Effects of dynamic-range compression on temporal acuity

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Some of the challenges that hearing-aid listeners experience with speech perception in complex acoustic environments may originate from limitations in the temporal processing of sounds. To systematically investigate the influence of hearing impairment and hearing-aid signal processing on temporal processing, temporal modulation transfer functions (TMTFs) and "supra-threshold" modulation-depth discrimination (MDD) thresholds were obtained in normal-hearing (NH) and hearing-impaired (HI) listeners with and without wide-dynamic range compression (WDRC). The TMTFs were obtained using tonal carriers of 1 and 5 kHz and modulation frequencies from 8 to 256 Hz. MDD thresholds were obtained using a reference modulation depth of −15 dB. A compression ratio of 2:1 was chosen. The attack and release time constants were 10 and 60 ms, respectively. For both carrier frequencies the TMTF thresholds decreased with the physical compression of the modulation depth due to the WDRC. Indications of reduced temporal resolution in the HI listeners were observed in the TMTF patterns for the 5-kHz carrier. Significantly higher MDD thresholds were found for the HI group relative to the NH group. No relationship was found between the MDD thresholds and the TMTF threshold. These findings indicate that the two measures may represent different aspects of temporal processing.

INTRODUCTION

Modern hearing aids use wide-dynamic range compression (WDRC) as an amplification strategy to compensate for loudness recruitment in sensorineural hearing-impaired (HI) listeners (Ricketts and Bentler, 1996). This is typically accomplished by providing a higher gain for low-level sounds than for high-level sounds (Jenstad *et al.*, 2000). Besides restoring audibility of a wide dynamic range of sound levels, fast-acting WDRC reduces the depth of low-frequency amplitude modulations and distorts the temporal envelope waveform. The degree of the temporal distortion and reduction in modulation depth depends on the settings of WDRC system (Stone and Moore, 1992).

Temporal changes in the envelope (amplitude modulations) of speech convey linguistic information about consonant manner and voicing as well as prosodic cues

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(e.g., Rosen, 1992). Amplitude modulations have been shown to contribute significantly to high speech recognition (Shannon *et al.*, 1995; Stone *et al.*, 2011). Hence, modulation depth reduction and temporal distortion of speech by fast-acting WDRC may impair speech recognition (Stone and Moore 2003).

Temporal modulation transfer functions (TMTFs) and "supra-threshold" modulation-depth discrimination (MDD) have previously been used as measures of temporal processing (Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001; Lee and Bacon, 1997). In a TMTF experiment, amplitude modulation detection thresholds are measured as a function of modulation frequency. In an MDD experiment the just-noticeable increase in modulation depth from a (supra-threshold) standard modulation depth is measured as a function of modulation frequency.

In the present study, the influence of hearing impairment and WDRC on temporal envelope encoding was investigated. TMTF and MDD thresholds were obtained in normal-hearing (NH) and hearing-impaired (HI) listeners with and without WDRC. Tonal carriers were used. Compared to noise carriers, tonal carriers have the advantage that they do not contain any intrinsic modulations which may mask, and thereby limit, the detectability of the imposed modulation (Dau *et al.*, 1997; 1999). However, the disadvantage is that the imposed modulation introduces spectral sidebands which may be perceived as separate tones, if the sidebands are sufficiently far in frequency from the carrier frequency (Kohlrausch *et al.*, 2000). This is not a problem for broadband carriers as the modulation sidebands generally fall within the spectrum of the carrier and are therefore masked. Hence, results obtained with tonal carriers may provide a better measure of temporal resolution of the auditory system than modulation results using noise carriers, provided that the modulation frequency is within the range where spectral resolution does not play a major role.

METHOD

Listeners

Nine adult listeners (5 males and 4 females) with normal hearing were tested, with ages ranging from 21 to 50 years. All had absolute thresholds better than 20 dB hearing level at all audiometric frequencies. Seven adult listeners (4 males and 3 females) with mild to moderate/severe sensorineural hearing loss were tested, with ages ranging from 50 to 73 years. Their absolute thresholds for the test ear, measured using conventional audiometry, are shown in Fig. 1.

Procedure

The TMTF was measured using an adaptive three-alternative forced-choice 3-down 1-up procedure tracking the 79.4% point on the psychometric function. The gated carrier was unmodulated in two of the intervals and modulated in the other; the listeners had to select the interval containing the modulated carrier. The step size was 5 dB down to the reversal and 2 dB thereafter. Each run was terminated after seven reversals, and the threshold estimate for that run was computed as the mean value of $20 \log(m)$ at the last six reversals (where m is the modulation index). Three runs were obtained for each condition.

