

Effects of Age and Hearing Loss on the Processing of Auditory Temporal Fine Structure

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Abstract Within the cochlea, broadband sounds like speech and music are filtered into a series of narrowband signals, each of which can be considered as a relatively slowly varying envelope (ENV) imposed on a rapidly oscillating carrier (the temporal fine structure, TFS). Information about ENV and TFS is conveyed in the timing and short-term rate of nerve spikes in the auditory nerve. There is evidence that both hearing loss and increasing age adversely affect the ability to use TFS information, but in many studies the effects of hearing loss and age have been confounded. This paper summarises evidence from studies that allow some separation of the effects of hearing loss and age. The results suggest that the monaural processing of TFS information, which is important for the perception of pitch and for segregating speech from background sounds, is adversely affected by both hearing loss and increasing age, the former being more important. The monaural processing of ENV information is hardly affected by hearing loss or by increasing age. The binaural processing of TFS information, which is important for sound localisation and the binaural masking level difference, is also adversely affected by both hearing loss and increasing age, but here the latter seems more important. The deterioration of binaural TFS processing with increasing age appears to start relatively early in life. The binaural processing of ENV information also deteriorates somewhat with increasing age. The reduced binaural processing abilities found for older/hearing-impaired listeners may partially account for the difficulties that such listeners experience in situations where the target speech and interfering sounds come from different directions in space, as is common in everyday life.

Keywords Frequency discrimination · Envelope · Binaural processing · Interaural phase discrimination · Envelope processing · Intelligibility · Processing efficiency · Sound localization · Pitch

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P. van Dijk et al. (eds.), *Physiology, Psychoacoustics and Cognition in Normal and Impaired Hearing*, Advances in Experimental Medicine and Biology 894,
DOI 10.1007/978-3-319-25474-6_1

1 Introduction

Within the healthy cochlea, broadband sounds are decomposed into narrowband signals, each of which can be considered as a relatively slowly varying envelope (ENV) imposed on a rapidly oscillating carrier (the temporal fine structure, TFS). Information about ENV and TFS is conveyed in the timing and short-term rate of nerve spikes in the auditory nerve (Joris and Yin 1992). Following Moore (2014), a distinction is made between the physical ENV and TFS of the input signal (ENV_p and TFS_p), the ENV and TFS at a given place on the basilar membrane (ENV_{BM} and TFS_{BM}), and the neural representation of ENV_{BM} and TFS_{BM} (ENV_n and TFS_n). This paper reviews studies that separate the effects of hearing loss and age on the auditory processing of ENV and TFS.

2 Effects of Age

2.1 *Monaural Processing of TFS*

It is widely believed that the difference limen for frequency (DLF) of pure tones depends on the use of TFS information for frequencies up to 4–5 kHz (Moore 1973), and perhaps even up to 8 kHz (Moore and Ernst 2012). If so, the DLF at low and medium frequencies provides a measure of TFS processing. Abel et al. (1990) and He et al. (1998) compared DLFs for young and older subjects with normal hearing (audiometric thresholds ≤ 20 dB HL from 0.25 to 4 kHz). In both studies, DLFs were larger by a factor of 2–4 for the older than for the younger subjects, suggesting that there is an effect of age. However, performance on other tasks (duration discrimination for Abel et al. and intensity discrimination for He et al.) was also poorer for the older group, suggesting that there may be a general effect of age that leads to reduced “processing efficiency”. The effect of age cannot be attributed to reduced frequency selectivity, since auditory filters do not broaden with increasing age when absolute thresholds remain normal (Lutman et al. 1991; Peters and Moore 1992).

Monaural TFS processing has also been assessed using the TFS1 test (Hopkins and Moore 2007; Moore and Sek 2009). This requires discrimination of a harmonic complex tone (H) from an inharmonic tone (I), created by shifting all components in the H tone up by a fixed amount in hertz, Δf . The value of Δf is adaptively varied to determine the threshold. Both tones are passed through a fixed bandpass filter centred on the higher (unresolved) components, and a background noise is used to mask combination tones and components falling on the skirts of the filter. Evidence suggesting that performance on this test reflects sensitivity to TFS rather than the use of excitation-pattern cues is: (1) Performance on the TFS test does not worsen with increasing level, except when the level is very high (Moore and Sek 2009, 2011; Marmel et al. 2015); (2) Randomizing the level of the individual components would be expected to impair the ability to use excitation-pattern cues, but this has

very little effect on performance of the TFS1 test (Jackson and Moore 2014); (3) Differences in excitation level between the H and I tones at the threshold value of Δf , estimated using the H and I tones as forward maskers, are too small to be usable (Marmel et al. 2015).

Moore et al. (2012) used the TFS1 test with centre frequencies of 850 and 2000 Hz to test 35 subjects with audiometric thresholds ≤ 20 dB HL from 0.25 to 6 kHz and ages from 22 to 61 years. There were significant correlations between age and the thresholds in the TFS1 test ($r=0.69$ and 0.57 for the centre frequencies of 850 and 2000 Hz, respectively). However, TFS1 scores at 850 Hz were correlated with absolute thresholds at 850 Hz ($r=0.67$), even though audiometric thresholds were within the normal range, making it hard to rule out an effect of hearing loss.

