Simultaneous reflection masking: dependency on direct sound level and hearing-impairment

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Simultaneous reflection masked thresholds (RMTs) were measured for 3 normal-hearing (NH) and 3 hearing-impaired (HI) subjects as a function of reflection delay. All stimuli were presented diotically and dichotically, using a 200-ms long broadband noise (100-50000 Hz) as input signal. For 55 dB-SL direct sound level, NH-listeners showed a binaural suppression effect for delays smaller than 7-10 ms and a binaural enhancement effect for larger delays. When decreasing the direct sound level to 15 dB-SL, the only significant change observed was that the dichotic RMT increased for delays larger than about 7 ms. In consequence, the binaural enhancement effect was strongly reduced, but the binaural suppression effect was unchanged. HI-listeners (at 30 dB-SL) showed a strong binaural suppression effect for delays smaller than about 3ms and only a very small binaural enhancement effect for larger delays. Hence, in contrast to binaural reflection enhancement, binaural reflection suppression seems to involve mechanisms that are robust to auditory-internal noise-floor and hearing-impairment. Moreover, differences between the RMTs for HI- and NH-listeners were in principal agreement with differences expected from changed auditory filter bandwidth and audibility. However, the level-dependency of the auditory filters' bandwidth was not reflected in the SRMT data.

INTRODUCTION

Reflection masking (RM) refers to the specific masking condition in which the masker is realized by a direct sound and the test signal by a reflection (i.e., a delayed and attenuated copy of the direct sound). RM is quantified by the reflection masked threshold (RMT) and can be employed to studying the general auditory processing of reverberant sounds. For small reflection delays (i.e., delays smaller than about 15 ms), spectral coloration provides the main cue in RM (e.g., Buchholz, 2007). Spectral coloration has usually been associated with spectral modulations (or ripples) that are introduced (by the reflection) to the power spectrum of the original sound (see section II). Since the limited resolution of the auditory filters reduces the depth of such spectral modulations, the auditory filters are expected to largely determine auditory sensitivity to early reflections. Throughout the present study, the effect of the auditory filters' bandwidth on reflection masking (RM) is investigated by: (i) varying the sound pres-sure level of the direct sound and (ii) considering hearing-impaired (HI) listeners. These two conditions take advantage of the observation that: (i) with increasing sound pressure level the bandwidth of the auditory filters generally increases (e.g., Moore, 2003) and (ii) sensorineural HI-listeners typically show reduced spectral resolution, indicating auditory filters with increased bandwidth (e.g., Moore, 2003).

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MODEL-BASED EXPECTATIONS

When a reflection is added to a sound signal, spectral modulations or "ripples" are introduced to the signal's power spectrum. In Fig. 1, an auditory-internal power spectrum Δ of the im-pulse response of a single reflection is exemplarily shown for a reflection delay of $\tau = 3$ ms (solid line) and $\tau = 10$ ms (dotted line). The reflection gain was $g_{dB} = -10$ dB. The limited spectral resolution of the auditory filters leads to a frequency-dependent spectral smoothing of the power spectrum which results in a reduction of the depth of the spectral modulation (Buchholz, 2007). Comparing the power spectra given in the left and right panel of Fig. 1, it is obvious that an increase (here doubling) of the auditory filters' bandwidth would result in a further reduction of the spectral modulation depth.

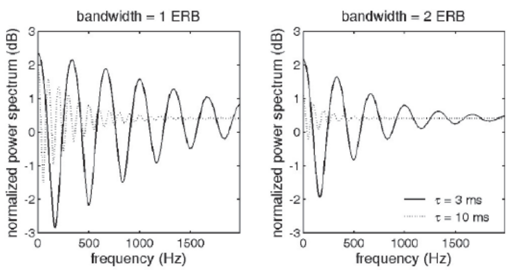

Fig. 1: Auditory-internal power spectra of the impulse response of a single reflection. For the spectra in the right panel, filters were used that had twice the bandwidth of the filters used in the left panel. τ: reflection delay.

