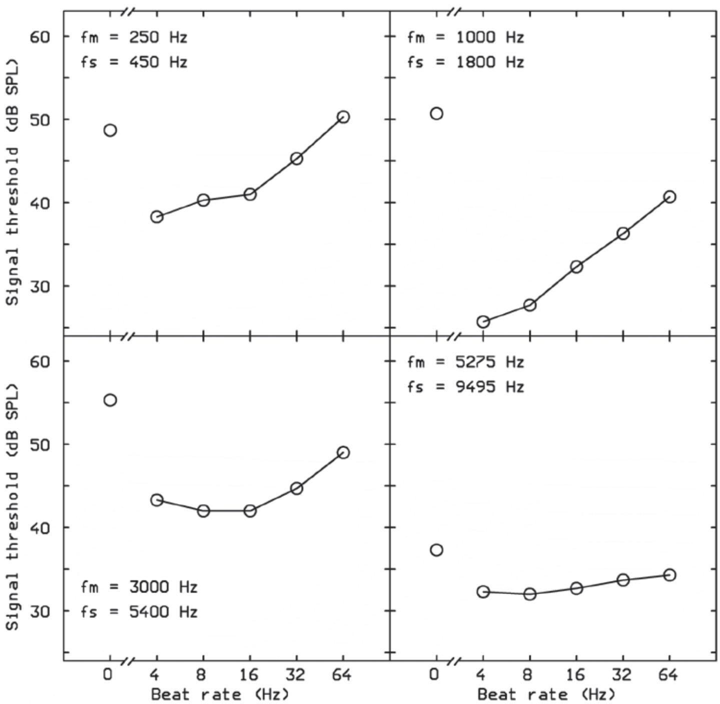

Fig. 3: Thresholds for detecting a sinusoidal signal in a masker consisting of a single sinusoid (beat rate = 0) or a pair of sinusoids with beat rate as indicated.

These results are consistent with the idea that TFS provides a cue that allows effective dip listening when the masker and signal frequencies fall in the range where phase locking occurs. The decrease in masking release with increasing masker beat rate is consistent with the idea that the mechanism that “decodes” TFS information is sluggish, and cannot track rapid changes in TFS. When TFS cannot be processed, because the masker and signal frequencies are too high to support phase locking, some masking release still occurs, but it is smaller and depends only slightly on the masker beat rate. Presumably, some other mechanism leads to masking release in this case, for example, comparison of short-term levels across frequency channels or a shift in the position of the excitation pattern as the masker envelope passes through a minimum; this mechanism appears to be only slightly sluggish.

Comodulation masking release

The threshold for detecting a sinusoidal signal centred in a fluctuating masker, such as a narrowband noise (called the on-frequency band), can be reduced by adding to the masker one or more bands centred well away from the signal frequency (called flanking bands), provided the envelopes of the flanking bands are correlated with that of the on-frequency band. This threshold reduction is called comodulation masking release or CMR (Hall *et al.*, 1984). CMR was first thought to reflect the comparison of the outputs of different auditory filters (across-channel processes), but there is evidence that cues available at the output of the single auditory filter centred near the signal frequency can also play a role (within-channel processes; see Schooneveldt and Moore, 1987; 1989; Moore, 1992; Verhey *et al.*, 1999).

Schooneveldt and Moore (1987) studied CMR using as a baseline condition the threshold for detecting a sinusoidal signal centred in a 25-Hz wide noise (the on-frequency band). The signal frequency, *fs*, ranged from 250 to 8000 Hz in one-octave steps. They measured the effect on the signal threshold of adding a second 25-Hz wide noise (the flanking band) to the masker, either in the same ear as the signal and on-frequency band (monaural condition) or in the opposite ear (dichotic condition). The envelope of the flanking band was either the same as (correlated with) that of the on-frequency band, or was uncorrelated with it. The amount of CMR was defined as the difference between thresholds for the uncorrelated and correlated conditions, called CMR(U-C). The results (mean across three subjects) for the three highest signal frequencies are shown in Figure 4. Schooneveldt and Moore suggested that there were two components to the CMR(U-C): (1) a broadly tuned component, occurring for all signal frequencies and flanking-band frequencies, for both the monaural and dichotic conditions; (2) a sharply tuned component that was present only in the monaural condition and only when the flanking band was centred close to *fs*. This sharply tuned component was small for low *fs*, increased markedly for *fs* = 2000 and 4000 Hz, and decreased at 8000 Hz.

