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Research paper

Binaural release from masking in forward-masked intensity discrimination: Evidence for effects of selective attention

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ABSTRACT

In a forward-masked intensity discrimination task, we manipulated the perceived lateralization of the masker via variation of the interaural time difference (ITD). The maskers and targets were 500 Hz pure tones with a duration of 30 ms. Standards of 30 and 60 dB SPL were combined with 60 or 90 dB SPL maskers. As expected, the presentation of a forward masker perceived as lateralized to the other side of the head as the target resulted in a significantly smaller elevation of the intensity difference limen than a masker lateralized ipsilaterally. This binaural release from masking in forward-masked intensity discrimination cannot be explained by peripheral mechanisms because varying the ITD leaves the neural representation in the monaural channels (i.e., in the auditory nerve) unaltered. Instead, our results are compatible with the assumption that lateralization differences between masker and target promote object segregation and therefore facilitate object-based selective attention to the target.

1. Introduction

A precise perception of the intensity of auditory events in a noisy environment is important in numerous situations in everyday life. For example, if a pedestrian wants to cross a road, then the acoustic intensity (change) provides information about the distance or the time-to-contact of an approaching car (e.g., Button and Davids, 2004). Concerning intensity discrimination and detection in a noisy setting, simultaneous and non-simultaneous masking can be distinguished. The latter is also known as temporal masking or, depending on the temporal position of the masker relative to the target sound, forward- and backward-masking. The auditory mechanism underlying temporal masking is still less well understood than simultaneous masking (e.g., Plack, 1996; Zeng, 1998; Plack et al., 2002; Oberfeld, 2008, 2009; Laback et al., 2011). In applied contexts like audio coding or communication engineering there is still a potential for integrating effects of temporal masking into the models (e.g., Dai and Soon, 2011; Gunawan et al., 2010; Rhebergen et al., 2010).

Despite the seemingly simple stimulus configuration of a target tone preceded or followed by a single temporally non-overlapping masker, a rather complex pattern of effects of forward- and backward-masking on auditory intensity resolution has been reported. An important finding is that with an intense masker (e.g., 90 dB SPL) the masker-induced elevation of the intensity difference limen (DL) is smaller for both a low-level and a high-level standard than for a mid-level standard. Thus, the relationship between standard level and the DL-elevation is non-monotonic, showing the so-called mid-level hump in intensity discrimination (Zeng et al., 1991). Several explanations for this somewhat counterintuitive result have been proposed (for reviews see Oberfeld, 2008, 2009).

Zeng et al. (1991) suggested that the relatively slow recovery of low spontaneous-rate neurons in the auditory nerve creates a “coding gap” for mid-level standards if an intense forward masker is presented. However, subsequent experiments showed a strong effect of backward maskers (Plack and Viemeister, 1992; Plack et al., 1995; Oberfeld and Stahn, in press) and a small but significant effect of contralateral maskers (Schlauch et al., 1999). These findings cannot be explained by adaptation in the auditory nerve. As a consequence, several explanations for the effects of non-simultaneous masking on intensity resolution based on more central mechanisms have been proposed (Carlyon and Beveridge, 1993; Oberfeld, 2008; Plack and Viemeister, 1992). Detailed descriptions of these models can be found in Oberfeld (2008, 2009). In brief, the *referential encoding*

Abbreviations: 2I, 2AFC, two-interval, two alternative forced-choice; ΔI, intensity increment (intensity difference between the two intervals); BMLD, binaural masking-level difference; CI, confidence intervals; DL, difference limen; HL, hearing level; ILD, interaural level difference; IPD, interaural phase difference; ISI, inter-stimulus-interval; ITD, interaural time difference; LED, light-emitting diodes; M, mean; rmANOVA, repeated-measures analysis of variance; SD, standard deviation.

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hypothesis (Plack and Viemeister, 1992; Carlyon and Beveridge, 1993) attributes the effects of non-simultaneous maskers to the use of a different and less precise type of memory representation than in a condition without masker (cf. Durlach and Braida, 1969). Based on similar patterns of results regarding the effects of non-simultaneous maskers on target loudness and on intensity resolution, the *loudness enhancement hypothesis* (Carlyon and Beveridge, 1993) proposes that the masker-induced DL-elevations are due to variability in the loudness representation of the target, induced by systematic changes in target loudness caused by the masker (cf. Oberfeld, 2007).

It is important to note that all of the three suggested explanations assume that the maskers reduce the precision of the information about target intensity, either already at the level of the auditory nerve or at later processing stages. An alternative explanation is that even with non-simultaneous maskers a precise representation of target intensity is available at the processing stage where the decision concerning target intensity is made, but that this information is not used in an optimal fashion. This might for example be the case because the task-irrelevant and to-be-ignored information about masker intensity systematically influences the decision. Evidence for masker intensity being factored into the decision has been reported by Oberfeld (2009).