The auditory-internal power-spectra shown in Fig. 1 were based on an analytical description derived by Salomons (1995) and given by:

$$\Delta(f_0,\tau) = 10 \cdot \log_{10}\left(1 + g^2 + 2g\left(1 + (0.5\pi\tau B(f_0))^2\right)^{-2}\cos(2\pi f_0\tau)\right) \qquad \text{(Eq. 1)}$$

with $B(f_0)$ the equivalent rectangular bandwidth of the considered auditory filter in Hertz, taken from Patterson and Moore (1986), and given by:

$$B(f_0) = 6.23 \cdot 10^{-6} f_0^2 + 93.39 \cdot 10^{-3} f_0 + 28.52 \qquad \text{(Eq. 2)}$$

where f_0 is the centre frequency of the considered auditory filter in Hertz, f the physical frequency in Hertz, and g the reflection gain ($g_{dB} = 10 \cdot \log_{10}(g)$). Equation 1 approximates a logarithmically compressed power spectrum at the output of a gammatone filterbank with an impulse response of a single reflection as input. In the left panel of Fig. 1, the filter bandwidth given in Eq. 2 was directly applied to Eq. 1, whereas in the right panel, Eq. 2 was first multi-plied with a factor of 2.

In order to predict the effect of the auditory filters' bandwidth on the RMT, the detection stage described by Buchholz (2007) was applied to the above auditory-internal power spectrum Δ. The resulting diotic RMT predictions are shown in Fig. 2 (left panel). The RMT in-creases monotonically with increasing delay up to a maximum delay τ_m, above which the RMT is constant. With increasing auditory filter bandwidth the RMT values increase and the value of the maximum delay τ_m decreases.

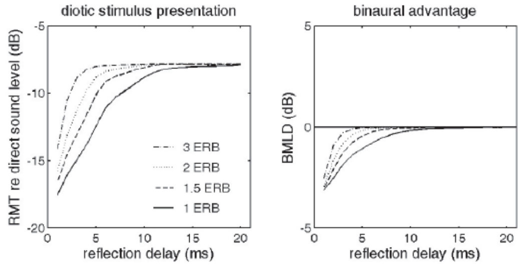

Fig. 2: Model predictions of the RMT with the auditory filter bandwidth as parameter. The BMLD is calculated by the difference between the diotic and dichotic RMT predictions.

Binaural processes are realized within the model by applying the above power-spectrum derivation separately to the left and right ear's input signal and then calculating the mean spec-trum (Zurek, 1979). Although such simple binaural model approach can not account for bin-aural reflection-enhancement effects, it can (qualitatively) describe different important aspects of binaural reflection-suppression (Buchholz, 2007). The difference between the diotic and dichotic RMT predictions, the BMLD, is shown in Fig. 2 (right panel). The predicted BMLD is negative (i.e., the binaural system deteriorates auditory sensitivity) and decreases with increasing delay up to a maximum delay τ_0, above which the BMLD is zero. With increasing auditory filter bandwidth the (negative) value of the BMLD decreases and also the value of the maximum delay τ_0.

EXPERIMENT 1: NORMAL-HEARING LISTENERS

As described in the introduction of this manuscript, the "effective" bandwidth of the auditory filters generally increases with increasing stimulus level. Hence, in order to investigate the potential influence of the bandwidth of the auditory filters on reflection masking (RM), reflection masked thresholds (RMTs) were measured at two different direct sound levels.

A. Methods

Subjects: Two male subjects (PK and PM) and one female (SB) subject aged between 24 and 34 took part in the experiment. All subjects were of normal hearing and were very experienced listeners.