Schooneveldt and Moore (1987) argued that the sharply tuned component of the CMR(U-C) could be explained in terms of a temporal interaction between the on-frequency and flanking bands (a form of beats), which led to periodic zeros in the envelope of the composite masker. When the signal was present, each time the masker composite waveform passed through a minimum, there was a change in the TFS and a shift in the position of the peak in the excitation pattern. These cues for signal detection would initially become more effective as the flanking-band frequency was moved away from *fs*, because the difference between the centre frequency of the composite masker and *fs* would increase, increasing the salience of the change in excitation pattern or TFS. However, when the flanking-band frequency was further removed from *fs*, the beats in the envelope of the composite masker would become more rapid, leading to very brief dips and very rapid fluctuations in TFS. Also, for the lower signal frequencies, the flanking band would fall outside the passband of the auditory filter centred at *fs*, which would reduce the size of the dips in the envelope of the composite masker. The combination of these effects would explain why the CMR(U-C) at first increased as the flanking-band frequency was moved away from *fs*, and then decreased.

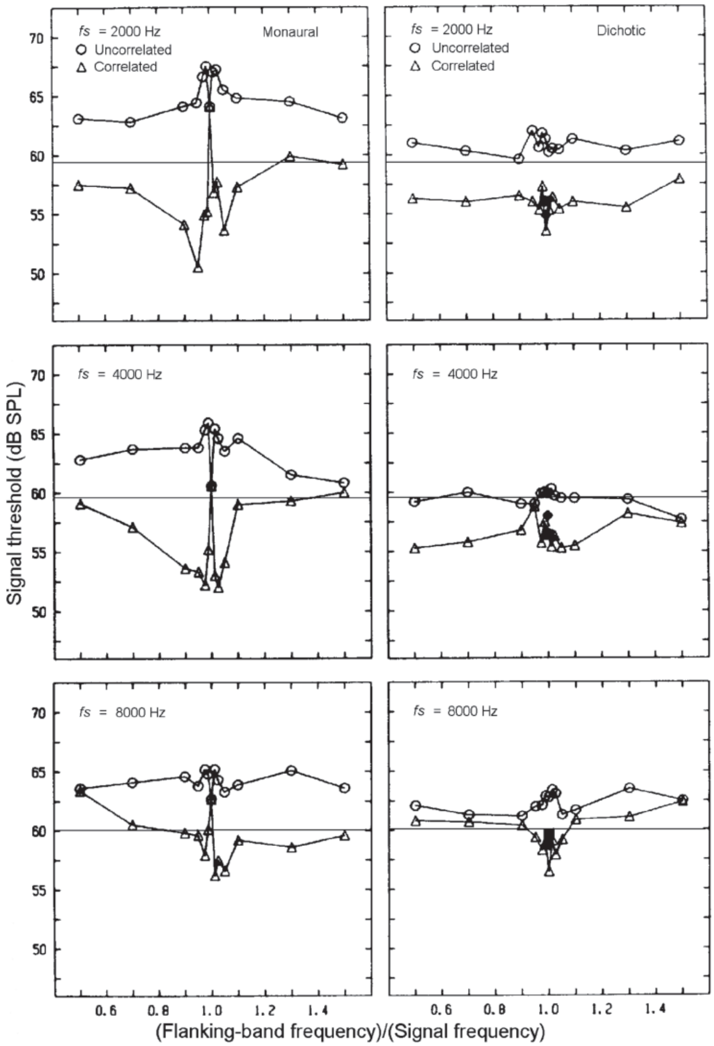

Fig. 4: The threshold for detecting a sinusoidal signal in the on-frequency band alone (thin horizontal lines), and with an added flanking band whose envelope was correlated with the on-frequency band (triangles) or uncorrelated with it (circles).

