Relations between perceptual measures of temporal processing, auditory-evoked brainstem responses and speech intelligibility in noise

Papakonstantinou, Alexandra; Strelcyk, Olaf; Dau, Torsten

Published in:
Hearing Research

Link to article, DOI:
10.1016/j.heares.2011.02.005

Publication date:
2011

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
1. Introduction

One of the most common complaints of people with cochlear hearing loss concerns difficulty with speech communication. People with mild or moderate losses can typically understand speech reasonably well when they are in a quiet room with only one person talking. However, they experience difficulty when more than one person is talking or when background noise or reverberation is present (e.g., Plomp, 1978, 1994; Bronkhorst, 2000; Helfer and Wilber, 1990). People with severe or profound losses often have problems even when listening to a single talker in a quiet room, and they generally have severe problems when background noise is present. Even if provided with hearing aids, many listeners still experience problems with speech communication particularly in situations with background noise. Despite the enormous technological progress in hearing-aid technology in the past decade, the benefit from hearing aids seems to vary greatly among individual listeners, even among those showing similar audiograms. This indicates the insufficiency of audibility as a predictor of speech intelligibility in noise (e.g., Dreschler and Plomp, 1985).

There has been considerable controversy in the literature about the reasons for the difficulties in understanding speech (see Moore, 1995, for a review). Some studies have suggested that the difficulties arise primarily from reduced audibility: Absolute thresholds are higher than normal such that the audible proportion of the speech spectrum is reduced for hearing-impaired (HI) listeners (Humes et al., 1987; Zurek and Delhorne, 1987; Lee and Humes, 1995). Others argued that the difficulty understanding speech arises, at least partly, from deficits in the ability to discriminate sounds that are well above absolute threshold (Plomp, 1978; Dreschler and Plomp, 1980, 1985; Glasberg and Moore, 1989). Examples of such deficits include reduced frequency selectivity (e.g., Glasberg and Moore, 1986; Tyler et al., 1986) and deficits in temporal processing abilities (e.g., Fitzgibbons and Wightman, 1982; Tyler et al., 1982; Lorenzi et al., 2006; Hopkins et al., 2008; Strelcyk and Dau, 2009).
In most studies, subjects with a wide range of audiometric configurations were used. Typically, the average degree of hearing loss and the slope of the audiogram varied considerably across subjects. However, several issues may arise when considering such heterogeneous subject groups. For example, it can be difficult to decide whether to compare subject performance at equal sensation level (SL) or equal sound pressure level (SPL). Also, in experiments testing speech intelligibility, the proportion of the speech spectrum that exceeds the absolute threshold varies largely from one subject to another. Furthermore, large variability in the audiometric configuration can obscure effects of other auditory functions such as frequency selectivity as well as monaural and binaural temporal processing. Therefore, in the present study, a homogeneous group of listeners was chosen, minimizing confounding effects of audibility.

The study focused on measures of temporal processing and their relation to speech intelligibility. Temporal processing at low frequencies was addressed via behavioural experiments investigating frequency discrimination, binaural masked detection and amplitude modulation (AM) detection. The first two tasks are supposed to crucially depend on temporal-fine-structure (TFS) information, which refers to the temporal fine structure at the output of the cochlear filters. This fine structure evolves phase-locodendritic activity, i.e. synchronized timing of action potentials, in the subsequent stages of neural processing. Deficits in TFS processing have been found in some earlier studies on, e.g., pure-tone frequency discrimination (e.g., Turner and Nelson, 1982; Freyman and Nelson, 1991), low-rate frequency-modulation detection (e.g., Zurek and Formby, 1981; Moore and Skrozdka, 2002; Buss et al., 2004; Strelcyk and Dau, 2009) and binaural masked detection (e.g., Hall et al., 1984; Gabriel et al., 1992). Also, several studies suggested a relation between ageing and deficits in TFS processing as well as speech reception (e.g., Pichora-Fuller and Schneider, 1992; Strouse et al., 1998; Schneider et al., 2002; Ross et al., 2007; Hopkins et al., 2008; Strelcyk and Dau, 2009). In contrast, AM detection is naturally associated with envelope-based processing. The processing and coding of envelope fluctuations, or amplitude modulations, in the auditory system may be related to the ability to understand speech (e.g., Steeneken and Houtgast, 1980). Mainly modulation frequencies below about 16 Hz have been shown to be crucial for speech intelligibility (e.g., Drullman et al., 1994), but also frequencies above 20 Hz can be important, for example, for the identification of consonants (Christiansen and Greenberg, 2005; Christiansen et al., 2007), particularly in the presence of background noise.