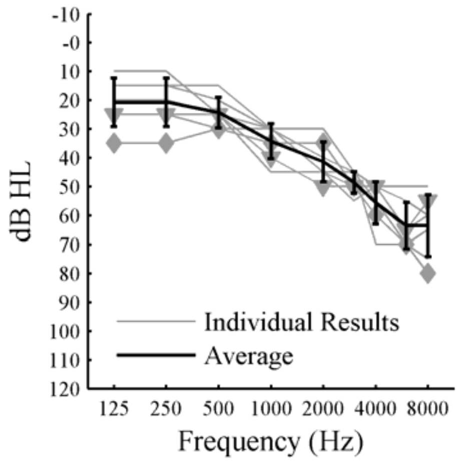

Fig. 1: Individual and average absolute thresholds for the tested ear of the hearing-impaired (HI) listeners, measured using conventional manual audiometry, and expressed in dB HL. The error bars represents ±1 standard deviation (SD). The thresholds for two of the listeners are displayed with symbols as their TMTF results at 1 kHz differ from the others.

The procedure was the same for measuring the MDD as the TMTF procedure, except that the carrier was modulated with a constant standard modulation depth (m_s) in two of the intervals and modulated with a higher modulation depth ($m = m_s + \Delta m$) in the other; the listeners had to select the interval containing the carrier with the highest modulation depth. The modulation depth of the target was adjusted in steps of 2 dB, and thereafter 1 dB.

Stimuli

In both experiments, tonal carriers and modulators were used. The frequency of the carrier was either 1 kHz or 5 kHz. The modulation frequencies were 8, 16, 32, 64, 128, and 256 Hz in the unprocessed condition and 8, 16, 32 Hz in the WDRC condition. The presentation intervals were 600 ms in duration with 30-ms rise and fall times. The pause between presentations within a trial was 500 ms. The overall level of the presentations was the same, regardless of modulation depth and WDRC processing. For the NH listeners, the presentation level was 65 dB SPL. For the HI listeners, the presentation level was increased according to a NAL-R(P) frequency dependent prescription gain that depends on their individual audiometric thresholds (Byrne *et al.*, 1990). The standard modulation depth m_s was 0.18 (−15 dB). The frequency response of the headphones at the eardrum was estimated using an ear simulator.

All signals were generated digitally with a sampling rate of 44.1 kHz and were presented to the listeners via an RME soundcard and DT 770 PRO Beyerdynamic headphones. The listeners were seated in sound-attenuating booth and the sound was played monaurally to the audiometric best ear.

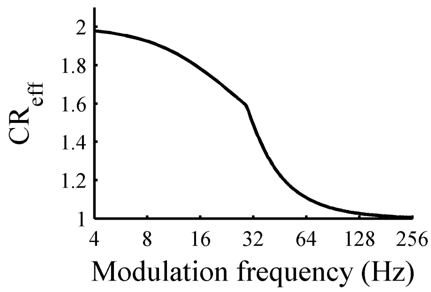

Fig. 2: The effective compression ratio (CR_{eff}) for the used WDRC system as function of modulation frequency (e.g., Stone and Moore, 1992).

WDRC system

The WDRC system was implemented in Matlab. The envelope of the incoming signal was extracted using a Hilbert transform and smoothed using single-pole low-pass filters. The smoothed envelope was converted to dB SPL and was input to a broken-stick gain function (linear gain below the compression kneepoint and constant compression above). The resulting gain was applied to the input. The static compression ratio was set to 2:1. The attack and release time constants were 10 and 60 ms, respectively. The compression kneepoint was set to 20 dB SPL. The effective compression ratio for this WDRC system as a function of modulation frequency is shown in Fig. 2.

RESULTS

The TMTF thresholds for the NH listeners are shown in Fig. 3. The average data (without compression) for both carrier frequencies are consistent with earlier work (Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001). For the 1-kHz carrier (top panel), the threshold decreases with increasing modulation frequency above 64 Hz. This reflects the detection of spectral sidebands, as shown in Kohlrausch *et al.* (2000). For the 5-kHz carrier (bottom panel), the threshold tends to increase slightly as the modulation frequency is increased from 128 Hz to 256 Hz. For both carrier frequencies, the modulation detection thresholds are increased when compression is applied.

