The processing of complex envelopes in the normal-hearing and the hearing-impaired auditory system

Jesko L. Verhey[1], Stephan D. Ewert[2], Torsten Dau[2]

[1] *Institut für Physik, D-26111Oldenburg, Germany, Email: jesko.verhey@uni-oldenburg.de*

[2] *Centre for Applied Hearing Research, Acoustic Technology, Ørsted-DTU, Technical University of Denmark*

Introduction

Many natural sounds including speech exhibit a complex temporal envelope. Psychoacoustical modulation masking data (e.g., [1]) suggest that the auditory system may perform a frequency-selective analysis in the envelope-frequency domain comparable to the well known frequency selectivity in the audio-frequency domain. Ewert and Dau [2] proposed a model that assumed a linear processing of the envelope prior to a filter-bank. However, recent modulation detection experiments using complex envelopes indicate that the auditory system is sensitive to slow variations of the modulation depth which are not present in the linear modulation spectrum of the acoustical signal. In modulation masking experiments the slow variations can be used as a detection cue [1] or can affect the detectablility of test-modulation at the rate of the slow variations [3, 4]. The underlying mechanism that extracts these slow variations is still unclear. It was argued that a nonlinearity may extract the slow variations [1, 3, 4]. It is, however, also possible that off-frequency filters might be used in certain stimulus configurations, where the slow variations are converted in amplitude modulations (e.g. [1]).

The present study investigates the role of peripheral compressive nonlinearity in the perception of the slow variations by collecting data for hearing impaired subjects with a hearing impairment of primarily cochlear origin, i.e. where the peripheral compression is reduced (or absent). The role of envelope processing in peripheral off-frequency channels is investigated using different carrier frequencies and different complex masker modulators.

Methods

A 600-ms sinusoidal carrier including 20-ms cosine-squared rise/fall times was used. Modulation was applied during the whole period of the carrier. The expression describing the test modulation is

$$\mathrm{mod}_T(t) = m_T \cos(2\pi f_T t + \varphi) \ , \qquad (1)$$

where f_T denotes the test-modulation frequency, m_T the modulation depth and φ the phase of the test modulation. The expression describing the masker modulation is

$$\mathrm{mod}_m(t) = m_m(1+\cos(2\pi f_T t))\cos(2\pi f_m t) \ , \qquad (2)$$

i.e., the masker consists of a modulation at f_m that itself is sinusoidally amplitude modulated in depth at a rate equal to the test-modulation frequency f_T. This “second-order modulation” (modulation of the modulation depth) can be extracted by calculating the Hilbert envelope of the envelope and will be referred to as the “venelope” [2]. The mean modulation depth is m_m. Both modulations are applied to the same carrier. The stimuli were generated digitally at a sampling rate of 48 kHz. The stimuli were presented monaurally via Sennheiser HD 580 headphones. Subjects were seated in a double-walled sound-attenuating booth. Four normal-hearing and five hearing impaired subjects with a flat, mildly downward sloping, sensori-neural hearing loss of about 40 to 60 dB HL participated in the experiments.

Results and Discussion

Phase effect for normal hearing subjects

In off-frequency filters the venelope will be partly demodulated to the envelope domain [1]. Thus, part (or all) of the masking effect may be due to (first-order) envelope masking in off-frequency filters. Such a mechanism will depend on the spread of excitation in the cochlea and thus will be susceptible to changes in the masker modulation frequency f_m, the carrier frequency and the carrier level.

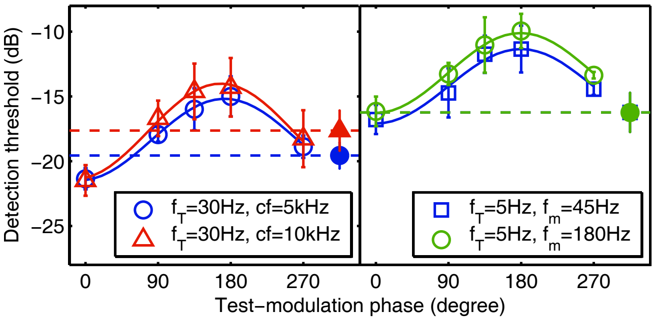

Figure 1: Modulation depth at threshold as a function of the phase φ of the test modulation f_T. Mean measured data across three normal-hearing subjects and interindividual standard deviations are shown. Left panel: Two center frequencies. Right panel: Two different masker modulation frequencies. Open symbols indicate thresholds in the presence of the masker. The dashed horizontal lines and closed symbols indicate thresholds without masker (quiet threshold). The solid lines represent a sinusoidal function fit to the data.

The left panel of Figure 1 shows mean modulation depth at threshold for a 30-Hz test modulation in the presence of a 180-Hz masker modulation f_m with a 30-Hz venelope as a function of the test-modulation phase for two carrier frequencies. The masker-modulation depth m_m was -14 dB. The carrier level was 35 dB SPL for 5 kHz and 50 dB SPL for 10 kHz. This corresponds to about 35 dB HL for both carrier frequencies. The level is substantially lower than in an earlier study ([4], 70 dB SPL at 5 kHz). This low level is chosen in order to limit the spread of excitation. For both carrier frequencies the same threshold curve was obtained. Threshold is lowest when the test modulation is in phase with the masker venelope (0 degrees) and highest for the anti-phase condition (180 degrees). The quiet thresholds (dashed lines) for the two carrier frequencies differ slightly (< 2 dB).