In addition, auditory brainstem responses (ABRs) to transient broadband chirps (Dau et al., 2000) were recorded in the present study. ABRs reflect synchronized neural activity from different levels along the auditory brainstem. In general, the higher the stimulus level the more neurons are activated due to spread of excitation in the cochlea. Typically, stimulus onsets or offsets produce effective responses since many neurons are activated by these transients. However, it is not the spectral content of the input stimuli but the amount of synchronization after cochlear processing that appears to dominate the response amplitude (e.g., Dau et al., 2000; Dau, 2003; Elberling et al., 2007; Wegner and Dau, 2002; Fobel and Dau, 2004). The chirp was originally designed to compensate for cochlear travel time differences across frequencies and was found to produce larger wave-V amplitudes than the traditional click stimulus presented at same stimulation levels (e.g., Dau et al., 2000; Elberling et al., 2007). In the present study, ABR threshold was considered, i.e., the lowest stimulus level at which a repeatable response could be identified, and not ABR at suprathreshold levels. It has been shown recently that the amount of neural across-frequency synchronization can be affected in some listeners despite normal hearing thresholds (Kujawa and Liberman, 2009). Also, it is possible that synchronization plays a role for encoding weak signals in a noise background, for example through spatio-temporal processing (e.g., Carney et al., 2002; Deng and Geisler, 1987). In the present study, it is hypothesized that a reduced amount of synchronized neural activity at cochlear and brainstem level, which could be reflected in raised ABR thresholds, may affect TFS processing. Therefore, the relation between the behavioural measures of temporal processing and the "objective" electrophysiological measure of temporal processing was considered here.

2. Materials and methods

2.1. Listeners

Overall, twelve subjects participated in the current study. The HI group consisted of one female and six males, ranging between 54 and 81 years in age, with a median age of 66 years. They had bilaterally symmetric high-frequency hearing losses above about 2 kHz, with a difference between left and right thresholds of maximally 20 dB at individual frequencies. The sensorineural origin of the hearing losses was confirmed by means of bone-conduction and tympanometric measurements. Fig. 1 shows the audiometric results of the selected HI ears, identified by a code name. The ears were selected such that the audiograms were most similar across listeners. The test ears were the same in all experiments (binaural masked detection involved both ears). In the following, the HI listeners are ordered according to their pure-tone average thresholds (PTAs) at the frequencies 0.5, 1, 2 and 4 kHz. For example, listener HI1 had a PTA of 35 dB hearing level (HL; ISO 389–8, 2004) and HI7 had a PTA of 48.75 dB HL. At low frequencies, all subjects had pure-tone thresholds within 20 dB HL. The subject group can be considered as homogeneous in terms of the audiogram, but this does not necessarily imply homogeneity in terms of suprathreshold and potential retrocochlear deficits.

The control group of the NH listeners consisted of three males and two females, ranging in age from 24 to 29 years. Thus, this group was not age-matched to the group of the HI listeners in the present study. They had pure-tone thresholds of 10 dB HL or less for frequencies between 125 and 3000 Hz, and 20 dB HL or less for frequencies between 4000 and 8000 Hz. All listeners received an hourly compensation for their participation in the study and all experiments were approved by the Ethics Committee of Copenhagen County.