Following this line of reasoning, we propose that the failure of selective attention to the target is a useful framework for understanding the effects of non-simultaneous masking on intensity resolution. Results from a recent study from our lab (Oberfeld and Stahn, in press) are consistent with this concept. In a two-interval intensity discrimination task, we presented conditions either favoring that the maskers and targets be grouped together (i.e., perceived as one unitary object) or favoring the processing of the maskers and the targets as two separate auditory objects (Kubovy and Van Valkenburg, 2001; Shinn-Cunningham, 2008). For example, in one of the experiments the targets were presented in a longer regular sequence of maskers. In this condition, listeners reported to receive the maskers as one auditory stream (cf. Moore and Gockel, 2012; Bregman, 1990) and the targets as separate events. Research on *object-based attention* in both the auditory and the visual modality demonstrated that it is more difficult to selectively attend to a feature within an object than to attend to one object while ignoring another object (e.g., Kahneman and Henik, 1981; Scholl, 2001; Best et al., 2008). Compatible with this prediction, in both experiments by Oberfeld and Stahn (in press) the elevation of the intensity DL caused by the maskers was significantly smaller in conditions favoring the processing of maskers and targets as separate auditory objects or streams. Results from studies demonstrating that reducing the perceptual similarity between masker and target also reduces the masker-induced DL-elevation (Schlauch et al., 1999, 1997; Oberfeld, 2008) would be directly compatible with the proposed framework of selective attention, while the three models introduced above cannot account for similarity effects without modifications (cf. Oberfeld, 2008).

An important caveat to testing the effects of selective attention by varying the perceptual grouping or similarity of masker and target is that experimental manipulations affecting grouping or similarity will often simultaneously alter the representations of masker and target in the auditory nerve. For example, frequency differences are one of the strongest cues favoring auditory stream segregation (Bregman, 1990; Moore and Gockel, 2002, 2012). However, increasing the frequency difference between masker and target will also cause the two tones to activate different locations on the basilar membrane (cf. Yates, 1995). As a consequence, peripheral adaptation effects, for example in auditory nerve neurons, would be reduced by the frequency separation between masker and standard (e.g., Harris and Dallos, 1979). Thus, it is difficult to decide whether peripheral adaptation effects, effects related to auditory grouping, or both are responsible for the reduction in the masker-induced DL-elevation observed if masker and standard differ in frequency (Zeng and Turner, 1992).

To avoid these potential confounds, in the present study we selected experimental conditions differing in the similarity of masker and target but maintaining identical representations of the tones in the auditory nerve. We varied the perceived lateralization of binaurally presented maskers relative to the targets by manipulating the interaural time difference (ITD) of the masker. This enabled us to present maskers lateralized either to the same side of the head as the target (ipsilateral masker), or to the opposite side (contralateral masker). We expected the difference in lateralization to promote object separation between masker and target, which should facilitate selective attention to the target and therefore result in smaller DL-elevations than for the ipsilateral masker. Importantly, as we varied only the masker ITD, the waveform delivered to each of the two ears (i.e., the monaural channels) was identical in the conditions with ipsilateral and contralateral masker. This ensured that the representation of masker and target in the auditory nerve did not differ between the two masker lateralizations.

Two different standard levels (30 and 60 dB SPL) were presented in quiet and combined with a 90 dB SPL masker. Thus, we presented masker-standard level combinations representing the mid-level hump. Additionally, a 60 dB SPL masker combined with the 30 dB SPL standard represented a medium-sized difference between masker and standard level (Oberfeld, 2008). For each level combination, we compared the effect of an ipsilateral and a contralateral masker. Presenting the masker contralaterally was expected to result in release from masking,[1] that is, in smaller DL-elevations compared to conditions with ipsilateral masker.

2. Method

2.1. Subjects

Ten students at the Johannes Gutenberg – Universität Mainz participated in the experiment voluntarily (6 females, 4 males; aged 20–28 years). They either received partial course credit or were paid for their participation. All listeners reported normal hearing. Detection thresholds measured by Békésy tracking (Békésy, 1947; Hartmann, 2005) with pulsed 270-ms tones including 10-ms $\cos^2$ on- and off-ramps were better than 20 dB HL between 125 Hz and 8 kHz, for both ears. Listener were screened for having target detection thresholds below 20 dB SPL in all conditions presenting a forward masker, to ensure that all target tones in the intensity discrimination task were presented at levels at least 10 dB above absolute threshold. Once the topic of the study and potential risks had been explained to them, all participants gave written informed consent according to the Declaration of Helsinki. They were uninformed about the experimental hypotheses. The study was approved by the ethical review board of the Department of Psychology at the Johannes Gutenberg-Universität Mainz.

2.2. Stimuli and apparatus

The target and the masker were 500-Hz pure tones with a steady-state duration of 20 ms. The tones were gated on and off

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[1] The term “masking” is often – and somewhat imprecisely – used to imply masking of *detection*, and the term “release from masking” often designates better detection performance. We did not study detection but intensity discrimination, and use the term “release from masking” to describe better intensity resolution. In other words, we are studying release from masking in the analysis of a suprathreshold signal (e.g., Hall and Grose, 1992; Ihlefeld and Shinn-Cunningham, 2008).

with 5-ms cosine-squared ramps. Each sinusoid started at zero phase. An increment – that is, a pure tone of the same frequency, duration and temporal envelope – was added in-phase to the standard in one of the observation intervals. Two standard levels (30 and 60 dB SPL) were presented in quiet and combined with a 90 dB SPL forward masker. The 30 dB SPL standard was additionally presented combined with a 60 dB SPL masker. The silent interval between masker offset and standard onset was 100 ms, measured between zero-voltage points. The temporal interval between the onsets of the two target tones (standard and standard-plus-increment) was 800 ms. The standard was presented binaurally with an ITD of +500 μs (i.e., the waveform presented to the right ear started 500 μs earlier than the signal to the left ear). This value corresponds to an interaural phase difference (IPD) of 90°. The standard was perceived as lateralized to the right side of the head (see Section 3.1). According to the literature on the binaural masking-level difference (BMLD) in detection thresholds (pioneered by Hirsh, 1948; Licklider, 1948) this signal would be described as $S_{\pi/2}$. The masker was presented binaurally with an ITD of either +500 μs or −500 μs. As a consequence, the masker was either perceived as lateralized to the same (right) side of the head as the standard (ipsilateral masker; $N_{\pi/2}S_{\pi/2}$), or as lateralized to the other (left) side (contralateral masker; $N_{-\pi/2}S_{\pi/2}$). The interaural level difference (ILD) was adjusted individually so that tones with an ITD of 0 μs would have been lateralized in the center of the head (see Section 2.3.3).