Stimuli: The stimuli were composed of a direct sound (the masker) and a test reflection (the signal), presented via headphones (Sennheiser HD-580) in a double-walled sound-attenuating booth. The direct sound was a bandpass filtered white noise (100-5000 Hz) with a total duration of 200 ms. The test reflection was a delayed and attenuated copy of the direct sound. In order to avoid offset-listening effects, the reflection offset was truncated such that the direct sound and the reflection had a common offset. Two spatial stimulus conditions were considered: (i) a diotic condition and (ii) a dichotic condition. In the diotic condition, the left and right headphone signals were identical, whereas in the dichotic condition, the direct sound was presented diotically and the test reflection contained an interaural time delay (ITD) of 0.5 ms. This ITD was realized by decreasing the delay for the left ear signal by 0.25 ms and increasing it for the right ear by 0.25 ms. Two direct sound levels were considered: (i) a "low-level" condition of 25 dB-SPL (~15 dB-SL) and (ii) a "high-level" condition of 65 dB-SPL (~55 dB-SL). The reflection delays were 1, 3, 5, 7, 10, 15, and 20 ms. Additionally, the masked threshold for an "uncorrelated reflection" was measured for a delay of 20 ms. This "uncorrelated" reflection was realized by a noise that had the same signal-properties as the original reflection but was uncorrelated to the direct sound.

Procedure: RMTs were measured by employing a three-interval, three-alternative forced-choice (AFC) paradigm. A three-down one-up procedure was used to estimate the 79% point of the psychometric function (Levitt, 1970). All three intervals contained the direct sound and one randomly chosen interval additionally contained the test reflection. The direct sound was realized by "semi-random noise", i.e., for each trail a new noise sample was generated which was then used for all three direct sound realizations. The three stimulus intervals were separated by pauses of 500 ms duration. The starting level of the test reflection was the same as the level of the direct sound (i.e., 0 dB). The starting step size of the test reflection was 4 dB, which was reduced to the final step size of 1 dB after 4 reversals. Using this final step size, 6 reversals were measured and the mean value and standard deviation over these 6 reversals were calculated. At least two runs per subject were made for each RMT value.

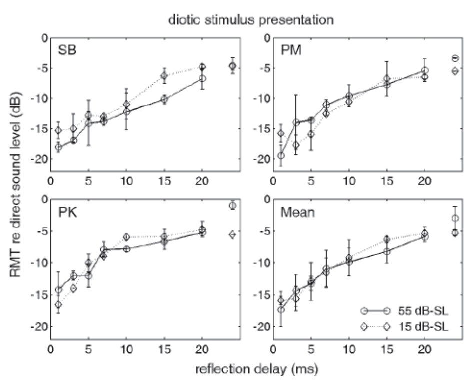

Fig. 3: Results of the diotic RMT measurements for the three normal-hearing subjects with the direct sound sensation-level as parameter. The case of a 20-ms delayed uncorrelated re-flection is given by the separated symbols on the right side of each panel. SL: sensation level.

Results

In Fig. 3, the measured RMTs for diotic stimulus presentation are shown as a function of reflection delay with the direct sound sensation level (SL) as parameter. The upper two panels and the lower left panel present the individual data and the bottom right panel presents the average data of all three subjects. The error bars in each panel indicate the standard deviation. Both RMTs increases monotonically with increasing reflection delay, indicating a decrease in auditory sensitivity with increasing delay. This behaviour is in general agreement with other relevant studies (e.g., Buchholz, 2007). No significant difference in the RMT can be observed for the two direct sound levels. Hence, the diotic RMT seems to be independent of the direct sound level. For large delays (i.e., 20 ms), the diotic RMTs approach the threshold for the case of an uncorrelated reflection (indicated by the unconnected symbols). Hence, evidence is provided that for reflection delays above about 20 ms, the auditory system processes the direct sound and the (original) reflection in a similar way as two uncorrelated signals (see also Buchholz, 2007).