The TMTF thresholds for the HI listeners are shown in Fig. 4. The data (without compression) for both carrier frequencies are consistent with earlier work on HI listeners (Moore and Glasberg, 2001). For the 1-kHz carrier (top panel), the threshold decreases with increasing modulation frequency for five of the seven listeners above 128 Hz. The remaining two listeners (marked by symbols) showed no corresponding decrease in threshold at the high modulation frequencies, probably because of reduced frequency selectivity. For the 5-kHz carrier, the thresholds tend to increase slightly with increasing modulation frequencies above 64 Hz. A two-way analysis of variance (ANOVA) indicated significantly higher thresholds for the NH listeners relative to the HI listeners for the 5-kHz carrier [$F(1,60) = 4.7$, $p = 0.03$]. The 95% confidence interval ranges from −0.2 dB to −3.6 dB. However, no significant differences in the TMTF thresholds were observed for the 1-kHz carrier.

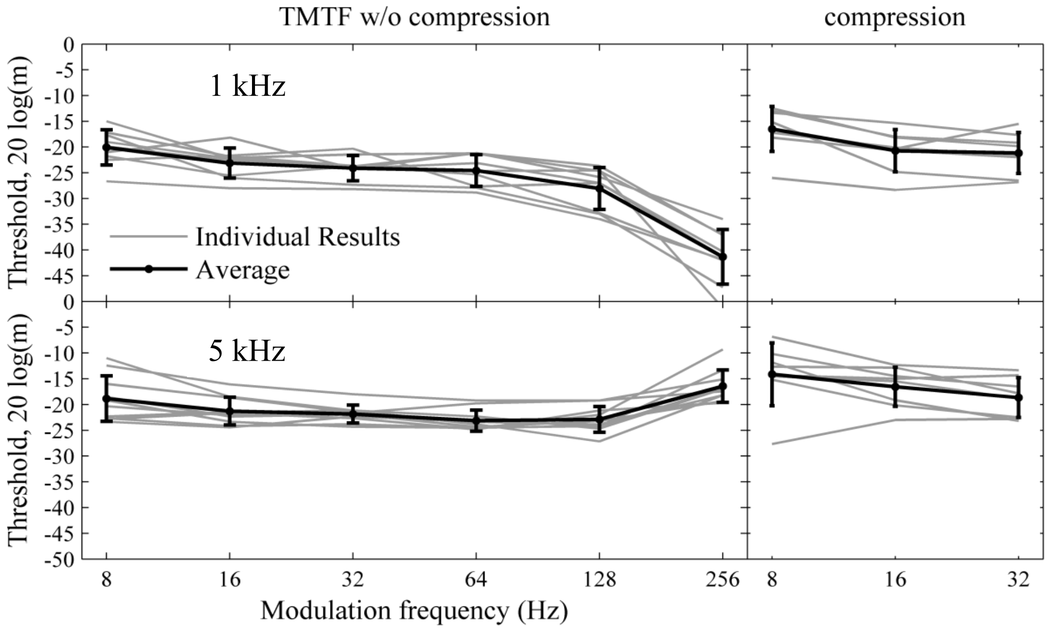

Fig. 3: Individual and average TMTF results for the NH listeners. The error bars represents ±1 SD. The modulation detection threshold ($20 \log m$) is shown as a function of modulation frequency. The upper panels show the results for the 1-kHz carrier, and the lower panels show the results for the 5-kHz carrier. The left panels show the results obtained without WDRC, and the right panel show the results obtained with WDRC.