A trial started with a visual attention signal that was on for 300 ms, followed by a blank interval of 500 ms, and then the onset of the first tone (forward-masked trials: masker; in quiet: target). The targets (standard and standard-plus-increment) were also marked by light-emitting diodes (LEDs). LED 1 was switched on 10 ms before the onset of the target in Interval 1 and switched off 10 ms after its offset and LED 2 marked the target presented in the second interval in exactly the same way. The silent interval between the offset of the last signal from the preceding trial to the onset of the first signal of the following trial was 2000 ms, with the restriction that the next trial never started before the response and the feedback to the preceding trial had been given. Visual trial-by-trial feedback was provided. The stimuli were generated digitally, played back via two channels of an RME ADI/S D/A converter (f_s = 44.1 kHz, 24-bit resolution), attenuated by a TDT PA5 programmable attenuator, buffered by a TDT HB7 headphone buffer, and presented to both ears via Sennheiser HDA 200 circumaural headphones calibrated according to IEC 318 (1970). The experiment was conducted in a double-walled sound-insulated chamber.

2.3. Procedure and experimental conditions

2.3.1. Intensity discrimination task

Intensity difference limens were measured using a two-interval, two alternative forced-choice task (2I, 2AFC) and an adaptive procedure with a 3-down, 1-up rule (Levitt, 1971). On each trial, there were two observation intervals. An intensity increment was added to the standard in one of the intervals (selected randomly). Listeners selected the interval containing the louder tone (that is, the standard-plus-increment).

In the adaptive procedure, the initial level of the intensity increment, expressed in terms of $10\log_{10}(\Delta I/I)$, where ΔI is the intensity difference between the standard-plus-increment and the standard, was 8 dB. The step size was 5 dB until the fourth reversal, and 2 dB for the remaining reversals. A track ended when 12 reversals had been obtained or when 70 trials had been presented, whichever occurred first. The arithmetic mean of $10\log_{10}(\Delta I/I)$ from the fifth reversal up to the last even-numbered reversal was taken as the difference limen corresponding to 79.4% correct. A track was discarded if the standard deviation of $10\log_{10}(\Delta I/I)$ at the counting reversals was greater than 6 dB. For each listener and for each standard level × masker level × masker lateralization combination, at least six blocks were obtained, in separate sessions. The order of conditions was randomized in each session. Time permitting, additional blocks were run if the standard deviation of the DLs estimated in the first six blocks exceeded 5 dB.

The data from the discrimination task were analyzed in terms of the DL-elevation, which denotes the difference between the DL (expressed as $10\log_{10}\Delta I/I$) under masking and the DL in quiet. For a given listener and condition, DL estimates exceeding an interval determined by adding 1.5 times the interquartile range to the upper and lower quartiles were classified as outliers (Lovie, 1986), resulting in the exclusion of at most two data points per listener and condition. For data analysis we conducted repeated-measures (rm) ANOVAs using a univariate approach with Huynh–Feldt correction for the degrees of freedom (Huynh and Feldt, 1976). The correction factor $\tilde{\varepsilon}$ is reported, and partial η^2 is reported as measure of association strength. The same type of ANOVAs was conducted for the other tasks. We used an α-level of 0.05 for all analyses.

2.3.2. Detection task

The sound pressure level needed to detect the standards presented in the discrimination task in quiet and under forward-masking was measured using essentially the same procedure as for the discrimination task. There was no masker in the in-quiet condition, and a forward masker was presented in both intervals. In one of the two observation intervals (selected randomly) the signal (500 Hz, 30 ms including 5 ms ramps, ITD = +500 μs) was presented. The other interval contained no signal. The level of the signal was adjusted by a 3-down, 1-up adaptive rule. Listeners selected the interval containing the signal and were instructed to ignore the maskers. The initial signal level was 30 dB SPL. The step size was 8 dB until the fourth reversal, and 2 dB for the remaining eight reversals. The arithmetic mean of the signal levels at the final eight reversals was taken as the detection threshold corresponding to 79.4% correct. For each listener, five blocks were presented for each of the five conditions (in quiet, with ipsi- or contralateral 60 dB SPL forward masker, with ipsi- or contralateral 90 dB SPL forward masker), in separate sessions. The order of conditions was randomized in each session. A block was discarded if the standard deviation of the signal levels at the eight final reversals was greater than 6 dB. The same procedure for outlier detection as in the discrimination task was used, also resulting in the exclusion of at most two data points per listener and condition.

2.3.3. Measurement of perceived lateralization

As a manipulation check, the perceived lateralization of the tones was measured in session 3. First, for a 500 Hz, 60 dB SPL tone with an ITD of 0 μs, the ILD corresponding to lateralization exactly in the center of the head was determined via an adaptive procedure. On each trial, the listener responded whether he or she heard the tone to the left or to the right of the center of the head. The ILD was adjusted by a simple up-down adaptive rule (Levitt, 1971). Three such blocks were run, and the individual average ILD from these blocks was used for the main experiment (discrimination task and detection task).