![Fig. 1. Pure-tone thresholds for the selected ears of the seven hearing-impaired (HI) listeners with bilaterally symmetrical, high-frequency sensorineural hearing losses.](image-url)
2.2. Speech intelligibility

SRTs in speech-shaped noise were measured using the DANTALE HI speech intelligibility test (Wagener et al., 2003). The SRT was defined as the signal-to-noise ratio at which 50% of the words were correctly identified. The speech was presented at a level of 75 dB SPL while the level of the speech-shaped noise was varied adaptively, starting at a level of 75 dB SPL. Each listener was trained on 60 sentences before data collection. The test was performed in a double-walled, sound attenuating booth. The speech and noise signals were generated in MATLAB and converted to analogue signals using a 16-bit digital-to-analogue (D/A) converter (RME DIGI96/8) at a sampling rate of 44 100 Hz. The signals were presented via Sennheiser HDA200 headphones which were connected to a TDT HB7 audio amplifier.

2.3. Basic psychoacoustical tests

For all of the following tests, a three-interval, three-alternative, forced-choice (3I-3AFC) paradigm was used in combination with a one-up, two-down tracking algorithm converging at the 70.7% correct point of the psychometric function (Levitt, 1971). Listeners had to indicate the interval which contained the target stimulus and received a visual feedback indicating the correct response. Each run had a total of 12 reversals and thresholds were estimated as the average of the last 8 reversals. For each listener and condition, three runs were taken, and the mean thresholds as well as their standard deviations were calculated from the corresponding three threshold estimates. The results for all basic behavioural tests were obtained after 30 min of training; potential benefits of longer training were not examined. The experiments were carried out using the same equipment as in the speech intelligibility test, with the only difference that Sennheiser HD580 headphones were used here.

Frequency discrimination thresholds were measured for tones at 250 and 1000 Hz, at a level of 75 dB SPL. The tones had a duration of 500 ms and the individual intervals were separated by 250 ms of silence. Listeners had to indicate the interval containing the target tone which had a higher frequency than the reference tone. The initial difference between target and reference frequency was 25%. This difference was either divided by a given step factor following two consecutive correct responses or multiplied by the same factor following a wrong response. The initial step factor was 2 and was multiplied by 0.75 after every second reversal. The minimum step factor was 1.125.

In the binaural masked detection experiment, masked thresholds were measured for the diotic N0S0 condition with noise and signal presented diotically, as well as for the dichotic N0S0 condition with diotic noise masker and signal in antiphase. Two signal frequencies were considered: 250 and 1000 Hz. The 480-ms long signal was temporally centred in the 500-ms long noise. The inter-stimulus interval was 250 ms. The masker was two octaves wide, geometrically centred at the signal frequency and had a fixed level of 65 dB SPL. The signal level was varied adaptively, with a final step size of 1 dB.

The modulation detection experiment was performed with a sinusoidal carrier at 65 dB SPL. The signal was defined as follows: 

\[ s(t) = \sin(2\pi f_c t) \left[ 1 + m \cos(2\pi f_m t) \right], \]

where \( f_c \) indicates the carrier frequency (500 Hz), \( m \) denotes the modulation depth (between 0 and 1), and \( f_m \) represents the modulation rate (either 8 or 32 Hz). Listeners had to indicate the interval which contained the modulated tone, while the modulation depth was varied adaptively in terms of \( 20 \times \log(m) \), with a final step size of 1 dB.

2.4. Auditory brainstem responses

ABRs elicited by chirp stimuli were recorded. The chirp developed by Dau et al. (2000) was used which was designed to compensate for cochlear travel-time differences across frequency. The waveform of the chirp was calculated on the basis of the cochlea model by de Boer (1980). The waveforms and (acoustic) magnitude spectra of the chirp are shown in Fig. 2. The chirp duration was 10.34 ms (starting and ending with zero crossings). The chirp had a flat magnitude spectrum corresponding to that of a click stimulus. As a consequence, the chirp started with very small amplitudes at the low-frequency end and increased nonlinearly in amplitude with increasing frequency.