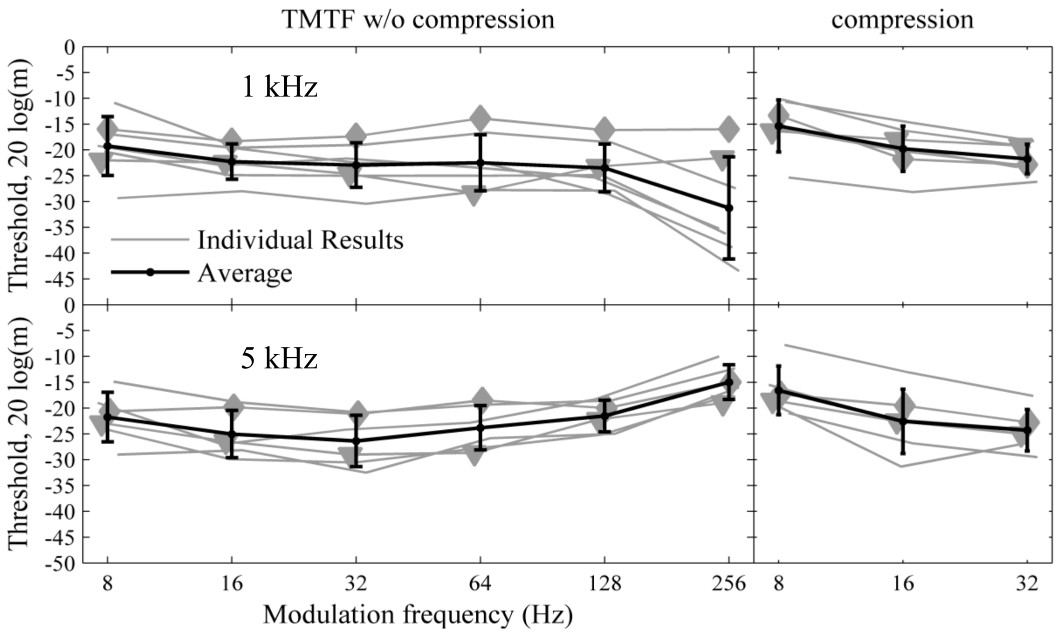

Fig. 4: Individual and average TMTF results for the HI listeners. Otherwise as in Fig. 3.

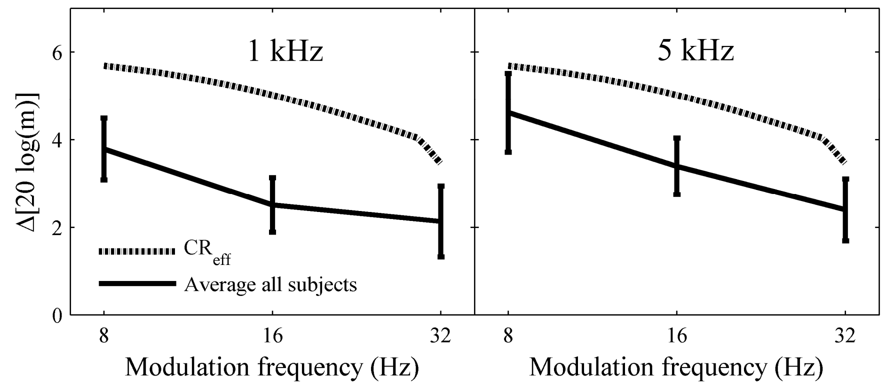

Fig. 5: The effect of WDRC on the modulation detection thresholds. The left panel is the result for the 1-kHz carrier and the right panel is the result for the 5-kHz carrier. For comparison, the black dotted curves display the physical reduction of the modulation depth from Fig. 2.

The effect of WDRC on the modulation detection thresholds is shown in Fig. 5. The effect is computed as the threshold for the non-compressed condition, in dB, subtracted from the threshold for the compressed condition, in dB (e.g., Edwards, 2004). It can be seen that the change in the modulation detection threshold due to WDRC is consistent with the physical reduction of the modulation depth.

The MDD thresholds for the NH listeners are shown in Fig. 6. The thresholds obtained without WDRC are consistent with those found by previous researchers (Lee and Bacon, 1997). The MDD threshold is rather insensitive to modulation frequency. The performance is not affected by compression. Hence, the reduction of the standard modulation depth due to compression does not seem to affect the discrimination performance.

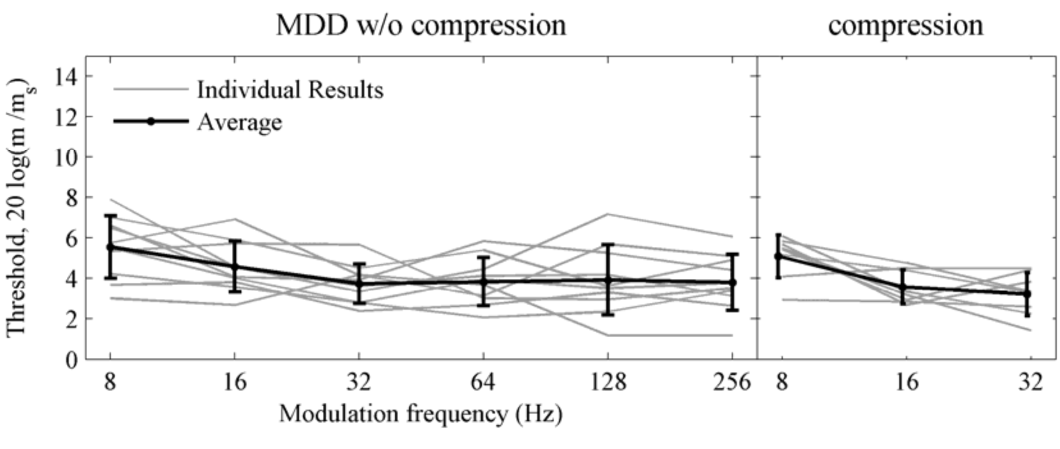

Fig. 6: Individual and average MDD results for the NH listeners for the 1-kHz carrier. The error bars represents ±1 SD. The modulation discrimination threshold (20 log (m/m_s)) is plotted as function of modula-tion frequency. The left panels show the results obtained without WDRC, and the right panel are the results obtained with WDRC.