Füllgrabe et al. (2015) eliminated confounding effects of hearing loss by testing young (18–27 years) and older (60–79 years) subjects with *matched* audiograms. Both groups had audiometric thresholds ≤ 20 dB HL from 0.125 to 6 kHz. The TFS1 test was conducted using centre frequencies of 1 and 2 kHz. The older subjects performed significantly more poorly than the young subjects for both centre frequencies. Performance on the TFS1 task was not correlated with audiometric thresholds at the test frequencies. These results confirm that increased age is associated with a poorer ability to use monaural TFS cues, in the absence of any abnormality in the audiogram. It is hard to know whether this reflects a specific deficit in TFS processing or a more general reduction in processing efficiency.

2.2 *Monaural Processing of ENV*

Füllgrabe et al. (2015) also assessed sensitivity to ENV cues by measuring thresholds for detecting sinusoidal amplitude modulation imposed on a 4-kHz sinusoidal carrier. Modulation rates of 5, 30, 90, and 180 Hz were used to characterize the temporal-modulation-transfer function (TMTF). On average, thresholds (expressed as $20\log_{10} m$, where m is the modulation index) were 2–2.5 dB higher (worse) for the older than for the younger subjects. However, the shapes of the TMTFs were similar for the two groups. This suggests that increasing age is associated with reduced efficiency in processing ENV information, but not with reduced temporal resolution for ENV cues. Schoof and Rosen (2014) found no significant difference in either processing efficiency or the shape of TMTFs measured with noise-band carriers between young (19–29 years) and older (60–72 years) subjects with near-normal audiograms. It is possible that, with noiseband carriers, amplitude-modulation detection is limited by the inherent fluctuations in the carrier (Dau et al. 1997), making it hard to measure the effects of age.

2.3 Binaural Processing of TFS

The binaural processing of TFS can be assessed by measuring the smallest detectable interaural phase difference (IPD) of a sinusoidal carrier relative to an IPD of 0° , keeping the envelope synchronous at the two ears. A task of this type is the TFS-LF test (where LF stands for low-frequency) (Hopkins and Moore 2010b; Sek and Moore 2012). Moore et al. (2012) tested 35 subjects with audiometric thresholds ≤ 20 dB HL from 0.25 to 6 kHz and ages from 22 to 61 years. The TFS-LF test was used at center frequencies of 500 and 850 Hz. There were significant correlations between age and IPD thresholds at both 500 Hz ($r=0.37$) and 850 Hz ($r=0.65$). Scores on the TFS-LF task were not significantly correlated with absolute thresholds at the test frequency. These results confirm those of Ross et al. (2007) and Grose and Mamo (2010), and indicate that the decline in sensitivity to binaural TFS with increasing age is already apparent by middle age.

Füllgrabe et al. (2015) used the TFS-LF task with their young and older groups with matched (normal) audiograms, as described above. The older group performed significantly more poorly than the young group at both centre frequencies used (500 and 750 Hz). The scores on the TFS-LF test were not significantly correlated with audiometric thresholds at the test frequencies. Overall, the results indicate that the ability to detect changes in IPD worsens with increasing age even when audiometric thresholds remain within the normal range.

The binaural masking level difference (BMLD) provides another measure of binaural sensitivity to TFS. The BMLD is the difference in the detection threshold between a condition where the masker and signal have the same interaural phase and level relationship, and a condition where the relationship is different. Although BMLDs can occur as a result of differences in ENV_n for the two ears, it is generally believed that the largest BMLDs result from the use of TFS_n . Because the BMLD represents a *difference* between two thresholds, it has the advantage that differences in processing efficiency across age groups at least partly cancel. Several researchers have compared BMLDs for young and older subjects with (near-) normal hearing (Pichora-Fuller and Schneider 1991, 1992; Grose et al. 1994; Strouse et al. 1998). All showed that BMLDs (usually for a 500-Hz signal frequency) were smaller for older than for young subjects, typically by 2–4 dB.

In summary, binaural TFS processing deteriorates with increasing age, even when audiometric thresholds are within the normal range.

2.4 Binaural Processing of ENV

King et al. (2014) measured the ability to discriminate IPD using amplitude-modulated sinusoids. The IPDs were imposed either on the carrier, TFS_p , or the modulator, ENV_p . The carrier frequency, f_c , was 250 or 500 Hz and the modulation frequency was 20 Hz. They tested 46 subjects with a wide range of ages (18–83 years) and degrees of hearing loss. The absolute thresholds at the carrier frequencies of 250 and 500 Hz were not significantly correlated with age. Thresholds for detect-

ing IPDs in ENV_p were positively correlated with age for both carrier frequencies ($r=0.62$ for $f_c=250$ Hz; $r=0.58$, for $f_c=500$ Hz). The correlations remained positive and significant when the effect of absolute threshold was partialled out. These results suggest that increasing age adversely affects the ability to discriminate IPDs in ENV_p , independently of the effects of hearing loss.