The stimuli for the NH and HI listeners were played back through EAR TONE 3A insert earphones. The presentation of the chirp stimuli was temporally jittered, with a mean presentation rate of 22 Hz (the resulting inter-stimulus intervals were equally distributed between 37 and 59 ms). The stimuli were presented at five different levels: 18, 24, 30, 36 and 42 dB SL. Here, the behavioural thresholds of the individual listeners, represented as peak equivalent sound pressure levels (peSPL), were determined in a 3I-3AFC experiment. Each ABR recording session started with the highest stimulation level of 42 dB SL. The level was then lowered successively in 6-dB steps.

Listeners lay on a couch in an acoustically and electrically shielded room. The ABRs were measured differentially between electrodes applied to the vertex (Cz in the 10/20 system) and the ipsilateral mastoid (M1 or M2). Another electrode, applied to the forehead (Fpz), served as ground. The electrode signals were acquired using a Nicolet spirit electrodagnostic system. They were processed by a 2nd-order Bessel low-pass digital filtering with a cut-off frequency of 3 kHz. For each stimulus condition, two recordings were obtained, each consisting of 2000 sweeps.

Evoked potential estimates were obtained by averaging the 2000 sweeps and wave Vs were detected by visual inspection of these evoked potential estimates. Wave-V peak-to-peak amplitude was measured from the peak to the largest negativity following it. The ABR wave-V threshold was defined as the lowest stimulus level at which a repeatable wave V could be identified in the response waveform. In addition, the following criteria had to be met: (i) wave-V peak had to fall within the time window of 3–8 ms after

Fig. 2. Left panel: Waveform of the chirp stimulus used in the ABR experiments, with a duration of 10.34 ms. Right panel: Acoustic magnitude spectrum of the chirp.

Please cite this article in press as: Papakonstantinou, A., et al., Relations between perceptual measures of temporal processing, auditory-evoked brainstem responses and speech intelligibility in noise, Hearing Research (2011), doi:10.1016/j.heares.2011.02.005
chirp offset; (ii) wave-V peak had to be reproducible for the two independent recordings, for each stimulus condition, and (iii) the shift in wave-V latency between the threshold level and the higher levels had to be smaller than 3 ms.

3. Results

3.1. Speech intelligibility

Fig. 3 shows the SRT results as a function of the PTA for the HI and NH listeners. As can be seen, SRTs varied strongly among the HI listeners, with values between −3 and +4 dB signal-to-noise ratio. The NH reference value shows an SRT of 8.4 dB obtained in Wagener et al. (2003). The group of the HI listeners of the present study was considered to be homogeneous in terms of the audiograms; nevertheless, some variability in the amount of hearing losses remained, mainly at high frequencies. However, SRTs (for the HI listeners) were not significantly correlated with the PTAs (Pearson correlation and two-tailed p-value: $R = -0.5$, $p > 0.05$). Hence, the variability within the audiograms cannot account for the observed variability in SRTs. In fact, listener HI1 had large difficulties understanding speech in noise (+4 dB signal-to-noise ratio) even though this subject had the highest pure-tone sensitivity and had reasonable access to the high-frequency parts of the speech signal since the signal level was above threshold. In contrast, subject HI7 which had the largest sensitivity loss showed relatively good ability to understand speech, with an SRT at a signal-to-noise ratio of −1.3 dB.