The individual ILD was also used in the remaining blocks in session 3, in which the listener rated the lateralization of the tones on a 41-point scale ranging from −20 (left ear) to +20 (right ear) (cf. Zhang and Hartmann, 2006). The scale was presented as 41 horizontally oriented radio buttons on the computer screen. The same stimuli as in the intensity discrimination task were presented (but without an intensity increment). For example, a pair of 60 dB SPL tones corresponded to an intensity discrimination trial for a 60 dB SPL standard in quiet. The same pair of tones was presented three times, and then ratings of the perceived lateralization were obtained. We presented 30 and 60 dB SPL tones in quiet, each with ITDs of -500, 0, and $+500$ μs. As a control condition, the tones were additionally presented monaurally, either to the left or to the right ear. Three ratings were obtained per condition, in random order.

Next, the six different standard level × masker level × masker lateralization combinations from the intensity discrimination task were presented. Again, the listeners heard three identical trials corresponding to the stimulus constellation of the intensity discrimination task under forward-masking, one after another. After these three trials, they first rated the perceived lateralization of the target tones, and then the perceived lateralization of the maskers. Three ratings were obtained per condition, in random order.

2.4. *Sessions*

Each listener participated in a total of nine experimental sessions, each with a duration of approximately 55 min. In sessions 1–3, practice blocks for all conditions in the intensity discrimination task and the detection task were run. Additionally, audiometric thresholds were measured in session 1. In session 3, an individual ILD was determined and the participants provided ratings of the lateralization of the tones in the different ITD conditions.

In sessions 4–9, intensity DLs were measured (one block per condition, random order). Additionally, in sessions 4–8, detection thresholds were obtained (one block per condition, random order).

3. Results

3.1. *Perceived lateralization*

Fig. 1 displays the average lateralization ratings obtained in session 3. Panel A shows the results for tones presented in quiet (i.e., without forward maskers). The variation in ITD had the expected effect on the perceived lateralization. A two-factorial rmANOVA with the within-subjects factors ITD and standard level showed a significant effect of ITD, $F(2, 18) = 85.34$, $p < 0.001$, $\tilde{\varepsilon} = 0.572$, $\eta^2 = 0.91$, no significant effect of standard level, $F(1, 9) = 0.10$, $p = 0.756$, and no significant interaction, $F(2, 18) = 0.34$, $p = 0.718$. Panel A also shows that the ITD-induced changes in lateralization were weaker than the lateralization difference caused by presenting the target monaurally either to the left or to the right ear.

Fig. 1, panel B shows the differences between the lateralization ratings of masker and target for each masker level × standard level × masker ITD combination. Note that the ITD for the standard was fixed at $+500$ μs. The difference between the lateralization rating for standard and masker was analyzed by a two-factorial rmANOVA with the within-subjects factors level combination (i.e., all three combinations of standard level and masker level) and masker ITD. There was a significant effect of masker ITD, $F(1, 9) = 266.40$, $p < .001$, $\eta^2 = 0.97$. Neither the effect of level combination, $F(2, 18) = 1.31$, $p = 0.294$, nor the interaction between level combination and masker ITD was significant, $F(2, 18) = 0.42$, $p = 0.666$. As a post-hoc test, six paired-samples *t*-tests between the lateralization ratings for the standard and the ratings for the masker were computed, using a sequentially acceptive step-up Bonferroni procedure (Hochberg, 1988). These tests showed that for all maskers presented with the same ITD as the target ($+500$ μs) the perceived lateralization of the masker and the standard did not differ significantly at an α-level of 0.05. In contrast, for all maskers presented with an ITD of -500 μs, the lateralization of masker and standard differed significantly. These analyses demonstrate that the variations in the masker ITD had the intended effect of causing significant differences in lateralization between masker and standard, for all masker-standard level combinations.

3.2. *Intensity resolution*

Fig. 2, Panels A and B display the mean DL-elevations for the six masker level × standard level × masker lateralization combinations. Table 1 contains the corresponding mean DLs in quiet and under masking. The strongest DL-elevations were observed for a 90 dB SPL masker combined with a 60 dB SPL standard, reflecting the mid-level hump. For each combination of masker and standard level, the DL-elevation was smaller for the contralaterally presented than for the ipsilaterally presented maskers, compatible with the expected release from masking.