The sharply tuned component of the CMR(U-C) could be based on either the change in TFS that occurred during masker minima or on changes in the excitation pattern that occurred close to masker minima, or both. However, Schooneveldt and Moore (1987) argued that the pattern of results across frequency suggested that sensitivity to TFS did play a role. Specifically, the decrease in the magnitude of the sharply tuned component when *fs* was increased from 4000 to 8000 Hz was taken as indicating an involvement of phase locking. The reason why the sharply tuned component was also reduced in magnitude for low values of *fs* (250 and 500 Hz) is not clear. It may be connected with the proposal of Moore and Sek, described earlier, that the mechanism that decodes TFS information is sluggish, and cannot track rapid changes in TFS. Possibly, the degree of sluggishness is dependent on the signal frequency; the TFS may need to be stable for a certain number of periods of the stimulus in order for TFS information to be extracted effectively. The minima in the masked thresholds for the correlated condition typically occurred when the flanking band was separated by about 100 Hz from *fs*. For this separation, there were 100 minima per second in the composite masker, and the duration of each minimum was only a few milliseconds. For low signal frequencies, the fluctuations in the TFS and the brief duration of the changes in TFS may have limited the effectiveness with which TFS information could be extracted.

Conclusions on the role of TFS in dip listening

The psychoacoustic experiments reviewed above support the idea that, when the frequency of a signal differs from that of a masking sound, and when the masking sound fluctuates in amplitude over time, the ability to extract information about the signal from the dips of the masking sound depends on the use of TFS, specifically on changes in TFS over time. For very high frequencies, for which TFS information is no longer coded in the auditory system, dip listening is less effective. TFS information is used most effectively when the TFS does not change too rapidly over time, perhaps reflecting sluggishness in the mechanism that decodes TFS information. The degree of sluggishness may increase at low centre frequencies.

THE EFFECT OF HEARING LOSS ON THE ABILITY TO USE TFS INFORMATION

Results from several psychoacoustic and speech perceptual studies suggest that hearing-impaired listeners have an impaired ability to use TFS information (Lacher-Fougère and Demany, 1998; 2005; Moore and Skrodzka, 2002; Moore and Moore, 2003a; Buss *et al.*, 2004; Lorenzi *et al.*, 2006; Moore *et al.*, 2006). I describe here a recent experiment of Hopkins and Moore (2007) that directly assessed the ability of subjects with moderate cochlear hearing loss to use TFS information. Hopkins and Moore measured the ability to discriminate a harmonic complex tone, with fundamental frequency (F0) = 100, 200 or 400 Hz, from a similar tone in which all components had been shifted up by the same amount in Hertz, ΔF. For example, for an F0 of 100 Hz, the harmonic tone might contain components at 900, 1000, 1100, 1200 and 1300 Hz, while the shifted tone might contain components at 925, 1025, 1125, 1225 and 1325 Hz; the value of ΔF in this example is 25 Hz. People with normal hearing perceive the shifted tone as having a higher pitch than the harmonic tone (de Boer, 1956;

Moore and Moore, 2003b). The envelope repetition rate of the two sounds is the same (100 Hz), so the difference in pitch is assumed to occur because of a difference in the TFS of the two sounds (Schouten *et al.*, 1962; Moore and Moore, 2003b). To reduce cues relating to differences in the excitation patterns of the two tones, Hopkins and Moore (2007) used tones containing many components, and the tones were passed though a fixed bandpass filter. Examples of the spectra of harmonic and frequency-shifted tones are shown in the left-hand part of Figure 5. Here, only one of their conditions is considered, for which the filter was centred on the 11th harmonic. To prevent components outside the passband of the filter from being audible, a background noise was added. In the presence of this noise, the differences in excitation patterns between the harmonic and frequency-shifted tones were very small. This is illustrated in the right-hand half of Figure 5.

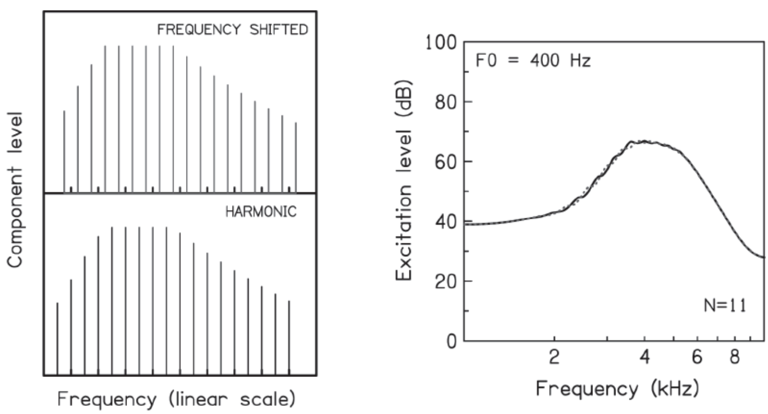

Fig. 5: The left part shows example spectra of harmonic (bottom) and frequency-shifted (top) tones, after bandpass filtering. The right part shows excitation patterns for normal hearing (Glasberg and Moore, 1990) for the bandpass-filtered tones in the presence of background noise. The value of F0 was 400 Hz and the filter was centred on the 11th harmonic.