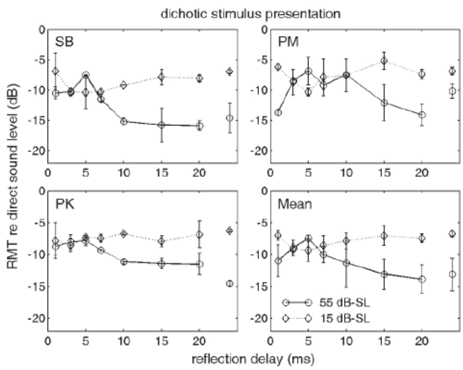

Fig. 4: As Fig. 3, except showing dichotic RMTs.

In Fig. 4, the measured RMTs for dichotic stimulus presentation are shown as a function of reflection delay with the direct sound level as parameter. For a direct sound level of 55 dB-SL (solid line), the RMT shows an increase in threshold with increasing delay τ up to about $\tau = 5$ ms, and monotonically decreases with further increasing delay. This behaviour is in agreement with other relevant studies (e.g., Buchholz, 2007). For a direct sound level of 15 dB-SL (dashed line), the RMT is basically independent of the reflection delay. Comparing the thresholds for the two direct sound level conditions, no significant difference can be observed for delays up to about 5-10 ms. For delays above about 5-10 ms, the two thresholds deviate, the 55 dB-SL threshold being below the 15 dB-SL threshold. This difference in threshold increases with increasing delay, resulting in a difference of up to 8 dB at a delay of 20 ms. Similar to the diotic RMT, for a delay of 20 ms, the dichotic RMTs approach the threshold for the case of an uncorrelated reflection (indicated by the unconnected symbols).

In Fig. 5, the binaural masking level difference (BMLD) is shown as a function of reflection delay with the direct sound level as parameter. The BMLD is calculated by the difference between the diotic RMT data (given in Fig. 3) and the dichotic RMT data (given in Fig. 4). For both direct sound level conditions, a negative BMLD of up to -8 dB is observed for short delays (i.e., the diotic RMT is below the dichotic RMT) and a positive BMLD of up to 9 dB for longer delays (i.e., the diotic RMT is above the dichotic RMT). Hence, a binaural reflection-suppression effect is observed for early reflections and a binaural reflection-enhancement effect is observed for later reflections. This behaviour is in general agreement with other rele-vant literature (e.g., Buchholz, 2007). Comparing the BMLDs for the two different direct sound levels, it can be observed that: (i) the binaural reflection-suppression effect is basically independent of direct sound level, (ii) the binaural reflection-enhancement effect is significantly reduced at low direct sound levels (i.e., a BMLD of up to +9 dB is observed for the 55 dB-SL condition, but only a BMLD of up to 1-2 dB is observed for the 15 dB-SL condi-tion), and (iii) for a lower direct sound level, the 0-dB BMLD intersect τ_0 is shifted towards longer delays (for the 55 dB-SL condition τ_0 = 7-10 ms and for the 15 dB-SL condition τ_0 = 10-15 ms). The reduction (or even loss) of binaural reflection-enhancement is similarly shown in the BMLD for an uncorrelated reflection (unconnected symbols).

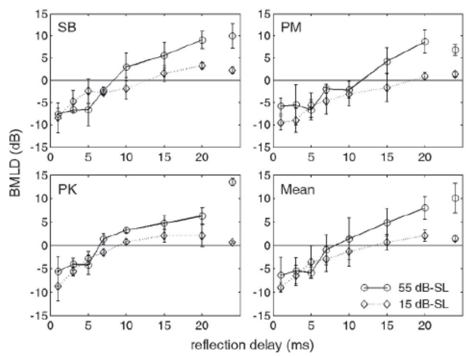

Fig. 5: As Fig. 3, except that here the Binaural Masking Level Difference (BMLD) is pre-sented. The BMLD is given by the difference between the diotic RMT data (given in Fig. 3) and the dichotic RMT data (given in Fig. 4).