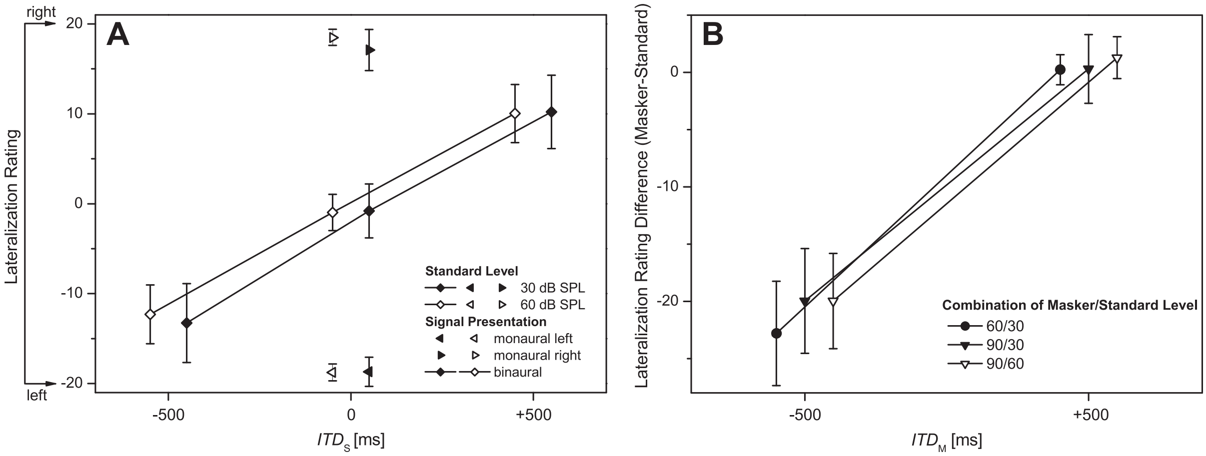

Fig. 1. Panel A: Average ratings of the perceived lateralization of the standard presented in quiet, as a function of ITD, standard level, and presentation mode. Diamonds: binaural presentation. Triangles pointing left and right: monaural presentation to the left or right ear, respectively. Filled symbols: 30 dB SPL. Open symbols: 60 dB SPL. On the vertical axis, the value of -20 represents the endpoint of the scale corresponding to the tone being perceived as lateralized to the left side of the head, and the value of $+20$ corresponds to the tone perceived as lateralized to the right side of the head. Panel B: Average difference of the perceived lateralization between masker and standard, as a function of masker ITD (standard ITD = $+500$ μs), and combination of standard and masker level. Circles: masker level = 60 dB SPL. Triangles: masker level = 90 dB. Filled symbols: standard level = 30 dB SPL. Open Symbols: standard level = 60 dB SPL. Error bars represent 95% confidence intervals (CIs).

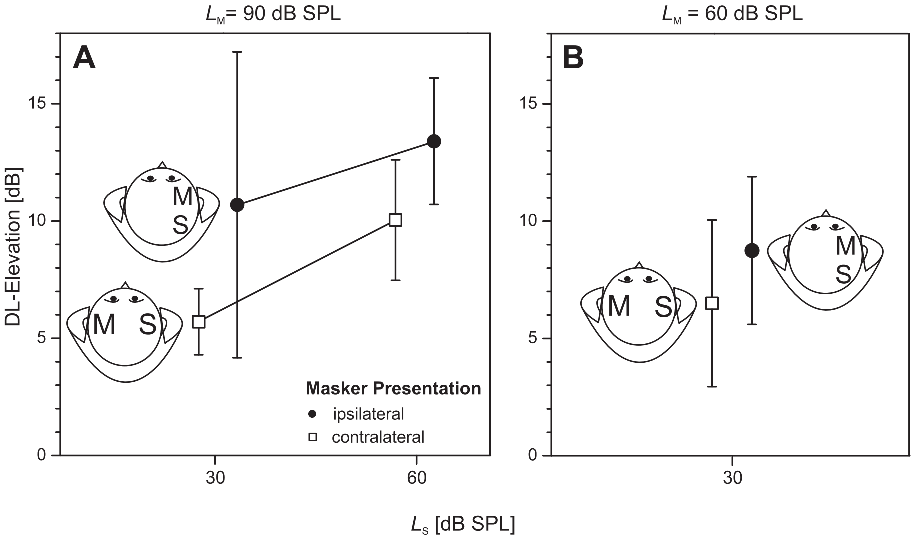

Fig. 2. Mean DL-elevations (i.e., difference between 10 $\log_{10} \Delta I/I$ under masking and in quiet), as a function of standard level (L_S), masker level (L_M) and masker lateralization. Panel A: $L_M = 90$ dB SPL. Panel B: $L_M = 60$ dB SPL. Filled circles: masker *M* perceived as lateralized ipsilaterally to the standard *S* (i.e., at the right ear). Open squares: maskers perceived as lateralized contralaterally (i.e., at the left ear). Error bars represent 95%-CIs.

Two separate repeated-measures ANOVAs were conducted.

For the conditions presenting a 90 dB SPL masker, an ANOVA with the within-subjects factors standard level and masker lateralization showed a significant effect of masker lateralization, $F(1, 9) = 5.61$, $p = 0.042$, $\eta^2 = 0.38$. Compatible with our hypothesis, the DL-elevation was on average 4.17 dB ($SD = 5.57$ dB) higher for the masker lateralized ipsilaterally to the standard than for the masker lateralized contralaterally to the standard, Cohen's (1988) $d_z = 0.75$. Cohen defines values of 0.2, 0.5, and 0.8 as small, medium, and large effects, respectively. The effect of standard level was marginally significant, $F(1, 9) = 5.13$, $p = 0.050$, $\eta^2 = 0.36$, the DL-elevation was more pronounced for the 60 dB SPL standard ($d_z = 0.72$), compatible with the expected mid-level hump. The standard level × masker lateralization interaction was not significant, $F(1, 9) = 0.51$, $p = 0.495$.

The second ANOVA was conducted for the data obtained at a standard level of 30 dB SPL, with the within-subjects factors masker level and masker lateralization. It showed a significant effect of masker lateralization, $F(1, 9) = 5.39$, $p = 0.045$, $\eta^2 = 0.38$. On average, the DL-elevations were 3.62 dB ($SD = 4.93$ dB) higher for the masker lateralized ipsilaterally, $d_z = 0.73$. The effect of masker level was not significant, $F(1, 9) = 0.43$, $p = 0.529$. The interaction was also not significant, $F(1, 9) = 1.02$, $p = 0.338$.