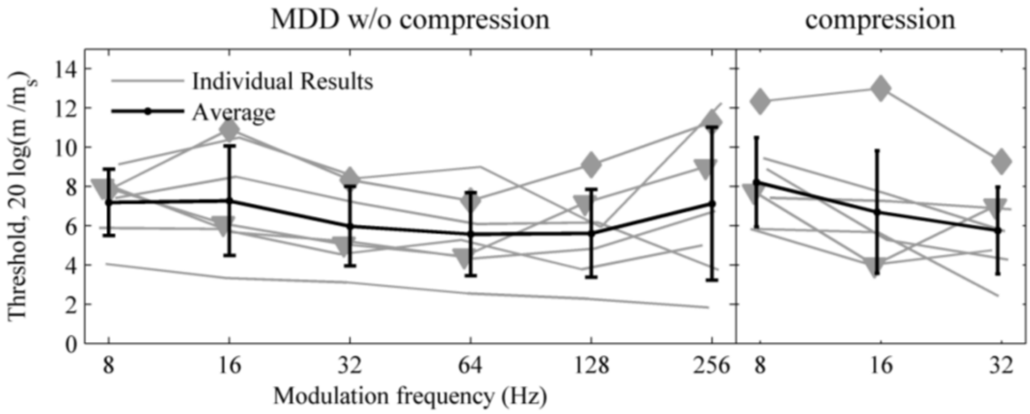

Fig. 7: Individual and average MDD results for the HI listeners for the 1-kHz carrier. Otherwise as in Fig. 6.

The MDD thresholds for the HI listeners are shown in Fig. 7. Larger individual differences across the HI listeners can be observed relative to the NH listeners. A two-way ANOVA indicated significantly lower MDD thresholds for the NH listeners than for the HI listeners [$F(1,60) = 18.2$, $p < 0.0001$]. The 95% confidence interval ranges from 1.0 dB to 2.7 dB.

DISCUSSION

The results obtained in the HI group revealed larger individual differences across listeners in the ability to discriminate amplitude changes in the envelope as well as in terms of spectral resolvability of the sidebands despite similar pure-tone sensitivity. The modulation detection thresholds were, on average, significantly lower for the HI listeners at the 5-kHz carrier in the "flat region" of the TMTF pattern. Thus, the HI listeners seem to have an improved ability to detect amplitude modulations. In contrast, higher MDD thresholds were observed in the HI group relative to the NH group. Hence, the ability to process amplitude changes of the envelope for a given modulation frequency seems to be reduced in the HI listeners. No significant correlation between the MDD thresholds and the TMTF thresholds was found, indicating that the two measures may represent different aspects of temporal processing.

Temporal resolution derived from TMTFs is often characterized by a time constant, τ, defined as $(2\pi f_c)^{-1}$, where f_c is the frequency at which sensitivity has declined by 3 dB relative to that measured for low modulation frequencies. A decline in sensitivity is thought to reflect a limitation in resolving fast amplitude modulations in the auditory system (Kohlrausch *et al.*, 2000). Such a measure cannot be applied to the data for the 1-kHz carrier due to resolved spectral sidebands at high modulation frequencies in this condition. For the 5-kHz carrier, a decreased sensitivity was observed at high modulation frequencies for both NH and HI listeners. For the average NH data, the value of f_c was 160 Hz ($\tau \approx 1.0$ ms), while the value for the HI listeners was around 93 Hz ($\tau \approx 1.7$ ms). Thus, there is some indication of reduced temporal resolution in the hearing-impaired listeners.

CONCLUSION

The encoding of temporal envelope fluctuations in the auditory system seems to be affected by sensorineural hearing impairment: The ability to detect slow and moderate envelope fluctuations can be superior in the hearing-impaired listeners at high carrier frequencies. In contrast, the ability to discriminate amplitude changes in the envelope and temporal resolution seems to be reduced. No indication of a relationship between modulation detection and modulation discrimination thresholds was found. Fast-acting WDRC was found to reduce the ability to detect slow envelope fluctuations.

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