3.2. Frequency discrimination

Fig. 4 shows the frequency discrimination thresholds (FDTs) at 250 Hz (left panel) and 1000 Hz (right panel) for the HI (code names) and the NH listeners (circles). The horizontal black lines denote the mean FDTs and the corresponding boxes represent ±1 standard deviation (SD) for the NH (white) and HI (grey) listeners, respectively. The FDTs are plotted on a logarithmic frequency scale, with the left and right ordinate indicating the FDTs as proportion of the signal frequency and in Hz, respectively. The results for the HI listeners are similar for the two frequencies which are consistent with previous studies (e.g., Sek and Moore, 1995). The thresholds did not differ significantly between the NH and HI listeners (two-tailed t-test at 250 Hz: $p > 0.05$; at 1 kHz: $p > 0.05$). For the HI listeners, a significant correlation between FDTs and SRTs was observed at both frequencies (250 Hz: $R = 0.96$, $p < 0.001$; 1 kHz: $R = 0.90$, $p < 0.005$). The listener with the worst performance in the speech intelligibility tasks (HI1) also showed the worst performance in the frequency discrimination task. The listener with the best speech performance actually showed FDTs in the range of values obtained in the normal-hearing listeners. FDTs were not significantly correlated with individual hearing thresholds, neither at the single frequencies of 250 Hz and 1 kHz nor in terms of the PTA ($p > 0.05$). Therefore, the correlation between FDTs and SRTs remained significant when individual hearing thresholds were partialled out (250 Hz: $R_{\text{partial}} = 0.96$, $p < 0.005$; 1 kHz: $R_{\text{partial}} = 0.91$, $p < 0.005$).
3.3. Binaural masked detection

Fig. 5 shows the binaural masked thresholds for the dichotic N0S\textsubscript{N} condition at 250 (left panel) and 1000 Hz (right panel) as a function of the SRT. The results for the HI and NH listeners are shown in a similar way as in Fig. 4. For 1 kHz (right panel), the HI listeners showed significantly higher N0S\textsubscript{N} thresholds than the NH listeners (two-tailed t-test: \( p = 0.04 \)) whereas the N0S\textsubscript{N} thresholds did not differ significantly between the two groups (\( p > 0.05 \); not shown). Nevertheless, the binaural masking level differences, i.e., the differences between N0S\textsubscript{N} and N0S\textsubscript{N} thresholds, did not differ significantly between the two groups (\( p > 0.05 \)). The N0S\textsubscript{N} thresholds at 1000 Hz were significantly correlated with SRTs (\( R = 0.76, p < 0.05 \)). This correlation was no longer significant when hearing thresholds at 1 kHz were partialed out (\( p = 0.06 \)). For 250 Hz (left panel), there was no significant difference between the N0S\textsubscript{N} thresholds obtained for the NH and HI listeners. Also, at this frequency, the N0S\textsubscript{N} thresholds were only marginally correlated with SRT (\( R = 0.70, p = 0.08 \)). Here, it should be kept in mind that the SRTs were measured only for one ear. This may explain why the correlation found here between dichotic masked detection and monaural speech reception was weaker than the correlation between dichotic masked detection and monaural speech reception was found here between dichotic masked detection and monaural speech reception was weaker than the correlation between dichotic masked detection and monaural speech reception discussed above. Finally, a correlation between the N0S\textsubscript{N} thresholds and the monaural FDTs at 1 kHz just reached significance (\( R = 0.75, p = 0.05 \)).

3.4. Amplitude modulation detection with a sinusoidal carrier

While the frequency discrimination and binaural masked detection tasks are commonly associated with the ability to process TFS information, this experiment dealt with the perception of the envelope fluctuations of a sound. Fig. 6 shows the AM detection thresholds for 8 Hz (left panel) and 32 Hz (right panel), imposed on a 500-Hz carrier, as a function of the SRT. The results for the HI and NH listeners are indicated in a similar way as in Figs. 4 and 5. AM detection thresholds were not significantly different for the NH and HI listeners at both modulations frequencies (\( p > 0.05 \)). In fact, most of the HI listeners showed thresholds close to normal at both rates of 8 Hz and 32 Hz, with the highest threshold at around −15 dB. This is consistent with results from earlier studies on amplitude modulation detection in sensorineural HI listeners (e.g., Bacon and Gleitman, 1985). Furthermore, the AM detection thresholds were not significantly correlated with the SRTs (8 Hz: \( R = 0.21, p > 0.05 \); 32 Hz: \( R = 0.48, p > 0.05 \)). Also, the AM detection thresholds were not correlated with the individual hearing threshold at 500 Hz (\( p > 0.05 \)).