Fig. 3 shows the individual DL-elevations and demonstrates that the effect of presenting the masker contralaterally was rather consistent. Across the 30 combinations of listener and masker-target level combination, the DL-elevation was smaller for the contralateral than for the ipsilateral masker in 22 cases. In six cases the DL-elevation did not differ substantially between the two masker lateralizations, and in two cases the DL-elevation was higher for the contralateral than for the ipsilateral masker. There were some stronger inter-individual differences concerning the size of the DL-elevation and the size of the binaural release from masking in the intensity discrimination task. In particular, for listener 4 the DL-elevation caused by the ipsilateral 90 dB SPL masker was very high at the 30 dB SPL target level. Several previous studies also reported that some listeners exhibit such a pattern instead of the mid-level hump found for the majority of listeners (Oberfeld, 2008; Oberfeld and Stahn, in press; Carlyon and Beveridge, 1993; Zeng et al., 1991; Schlauch et al., 1999, 1997). Listener 4 very strongly benefited from the contralateral presentation of the masker. With the contralateral masker, her DL-elevations were comparable to the other listeners, and the DL-elevation was higher for the 60 dB SPL than for the 30 dB SPL target (mid-level hump).

Table 1
Mean intensity difference limens as a function of masker level (L_M), standard level (L_S), and masker lateralization.

	L_M (dB)	L_S (dB)	DL (10 $\log_{10} \Delta I/I$)
In quiet	–	30	−0.54 (0.57)
	–	60	−3.22 (0.52)
Masker ipsilateral	60	30	8.22 (1.86)
	90	30	10.15 (3.34)
	90	60	10.18 (1.49)
Masker contralateral	60	30	5.96 (1.95)
	90	30	5.17 (0.76)
	90	60	6.82 (1.24)

Note: Values in brackets represent the standard deviation.

Taken together, we found a significantly smaller masker-induced DL-elevation for maskers lateralized contralaterally to the targets ($M = 7.41$ dB, $SD = 2.20$ dB) compared to maskers lateralized ipsilaterally ($M = 10.95$ dB, $SD = 5.25$ dB). Across all level combinations, this binaural release from forward-masking in the intensity discrimination task was 3.53 dB ($SD = 3.91$; $t(9) = 2.86$, $p = 0.019$, $d_z = 0.90$).

3.3. *Detection*

Fig. 4 displays the average detection thresholds for all conditions. Averaged across all masker conditions, the detection threshold under forward-masking ($M = 11.98$ dB SPL, $SD = 2.66$ dB) was significantly higher than in quiet ($M = 8.15$ dB SPL, $SD = 1.82$ dB), $t(9) = 5.72$, $p < 0.001$, $d_z = 1.81$.

A two-factorial repeated-measures ANOVA analyzing the detection thresholds under forward-masking did neither show a significant effect of the within-subjects factor masker lateralization, $F(1, 9) = 3.28$, $p = 0.103$, nor of the within-subjects factor masker level, $F(1, 9) = 0.33$, $p = 0.579$. There was also no significant masker level × masker lateralization interaction, $F(1, 9) = 0.001$, $p = 0.971$.

Thus, both types of maskers resulted in slightly elevated detection thresholds but masker lateralization had no effect.

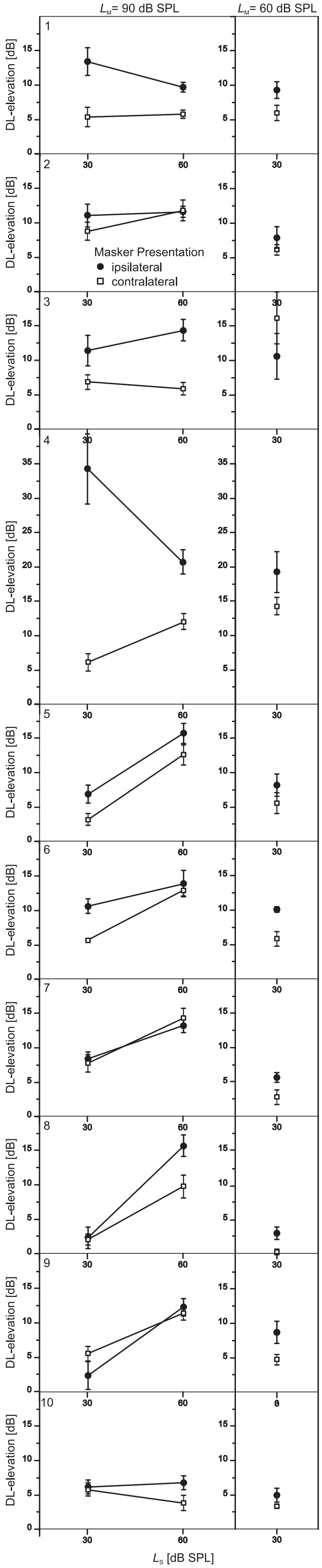

Fig. 3. DL-elevations per listener, as a function of L_S, L_M and masker lateralization. Rows represent listeners. Left panel: $L_M = 90$ dB SPL. Right panel: $L_M = 60$ dB SPL. Filled circles: masker lateralized ipsilaterally to the target. Open squares: masker lateralized contralaterally. Error bars show ±1 standard error of the mean.

4. Discussion

Given the fast recovery of auditory nerve neurons from prior stimulation (e.g., Harris and Dallos, 1979) and the steep slope of psychophysical forward-masking curves (e.g., Wojtczak and Oxenham, 2010) it seems surprising that an intense on-frequency forward masker can have such a substantial effect on the intensity DL for a brief pure tone target even at masker-target ISIs of 100–300 ms (e.g., Zeng et al., 1991; Plack et al., 1995). In our study, the average masker-induced DL-elevation for a 90 dB SPL ipsilateral masker combined with a 60 dB SPL target was 13.4 dB ($SD = 3.77$). This value is comparable to DL-elevations obtained in previous studies presenting maskers and targets with identical spectrum and duration. For example, Plack et al. (1995) found a DL-elevation of about 12 dB for a 1 kHz 80 dB SPL tone masker preceding a 50 dB SPL target. For the same masker level, frequency and masker-target ISI as in Plack et al. (1995), but with tone durations of 100 ms, the data by Schlauch et al. (1999) reflected the large inter-individual differences which are also obvious in our data. They obtained DL-elevations between 5 dB and 15 dB if a 60 dB SPL target was presented and DL-elevations between 5 dB and 25 dB for a 30 dB SPL target. Previous experiments from our lab also found DL-elevations in the vicinity of 12 dB for a 60 dB SPL target presented together with an ipsilateral monaural masker (Oberfeld, 2008; Oberfeld and Stahn, in press). As discussed by Oberfeld (2008), smaller DL-elevations are observed if masker and target differ in spectrum or duration (Schlauch et al., 1997; Zeng et al., 1991).