The right panel of Figure 2 shows the mean modulation depth at threshold for a 5-Hz test modulation as a function of the test-modulation phase for two different masker modulation frequencies f_m. For two of the three subjects, the carrier level was 20 dB SPL. At this carrier level, quiet threshold for the two subjects was around -16 dB. For one subject, the carrier level was set to 35 dB SPL in order to obtain a similar quiet threshold (-15 dB). The same threshold curve is obtained for the two masker modulations. For both masker modulation frequencies, thresholds are lowest for the in-phase condition and highest for the anti-phase condition.

Both results indicate that masking effect is not based on off-frequency information. Analytical calculations of the demodulated venelope in off-frequncy channels also showed that this component is too small to account for the phase effect in the present experiments (not shown). Thus the phase effect is most likely due to a mechanism in the filter at the carrier frequency that extracts the venelope.

Phase effect for hearing-impaired subjects

Moore et al. [3] argued that the compressive nonlinearity associated with the processing on the basilar membrane introduces a physical distortion component in the envelope at the venelope frequency which interacts with the signal-modulation frequency. In order to test this hypothesis, modulation depth at threshold for a 30-Hz test modulation in the presence of a masker with a masker modulation f_m of 180 Hz and a venelope frequency of 30 Hz were measured for subjects with hearing impairment of primarily cochlear origin. The carrier frequency was 3 kHz and the carrier level was either 80 dB SPL (subject WW, MG) or 85 dB SPL (subject LF, WF). The carrier level was about 25 to 40 dB above their individual threshold (comparable to the experiment for the normal hearing subjects with a 30-Hz test modulation). Figure 2 shows individual data and standard deviations for the four hearing impaired subjects. Individual differences in quiet threshold and the amount of the phase effect are apparent. However, as for the normal hearing subjects (Figure 1) thresholds are lowest when the test modulation is in phase with the masker venelope and highest for the anti-phase condition. Thus, peripheral compression is presumably not responsible for the phase effect.

The results are in agreement with simulations in [4]. They showed that compression predicts a phase effect opposite to the measured phase effect. Ewert et al. [1] proposed a model that extracts the venelope explicitly and adds it to the internal representation of the envelope. This model can predict the phase effect for normal-hearing subjects [4]. However, the model was not designed to predict the data of the hearing impaired. In order to account for the individual hearing impaired data the same kind of nonlinearity can be assumed (not shown). The difference between normal and hearing impaired subjects can be predicted by assuming an individual modulation threshold criterion. A constant criterion on a linear scale (as assumed in [4]) is combined with a criterion that is proportional to the modulation depth of the internal envelope at the signal modulation frequency (comparable to Weber's law). Recently, a similar criterion was proposed for the prediction of modulation depth discrimination data [5].

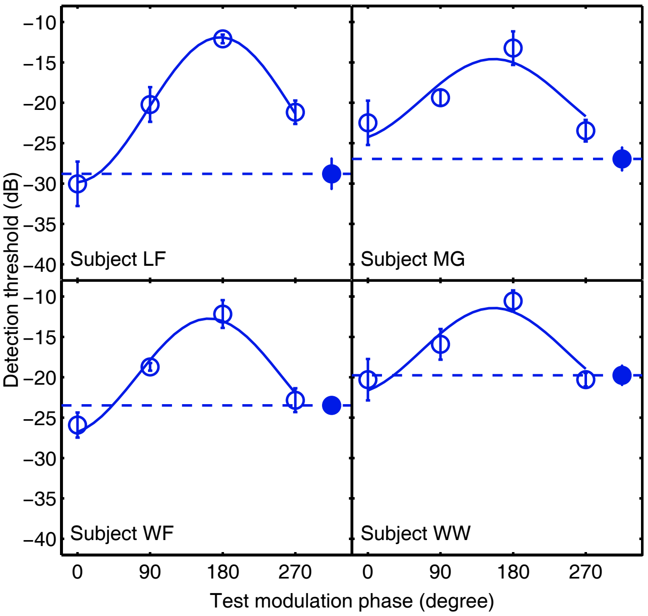

Figure 2: Modulation depth at threshold as a function of the phase φ of the test modulation (f_T=30Hz). Symbols and the solid line indicate masked thresholds in the presence of a complex masker with a masker-modulation frequency of 180 Hz and a venelope frequency of 30 Hz. The dashed lines and the filled symbols indicate the threshold in the absence of a masker (quiet thresholds). Individual data for four hearing impaired subjects with flat or moderately sloping hearing loss of primarily cochlear origin are shown. The pattern of results is in line with the results for the normal hearing subjects.

Summary

For normal hearing subjects, a phase effect can be measured down to very low carrier levels (20 dB HL). The same phase effect is found for 5-kHz and 10-kHz carriers and for masker modulation frequency of 45 Hz and 180 Hz. The shape of the phase effect in the hearing impaired subjects is similar to the one in normal hearing subjects. The results suggest that the effect is not a consequence of off-frequency information processing and does not originate from a peripheral (compressive) nonlinearity.

References

[1] Ewert, S.D., Verhey, J.L. and Dau, T., J. Acoust. Soc. Am. **112** (2002), 2921-2931

[2] Ewert, S.D., Dau, T., J. Acoust. Soc. Am. **108** (2000), 1181-1196

[3] Moore, B.C.J., Sek, A., Glasberg, B.R., J. Acoust. Soc. Am. **106** (1999), 908-918

[4] Verhey, J.L., Ewert, S.D., Dau, T., J. Acoust. Soc. Am. **114** (2003), 2135-2146

[5] Ewert, S.D., Dau, T., J. Acoust. Soc. Am. (2004), accepted