The normally hearing subjects tested by Hopkins and Moore (2007) were able to perform this task well, presumably reflecting the ability to discriminate changes in the temporal fine structure of the harmonic and frequency-shifted tones. The smallest detectable frequency shift (corresponding to $d' = 1$) was typically about 0.05F0. However, subjects with moderate cochlear hearing loss generally performed very poorly. For most subjects and F0s, performance was not significantly above chance even for the maximum frequency shift of 0.5F0. Above-chance performance occurred only when there was little or no hearing loss at the centre frequency of the filter passband. The results suggest that moderate cochlear hearing loss results in a reduced ability, or no ability, to discriminate harmonic from frequency-shifted tones based on TFS. It should be noted that this conclusion applies only to relatively high centre frequencies, since the lowest centre frequency tested by Hopkins and Moore was 1100 Hz. There is evidence that some hearing-impaired subjects can process TFS for lower centre frequencies, since, for example, they can recognise melodies played as a pattern of binaural pitches (Santurette and Dau, 2007). However, many hearing-impaired subjects do show a poorer than normal ability to process binaural TFS information for frequencies below 1000 Hz (Lacher-Fougère and Demany, 2005; Santurette and Dau, 2007).

The reduced ability of hearing-impaired subjects to process TFS information may largely account for the fact that they are much less able than normally hearing subjects to take advantage of temporal dips in background sounds when trying to understand speech; for a review, see Lorenzi and Moore (this volume).

The ability to process TFS information may have important implications for the choice of compression speed in hearing aids. Compression is used to squeeze the wide range of signal levels occurring in everyday life into the typically small dynamic range of the hearing-impaired person. An individual who has little or no ability to process TFS information will rely largely on temporal envelope cues in different frequency channels to understand speech. Fast-acting compression can disrupt envelope cues. In particular, when the input signal is a mixture of voices from different talkers, fast-acting compression can introduce cross-modulation between the voices, because the time-varying gain of the compressor is applied to the mixture of voices (Stone and Moore, 2004; 2007a; 2007b). Voices which are independently amplitude modulated at the input to the compressor acquire a common component of modulation at the output. This decreases the ability to perceptually segregate the voices, and leads to reduced speech intelligibility under conditions when TFS cues are removed by the use of a noise vocoder (Stone and Moore, 2004; 2007a). Hence, for an individual with little or no ability to process TFS information, slow-acting compression might be more effective than fast-acting compression.

For a hearing-impaired individual who retains some ability to process TFS, the situation is somewhat different. Fast-acting multi-channel compression can help to restore the audibility of low-level portions of signals (the dips), and information derived from TFS can be used to extract “glimpses” of the target speech during dips in a background sound. Thus, fast acting multi-channel compression may lead to improved intelligibility of speech in the presence of sounds with spectral and/or temporal dips for such an individual (Moore *et al.*, 1999). The conclusion from all of this is that measures of the ability to use TFS information might be useful in deciding the most appropriate speed of compression for a hearing-impaired individual.

The reason why hearing-impaired subjects have a reduced ability to process TFS information remains unclear. It might depend on any or all of the following:

(1) Reduced precision of phase locking. There is some controversy about whether or not this occurs (Harrison and Evans, 1979; Woolf *et al.*, 1981).

(2) A change in the relative phase of response at different points along the basilar membrane (Ruggero, 1994). This might affect mechanisms for decoding TFS based on correlation of the outputs of adjacent places (Loeb *et al.*, 1983; Carney *et al.*, 2002).

(3) More complex and more rapidly varying TFS resulting from broader auditory fil-

ters, which might make it more difficult for central mechanisms to decode the TFS information.

(4) A mis-match between place information and TFS information on the basilar membrane, resulting from a shift in frequency-place mapping produced by the hearing loss (Sellick *et al.*, 1982; Liberman and Dodds, 1984). It has been suggested that TFS information may be decoded on a place-specific basis (Moore, 1982; Srulovicz and Goldstein, 1983; Huss and Moore, 2005), so a mis-match may disrupt central mechanisms for decoding the TFS.

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