In the present study, we compared two masking conditions that provided identical input to each ear and therefore did not differ in the activation patterns in the auditory nerve, but at the same time resulted in a spatially separated perception of masker and target. We achieved this by introducing an ITD of the masker that differs from that of the target. The spatial separation was expected to result in a smaller masker-induced DL-elevation. This hypothesis originates from a framework of selective attention. According to this concept, the lateralization difference between masker and target promotes object separation between masker and target. This separation facilitates selective attention to the target, according to research on object-based attention (e.g., Kahneman and Henik, 1981; Scholl, 2001; Best et al., 2008; Alain and Arnott, 2000). In one condition (ipsilateral masker), the masker and the target were perceived as lateralized to the same side, corresponding to a high masker-target similarity and promoting the perception of masker and target as one unitary auditory object. In fact, in previous experiments conducted in our lab (Oberfeld, 2007, 2008, 2009, 2010) listeners frequently reported to perceive the standard as an "echo" of the masker, thus indicating that they perceived both tones as one unitary object. In contrast, when the masker was perceived as lateralized to the other side of the head as the target, the masker-target similarity was reduced, corresponding to a higher probability of perceiving the masker and the target as separate objects. Therefore, we expected the DL-elevation to be smaller with the contralateral than with the ipsilateral masker. Compatible with this hypothesis, we observed a significant release from masking ($M = 3.5$ dB) with the contralateral masker. Because the two conditions differed only in the masker ITD, this effect cannot be attributed to differences in peripheral activity.

The effect of the lateralization difference could be viewed as yet another example that the similarity between masker and standard

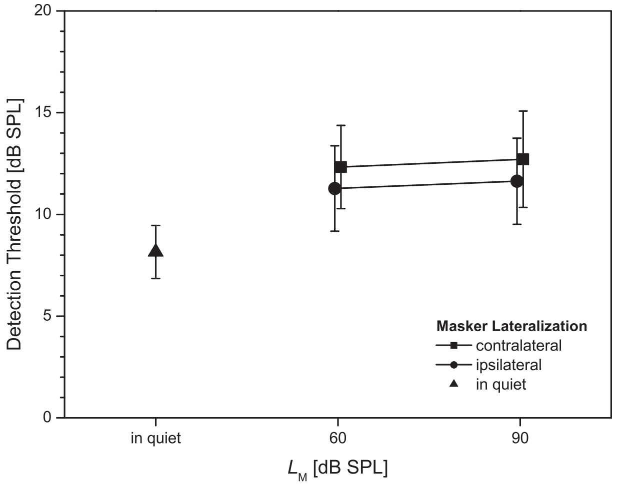

Fig. 4. Mean detection thresholds in quiet and with forward masker levels of 60 or 90 dB SPL. Circles: masker lateralized ipsilaterally to the standard. Squares: maskers lateralized contralaterally. Error bars represent 95%-CIs.

affects the masker-induced DL-elevation (Schlauch et al., 1999, 1997; Oberfeld, 2008). There is of course a strong link between similarity and object formation because according to Gestalt laws similarity is one attribute among others (like proximity) influencing the grouping of elements into one object (for an application to the auditory domain see Kubovy and Van Valkenburg, 2001). The new contribution of the present study is that we observed the effect even when manipulating the similarity of masker and target (in terms of lateralization) while leaving the inputs to the monaural channels unaltered. In previous studies varying for example the masker duration (Schlauch et al., 1997) differences in the representation of the tones in the auditory nerve presented a potential confound of the effect of masker-target similarity on intensity resolution.

In our experiment, the contralateral masker reduced the DL-elevation but did not eliminate it. There are at least two different explanations for this finding. First, both peripheral and central mechanisms are likely to be involved in intensity discrimination under non-simultaneous masking (e.g., Zeng, 1998). Thus, even if the difference in lateralization between masker and target completely eliminated the portion of the DL-elevation caused by central mechanisms like a failure of selective attention, peripheral processes like adaptation in the auditory nerve might still cause an impairment in intensity discrimination. Second, the lateralization difference between masker and standard may simply not have caused the maximum amount of object separation, given that ITD is only one of a variety of grouping cues. Oberfeld and Stahn (in press) induced object separation between masker and standard by sequential streaming or grouping by temporal proximity. Conditions favoring the segmentation of maskers and targets into separate objects resulted in 3–4 dB lower DL-elevations. Thus, the release from masking was comparable to the values observed in the present study.

Three studies compared the effects of an ipsilateral monaural and a binaural forward masker in an intensity discrimination task presenting a monaural target, thus also varying the lateralization of the masker relative to the target. Stellmack et al. (2007) found that a diotic masker resulted in only a weak, non-significant reduction in the DL-elevation compared to an ipsilateral monaural masker. In Experiment 1 by Plack et al. (1995), the DLs measured with the ipsilateral monaural and the diotic forward masker were identical at masker-target ISIs longer than 50 ms while at shorter ISIs the diotic masker produced a *higher* DL-elevation. Schlauch et al. (1999) presented a 93 dB SPL contralateral masker together with an 80 dB SPL ipsilateral masker. Due to the resulting ILD, listeners perceived this binaural masker as contralateral to the target. Compared to an ipsilateral monaural masker, a reduction of the DL-elevation was observed for 20 and 30 dB SPL targets, but not at higher target levels.