3.5. Auditory brainstem responses

The upper left panel of Fig. 7 shows the chirp-evoked ABR wave-V thresholds (in peSPL) for the individual listeners, including the normal-hearing listeners, as a function of the SRT. The two black horizontal bars and the corresponding white and grey boxes around them indicate the mean and ±1 standard deviations for the normal and the hearing-impaired listeners, respectively. Unfortunately, no reliable response could be obtained for listener HI7, i.e., the recordings were very noisy and a large number of recorded epochs was rejected. Thus, since responses from only six hearing-impaired listeners could be obtained in this study, it was not possible to perform a statistical correlation analysis between the ABR results and the results from the other measures. Nevertheless, the observed trends indicating possible relations between the different outcome measures will be discussed in the following. Thus, increasing wave-V thresholds tended to be associated with increasing SRTs, i.e., decreasing speech intelligibility. Wave V could not be detected for listener HI2. Therefore, for this subject, wave-V threshold was represented by the maximum stimulation level of 120 dB peSPL in the figure.

The upper right panel of Fig. 7 shows wave-V threshold as a function of the N0S\textsubscript{N} thresholds at 1 kHz for the individual listeners. It can be seen that larger ABR thresholds tend to be associated with larger binaural thresholds. The lower left panel shows the ABR threshold as a function of the FDT that was averaged between 250 Hz and 1 kHz for each individual listener. Increasing ABR thresholds seem to be associated with increasing FDTs. Finally, the lower right panel shows the ABR threshold as a function of the AM detection threshold for 8 Hz. There is no trend indicating a relation between evoked potential amplitude and modulation detection sensitivity. A similar result was observed for the modulation frequency of 32 Hz (not shown in the figure).

4. Discussion

The hypothesis of the current study was that speech reception in noise partly depends on the processing of temporal information at low frequencies. It was examined whether low-frequency temporal processing (< 1 kHz) could be affected in regions of normal hearing, for listeners with (steeply sloping) high-frequency hearing losses at higher frequencies, and whether potential deficits could be related to speech reception performance in noise. Furthermore, it was investigated, whether objective ABR wave-V thresholds obtained for the chirp stimuli were correlated with the behavioural measures of temporal processing.
Most of the HI listeners showed poorer results than the NH listeners both in the behavioural experiments testing frequency discrimination, binaural masked detection, and speech reception as well as in the objective measure using ABRs wave-V amplitude as an indicator of neural (temporal) synchronization across frequency. Fig. 8 illustrates the relationships observed in the present study. Hearing thresholds were not associated with any of the other measures. To some extent, this can be attributed to the fact that the HI listeners had similar audiograms and essentially normal (or close to normal) sensitivity at low frequencies. Regarding the speech results, high-frequency consonant information may have been inaudible to all of the HI listeners. This would explain why the measured SRTs did not reflect the across-subject variability within the high-frequency pure-tone thresholds. For the HI listeners, a correlation was observed between monaural frequency discrimination and binaural masked detection at 1 kHz, both supposed to rely on the ability to process TFS. These correlations are indicated in Fig. 8 as connecting lines between the measures (no arrowheads are shown since the order of processing in the auditory system is unclear). Furthermore, frequency discrimination was correlated with speech reception in noise, consistent with previous studies (Tyler et al., 1983; Glasberg and Moore, 1989; Noordhoek et al., 2001). Also, binaural masked N0S thresholds were correlated with the SRTs.

Regarding the ABR results of the present study, the chirp stimulation (at corresponding sensation levels) was less effective for the HI listeners than for the NH listeners. One reason for this could be due to alterations of cochlear travel times in the HI listeners as proposed in earlier ABR studies (Don et al., 1998; Strelcyk et al., 2001).

Fig. 6. Modulation detection thresholds for a sinusoidal carrier at 500 Hz for modulation frequencies of 8 (left panel) and 32 Hz (right panel) are shown as a function of SRT. The abscissa is broken for better visualization of the data.