3 Effects of Cochlear Hearing Loss

3.1 Monaural Processing of TFS

Many studies have shown that cochlear hearing loss is associated with larger than normal DLFs. For a review, see Moore (2014). However, in most studies the hearing-impaired subjects were older than the normal-hearing subjects, so some (but probably not all) of the effects of hearing loss may have been due to age. DLFs for hearing-impaired subjects are not correlated with measures of frequency selectivity (Tyler et al. 1983; Moore and Peters 1992), confirming that DLFs depend on TFS information and not excitation-pattern information.

Several studies have shown that cochlear hearing loss is associated with a greatly reduced ability to perform the TFS1 test or similar tests (Hopkins and Moore 2007, 2010a, 2011). Many hearing-impaired subjects cannot perform the task at all. Although the effects of hearing loss and age were confounded in some of these studies, the performance of older hearing-impaired subjects seems to be much worse than that of older normal-hearing subjects, suggesting that hearing loss *per se* adversely affects monaural TFS processing.

3.2 Monaural Processing of ENV

Provided that the carrier is fully audible, the ability to detect amplitude modulation is generally not adversely affected by cochlear hearing loss and may sometimes be better than normal, depending on whether the comparison is made at equal sound pressure level or equal sensation level (Bacon and Viemeister 1985; Bacon and Gleitman 1992; Moore et al. 1992; Moore and Glasberg 2001). When the modulation is clearly audible, a sound with a fixed modulation depth appears to fluctuate more for an impaired ear than for a normal ear, probably because of the effects of loudness recruitment (Moore et al. 1996).

3.3 Binaural Processing of TFS

Many studies of the effects of hearing loss on discrimination of interaural time differences (ITDs) are confounded by differences in age between the normal-hearing

and hearing-impaired subjects. One exception is the study of Hawkins and Wightman (1980). They measured just noticeable differences in ITD using low-frequency (450–550 Hz) and high-frequency (3750–4250 Hz) narrow-band noise stimuli. The ITD was present in both TFS_p and ENV_p, except that the onsets and offsets of the stimuli were synchronous across the two ears. Performance was probably dominated by the use of TFS cues for the low frequency and ENV cues for the high frequency. They tested three normal-hearing subjects (mean age 25 years) and eight subjects with hearing loss (mean age 27 years). The two groups were tested both at the same sound pressure level (85 dB SPL) and at the same sensation level (30 dB SL). ITD thresholds were significantly higher for the hearing-impaired than for the normal-hearing subjects for both signals at both levels. These results suggest that cochlear hearing loss can adversely affect the discrimination of ITD carried both in TFS_p and in ENV_p.

The study of King et al. (2014), described above, is relevant here. Recall that they tested 46 subjects with a wide range of ages (18–83 years) and degrees of hearing loss. Thresholds for detecting IPDs in TFS_p were positively correlated with absolute thresholds for both carrier frequencies ($r=0.45$ for $f_c=250$ Hz; $r=0.40$, for $f_c=500$ Hz). The correlations remained positive and significant when the effect of age was partialled out. Thus, hearing loss adversely affects the binaural processing of TFS.

Many studies have shown that BMLDs are reduced for people with cochlear hearing loss, but again the results are generally confounded with the effects of age. More research is needed to establish the extent to which BMLDs are affected by hearing loss *per se*.

3.4 Binaural Processing of ENV

Although the results of Hawkins and Wightman (1980), described in Sect. 3.3, suggested that hearing loss adversely affected the discrimination of ITD carried in ENV_p, King et al. (2014) found that thresholds for detecting IPDs in ENV_p were not significantly correlated with absolute thresholds. Also, Léger et al. (2015) reported that thresholds for detecting IPDs in ENV_p were similar for subjects with normal and impaired hearing (both groups had a wide range of ages). Overall, the results suggest that hearing loss does not markedly affect the ability to process binaural ENV cues.

4 Summary and Implications

The monaural and binaural processing of TFS is adversely affected by both increasing age and cochlear hearing loss. The efficiency of processing monaural ENV information may be adversely affected by increasing age, but the temporal resolution of ENV cues appears to be unaffected. The processing of binaural ENV information is adversely affected by increasing age. Cochlear hearing loss does not markedly affect the processing of monaural or binaural ENV information.

The effects of age and hearing loss on TFS processing may partially explain the difficulties experienced by older hearing-impaired people in understanding

speech in background sounds (Hopkins and Moore 2010a, 2011; Neher et al. 2012; Füllgrabe et al. 2015).

Acknowledgments This work was supported by grant G0701870 from the MRC (UK). I thank Tom Baer, Hedwig Gockel, and Pim van Dijk for helpful comments.

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