There are two possible explanations for these differences to the results obtained in the present study. First, the lateralization difference between the monaural target and the diotic masker may have been smaller than in our condition presenting the contralateral masker. Second and more important, monaural maskers presented to the contralateral ear were reported to produce a significant DL-elevation (Plack et al., 1995; Schlauch et al., 1999). Thus, if a binaural forward masker is combined with a monaural target, then both the ipsilateral and the contralateral masker component can be expected to have an effect on the intensity DL. As a consequence, compared to the ipsilateral *monaural* masker the lateralization difference between the target and the binaural masker may have reduced the effect of the masker, but at the same time the contralateral masker energy may have produced an opposing effect, which supposedly compensated the beneficial effect of the lateralization difference. In fact, in the study by Schlauch et al. (1999) for two of the three subjects the effect of a masker presented to the contralateral ear only was stronger at standard levels where the binaural masker did not produce a reduction in the intensity DL (see their Fig. 2).

From a physiological point of view, the mechanisms responsible for the observed binaural release from forward-masking in the contralateral condition can be assumed to be located in the superior olivary complex (Yin and Chan, 1990) or at later stages.

How do the observed effects relate to the influence of ITD differences between masker and signal on detection thresholds? For detection, a 180° phase shift between the simultaneous masker and the signal (e.g., N_0S_π) results in a detection threshold up to 15 dB lower than in the homophasic condition (N_0S_0) (e.g., Kohlrausch and Fassel, 1994; Buss and Hall, 2011). This BMLD (Hirsh, 1948; Licklider, 1948) in simultaneous masking can be explained by coincidence counters following an internal delay line (Jeffress, 1948; Colburn, 1977), or by an equalization–cancellation process (Durlach, 1963). Surprising at first sight, BMLDs of a few dB are also found in forward-masking where the masker and the signal do not overlap temporally. This effect is observed for masker-signal ISIs up to 100 ms for short signals ($\leq$10 ms; Yama, 1992; Berg and Yost, 1976) but only 2–3 ms after masker offset for longer signals (Kohlrausch and Fassel, 1994). Although the literature is not unequivocal, it seems that the BMLDs observed after masker offset can be attributed to monaural effects (Breebaart et al., 2001), and that a direct binaural interaction exists only when the signal is presented simultaneously with the masker or during the brief ringing of the basilar membrane after masker offset (Kohlrausch and Fassel, 1994). The observed binaural release from forward-masking in the discrimination task of the present study can therefore not be attributed to the exploitation of binaural cues influencing detection thresholds (Yost et al., 1982). This is also reflected in our data by the absence of an effect of masker lateralization on detection thresholds. Given the 30 ms target duration it is also unlikely that an “aftereffect” as reported by Yama (1992) is responsible for the smaller DL-elevation observed with the contralateral masker.

The effect of the masker-target lateralization difference on intensity resolution is compatible with effects of the spatial separation between target and interferers on free field speech reception thresholds (e.g., Hawley et al., 2004). However, in a free field setting a spatial separation between target and masker often results in both an ITD and an ILD (cf. Jones and Litovsky, 2011). Additionally, in a non-anechoic environment reflections can play a role (e.g., Rennies et al., 2011). The proposed origin of the observed effect of masker lateralization is compatible with effects of spatial separation on informational masking (Jones and Litovsky, 2008; Ihlefeld and Shinn-Cunningham, 2008), which by definition also represents the effects of processes beyond the auditory periphery (cf. Durlach et al., 2003). The beneficial effects of spatial separation in a cocktail-party situation (Cherry, 1953) have been attributed to both a release from energetic masking (e.g., a portion of the target speech signal is below the detection threshold owing to spectral overlap of the competing talkers) and a release from informational masking (e.g., Kidd et al., 2005). It is an interesting question whether effects of masking on intensity resolution rather than on detection might play a role for speech intelligibility in the presence of maskers/interferers. The speech signal produced by an interferer at time point t_n can act as a forward masker for the target speech at time point t_{n+1}. The target speech at time point t_{n+1} might still be audible (i.e., above the detection threshold), but the information about the intensity of the target speech at this time point might be impaired by forward-masking. As Rhebergen et al. (2010) pointed out, incorporating effects of non-simultaneous masking in models of speech perception would be desirable.

5. Summary and conclusion

- In an intensity discrimination task, we varied the perceived lateralization of forward masker by means of the ITD.
- Lateralization of the masker to the other side of the head as the target was expected to promote the processing of masker and target as separate objects. According to results on object-based attention, this should facilitate selective attention to the target.
- Compatible with this prediction, the presentation of forward maskers lateralized to the other side of the head as the targets significantly reduced the masker-induced DL-elevation compared to the ipsilateral condition. The average binaural release from forward-masking for the contralateral masker was 3.5 dB.
- As the waveform delivered to the two ears was identical for the conditions presenting ipsilateral and contralateral maskers, the observed release from masking in the intensity discrimination task cannot be explained by mechanisms up to the level of the auditory nerve.

Author contributions

Conceived and designed the experiments: DO. Performed the experiments: DO and PS. Analyzed the data: DO, PS, and MK. Wrote the paper: DO, PS, and MK.

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