Fig. 7. Chirp-evoked ABR wave-V threshold as a function of SRT (upper left panel), binaural masked detection threshold, N0Sx, at 1 kHz signal frequency (upper right panel), frequency discrimination threshold, FDT, averaged across 250 Hz and 1 kHz (lower left panel) and modulation detection threshold for a 500-Hz carrier modulated at 8 Hz (lower right panel). Wave V was not measurable for HI7 listener due to a large number of rejected epochs.

Please cite this article in press as: Papakonstantinou, A., et al., Relations between perceptual measures of temporal processing, auditory-evoked brainstem responses and speech intelligibility in noise, Hearing Research (2011), doi:10.1016/j.heares.2011.02.005
Such altered travel times would typically be associated with changes in frequency selectivity as one of the potential consequences of a cochlear hearing impairment. Alternatively, or in addition, HI listeners might not profit from chirp stimulation in the same way as NH listeners since the neural activity across frequency could be less synchronous in the HI listeners even in the case of “normal” cochlear delays. Interestingly, a trend was observed for ABR wave-V thresholds to increase with increasing SRTs, i.e., decreasing speech reception performance. Hence, the present ABR results may suggest that temporal synchronization of neural activity (at low-frequencies) at the level(s) of processing responsible for wave-V generation, can be affected in some of the HI listeners and that this, in turn, can affect speech intelligibility in noise. This hypothesis is further supported by the finding that chirp-evoked wave-V thresholds also tended to be associated with FDTs (at 250 Hz and 1 kHz) and N0S thresholds (at 1 kHz), both representing measures of TFS processing. These trends are indicated by the dashed lines in Fig. 8. However, in order to allow for a more solid statistical analysis of the relations between the ABR results and the other outcome measures, data from a larger group of listeners would be required.

Several studies suggested a relation between ageing and deficits in TFS processing as well as speech reception (e.g., Pichora-Fuller and Schneider, 1992; Strouse et al., 1998; Schneider et al., 2002; Ross et al., 2007; Hopkins et al., 2008; Strelcyk and Dau, 2009). It has also been demonstrated that human spiral ganglion cells decline with age (Otte et al., 1978) and this can be seen in areas remote from regions of threshold elevation (Felder and Schrott-Christiansen, T.-U., Dau, T., Greenberg, S., 2007. Spectro-temporal processing of time-frequency structures in the auditory nerve. J. Acoust. Soc. Am. 107, 1530) and this can be seen in areas remote from regions of threshold elevation (Felder and Schrott-Christiansen, T.-U., Dau, T., Greenberg, S., 2007. Spectro-temporal processing of time-frequency structures in the auditory nerve. J. Acoust. Soc. Am. 107, 1530).

The performance of some of the HI listeners in the present study bears similarity to what has been observed in people with auditory neuropathy (e.g., Rance et al., 2004; Zeng et al., 2005), albeit with less extreme performance abnormalities: The listeners H1 and H2 showed reduced ABR responses (as indicated by elevated ABR thresholds) and reduced performances in speech perception, frequency discrimination, AM detection, and fine-structure-based binaural processing. Hence, the auditory processing deficits observed in these two listeners may have had similar causes as those observed in listeners diagnosed with auditory neuropathy. Overall, the results from the present study suggest that deficits in the processing of low-frequency TFS information may affect speech reception in noise. Furthermore, they may suggest a relationship between TFS processing and ABR thresholds. However, additional data from a larger group of listeners are needed to confirm the significance of these relations. Eventually, a better understanding of the proposed relationships might help to provide persons with high-frequency hearing losses with better diagnosis and treatment options.

**Acknowledgements**

This study was supported by GN Resound, Oticon and Widex. We thank Anne Norby Rasmussen of the Rigshospitalet Copenhagen for his technical assistance in the measurements and his contribution in providing us with suitable test listeners. We also thank the associate editor Fan-Gang Zeng and the two anonymous reviewers for their constructive and helpful comments and suggestions.

**References**