Discussion

In the previous section it was found that the diotic RMT is independent of the direct sound level. This finding is rather surprising, because the increase of the auditory filter's bandwidth with increasing stimulus level was expected to produce a reduction in the overall depth of the spectral modulations inherent in the auditory-internal power spectrum (Fig. 1), which in turn should result in an increase in the overall RMT (Fig. 2, left panel). However, this observation is in agreement with studies on pitch-strength of ripple-noise pitch (Yost and Hill, 1978; Bilsen and Ritsma, 1970). Ripple-noise pitch is closely related to coloration-detection and coloration was the prevalent detection cue throughout the present diotic RMT measurements. The independency of the RMT on stimulus level might be explained by the assumption that subsequent auditory stages compensate for the level-dependency of the auditory filters. Such compensation process might be realized by a (neuronal) mechanism that filters (or sharpens) spectral modulations/variations (e.g., Yost, 1982; Shamma, 1985) in a level-dependent way. However, the unexpected level-independency of the RMT might here also be partly related to the absolute threshold of hearing. The increased auditory sensitivity at low stimulus level due to the narrower peripheral filters might be offset by the reduced sensitivity at absolute threshold (i.e., the modulations are partly masked by auditory noise).

The dichotic RMT results (Fig. 4) revealed that the direct sound level has basically no effect on RM for reflection delays below about 5-10 ms. For delays larger than 5-10 ms, an increase in direct sound level produced a significant reduction in threshold. In consequence, the binaural reflection-suppression effect was found to be independent of direct sound level, whereas the binaural reflection-suppression effect was found to be strongly reduced (or even lost) at low direct sound level (Fig. 5). This difference in behaviour suggests that the two phenomena involve different auditory mechanisms. Binaural reflection-enhancement seems to require a thorough analysis of interaural differences, which is deteriorated at low stimulus level (e.g., by auditory-internal noise). In contrast, binaural reflection-suppression seems to employ less analytical (and maybe less complicated) processes, which are therefore more robust at low stimulus level. The observation that the binaural reflection-enhancement effect decreases with decreasing direct sound level is in agreement with studies on binaural release from masking (e.g., Hall and Harvey, 1984), supporting the suggestion of Buchholz (2007) that both phe-nomena employ similar mechanisms.

EXPERIMENT 2: HEARING-IMPAIRED LISTENERS

As described in the introduction of this manuscript, the auditory filters for listeners with a sensorineural hearing loss are typically broader than in normal hearing (NH) listeners. Hence, the potential influence of the bandwidth of the auditory filters on reflection masking (RM) is here investigated by comparing RM data of listeners with a sensorineural hearing loss to according data for NH-listeners. While RMT results for NH-listeners were already described in the previous section, here, RMTs for hearing-impaired (HI) listeners will be discussed.

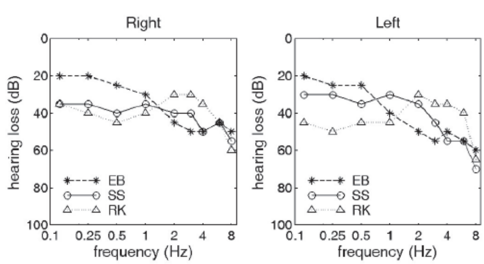

Fig. 6: Audiograms for the three hearing-impaired subjects.

Methods

The same stimuli and methods were used as described in experiment 1. The only differences were that: (i) only one stimulus level was considered and (ii) less reflection delays τ were considered (i.e., τ = 0/1, 2.5, 5, 7.5, 10, 20 ms). These changes were mainly due to the limited availability of HI-subjects. Three female subjects aged between 55 and 79 participated in the experiment. The subjects were chosen according to two main criteria: (i) they should have a similar hearing loss at both ears and (ii) they should only have a minor hearing loss at low frequencies. The audiograms for the three subjects are shown in Fig. 6. Throughout the ex-periment, the direct sound was presented at 30 dB-SL. In order to adjust this sensation level to the individual subjects, the absolute threshold for the direct sound alone stimulus was meas-ured for each of them (absolute thresholds: SS = 33 dB; EB = 40 dB; RK = 29 dB).

Results

In Fig. 7, the measured diotic (solid lines) and dichotic (dashed lines) RMTs for HI-listeners are shown as a function of reflection delay. In general, the RMTs for HI-listeners are significantly higher than the corresponding RMTs for NH-listeners (Fig. 3-5), indicating a reduced overall sensitivity for HI-listeners. The diotic RMT (solid lines) shows an initial increase with increasing reflection delay and saturates at a maximum delay τm of about 5-10 ms. Hence, the diotic RMT for HI-listeners saturates at significantly shorter delays than for NH-listeners ($\tau_m \geq 20$ ms; section III.B).

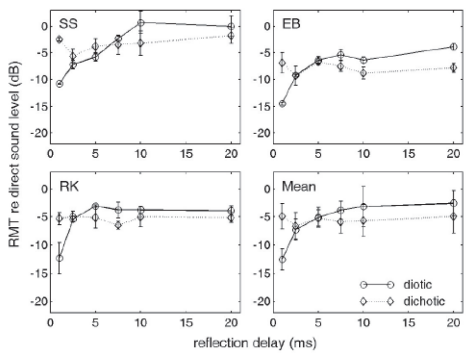

Fig 7: Results of the diotic and dichotic RMT measurements for the three HI-subjects.

The dichotic RMT for HI-listeners (Fig. 7, dashed lines) is independent of the reflection de-lay. Hence, the dichotic RMT behaves similarly to the one found for NH-listeners at a low stimulus level (Fig. 4, dashed lines). Calculating the difference between the diotic and dichotic RMTs given in Fig. 7, a BMLD of about -8dB is observed for a delay of 1 ms. With increasing delay the diotic and dichotic RMTs intersect, and for delays larger than about 3-7 ms, the dichotic RMT is slightly lower than the diotic RMT (i.e., a maximum positive BMLD of less than 1-2 dB is observed). The maximum binaural reflection-suppression effect at 1-ms delay is of similar value as for NH-listeners and thus, seems to be independent of stimulus level (section III.B) and hearing-impairment. However, the maximum delay τ_0, up to which this suppression effect can be observed, is strongly reduced for HI-listeners (i.e., for NH-listeners τ_0 = 7-10 ms at 55 dB-SL and τ_0 = 10-15 ms at 15-dB-SL, whereas for HI-listeners τ_0 = 3-5 ms). The observed reduction or loss of binaural reflection-enhancement for HI-listeners (i.e., the maximum BMLD is below 1-2 dB) is similar to the reduction for NH-listeners at low (15 dB-SL) direct sound level (section III.B).

Discussion

In the previous section it was highlighted that the increase of the diotic RMT with increasing delay saturates for HI-listeners at much shorter delays τm than for NH-listeners. Moreover, for HI-listeners the delay τ_0 at which the diotic and dichotic RMTs intersect was also found to be shifted towards shorter delays. Both observations are in general agreement with the assumption that HI-listeners employ broader auditory filters than NH-listeners, as conceptually discussed in section II. However, in section III.C it was discussed that RM might be influenced by two spectral mechanisms: (i) peripheral filtering and (ii) a (neuronal) mechanism that is located central to the peripheral filters. Hence, the effective broadening of the auditory filters observed for HI-listeners might reflect contributions from additional spectral processes and might not only be related to the characteristics of the peripheral filters.

SUMMARY

The influence of the bandwidth of the auditory filters on RM was investigated by: (i) varying the direct sound level for NH-listeners (bandwidth increases with increasing level) and (ii) measuring RMTs for HI-listeners (HI-listeners typically show broader auditory filters than NH-listeners). In the case of NH-listeners, the RMT results did not reflect the increase of auditory filter bandwidth with increasing direct sound level, indicating that additional (more central) spectral processes are involved in RM. However, the RMT data for the HI-listeners clearly reflected the increased auditory filter bandwidth.

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