Effect of duration and gating of the signal on the binaural masking level difference for narrowband and broadband maskers

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ABSTRACT

Thresholds were measured for a 250-Hz signal with an interaural phase difference of 0 (diotic) or 180° (dichotic), with signal durations of 12 and 60 ms (including 6-ms ramps) and 300 ms (including 6- or 50-ms ramps). The signal-centered diotic noise masker had a bandwidth of 20 or 200 Hz. For the 20-Hz wide masker, the binaural masking level difference (BMLD), i.e., threshold difference between diotic and dichotic signal, increased with signal duration and, for the 300-ms signal, the BMLD was larger with 50-ms rather than 6-ms ramps. These signal parameters hardly affected the BMLD for the 200-Hz wide masker.

Key words: Binaural, bandwidening experiment, off-frequency, duration effects

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1. Introduction

Contradictory results have been presented in the literature on how the binaural masking level difference (BMLD) depends on the masker bandwidth in a bandwidening type of experiment. In this type of experiment, thresholds of a pure-tone signal are measured in the presence of a signal-centered noise masker as a function of masker bandwidth. The present study investigates if the contradictory results are due to differences in the signal parameters used in these studies.

The bandwidening experiment is a classical type of masking experiment (Fletcher, 1940), initially developed to characterize monaural frequency selectivity but later also used to obtain an insight into the frequency selectivity of the binaural system (e.g., Sever and Small, 1979; Hall et al., 1983). Such studies usually measured thresholds in a condition where the signal had an interaural phase difference of 180° (S_π) in the presence of a diotic masker, N_0. For comparison, they also estimated the monaural critical bandwidth by measuring thresholds in a condition where both signal and masker were presented diotically. In the following text, these two interaural phase conditions are conventionally specified as N_0S_0 and N_0S_π and the difference between the thresholds in these two conditions as the BMLD. In most studies, the BMLD decreased as the masker bandwidth increased (e.g., Hall et al., 1983, van de Par and Kohlrausch, 1999). Since this decrease was observed even for bandwidths larger than the auditory filter widths (i.e., the critical bandwidth width derived from the N_0S_0 thresholds) it was initially argued that the effective binaural frequency selectivity was poorer than the monaural frequency selectivity (see also Yama and Robinson, 1982). Later studies hypothesized that the frequency selectivity was the same for monaural and binaural systems and that the smaller BMLD for broadband maskers compared to narrowband maskers reflects an across-frequency process.

According to Hall et al. (1983), binaural detection in an N_0S_π condition with a broadband masker is adversely affected by the information in critical bands around the critical band centered at the signal frequency (indicating no interaural difference), reducing the BMLD for broadband maskers. In contrast to this detrimental across-channel process, van de Par and Kohlrausch (1999) proposed a beneficial across-channel process where the BMLD magnitude for narrowband maskers centered at the signal frequency is increased, since off-frequency information can be used in the narrowband N_0S_π but not in the narrowband N_0S_0 condition or any broadband masking condition.

Recently, Yasin and Henning (2012) published data on the effect of a subtle stimulus change such as masker gating on the BMLD in a bandwidening type of experiment which seem to be at odds with previous results (and hypothesized underlying processes). For the two masking conditions of their study with a longer masker than signal duration, BMLD increased as the masker bandwidth increased, i.e., an effect opposite to that observed in previous studies. Yasin and Henning (2012) suggested this could be due to differences between the signal parameters used in their study compared to previous studies, but this has so far not been explicitly tested.

The present study investigates if the apparently contradicting results in the literature are indeed due to differences in the stimulus parameters. Yasin and Henning (2012) used relatively short signals [total duration of 12 ms including short (6 ms) on- and offset ramps] whilst previous studies used longer signals with longer ramps. For example, Hall et al. (1983) and van de Par and Kohlrausch (1999) used a signal duration of 300 ms and a ramp duration of 50 ms. In order to investigate if differences in the signal parameters were the reason for the seemingly contradictory results between Yasin and Henning (2012) and previous studies, thresholds were measured for a 250-Hz signal with three different durations (12, 60, and 300 ms) including 6-ms cos^2 on- and offset ramps and, for the longest signal duration of 300 ms, also including 50-ms ramps (as in Hall et al., 1983, van de Par and Kohlrausch, 1999). All signals were temporally centered in a 600-ms bandpass-filtered noise masker. If differences in signal parameters are indeed responsible for the seemingly contradictory results in the literature, then the effect of masker bandwidth on the size of BMLD should strongly depend on the signal's overall duration as well as the duration of the ramps.

2. Methods

Masked thresholds were measured for a 250-Hz pure tone target signal in the presence of a masking bandpass-filtered white Gaussian noise that was centered on the signal frequency. The masker bandwidth was either 20 or 200 Hz. The masker spectrum level was 50 dB, i.e., the overall masker level was 63 dB SPL for the 20-Hz wide masker and 73 dB SPL for the 200-Hz wide masker. A 600-ms long sample of bandpass-filtered noise was generated in the frequency domain by transforming a 600-ms Gaussian noise into the frequency domain via a fast Fourier transform and setting all Fourier components outside the desired passband to zero. A subsequent inverse Fourier transform on the complex buffer pair yielded the desired noise waveform. Random noise was used in the experiment, i.e., for each presentation of the masker a new noise sample was generated. The masker was gated on and off with 50-ms cos^2 ramps. The signal was 12, 60, or 300 ms long and temporally centered in the masker. Signals were gated on and off with 6-ms cos^2 ramps. In addition, thresholds were measured for a 300-ms signal with 50-ms cos^2 ramps. The masker was always presented in-phase at the ears (N_0), and the signal was either presented in-phase at the ears (S_0), or 180º out-of-phase at the ears (S_π).

Thresholds were measured with a 3-interval 3-alternative forced-choice procedure. Each of the three intervals contained the masker and one randomly chosen interval also contained the signal. The task of the listener was to indicate the interval containing the signal by pressing the corresponding button on a keyboard. For a given signal frequency, signal amplitude was adaptively varied using a two-down, one-up rule to estimate the 71% correct levels for signal detectability (Levitt, 1971) — two correct responses produced a reduction in signal level, one incorrect response, produced an increase in signal level. Each adaptive run started with a clearly audible signal. The initial stepsize for level changes was 6 dB; for the first sequence of trials where a trial with a false response was followed by two trials with correct responses (called the upper reversal) the stepsize was reduced to 3 dB. After the second upper reversal it was reduced to 1 dB. The adaptive run continued for another six reversals with the 1-dB stepsize. A threshold was estimated as the mean of the levels obtained at the six final reversals. For each signal, thresholds were measured at least four times. The average of the threshold estimates of the last three repetitions was taken as the threshold for this signal condition for the listener. The trials of the other repetitions were taken as practice trials. For each of the last three repetitions, the order of the runs for the different signal conditions (total eight conditions: two signal phase conditions x four combinations of signal duration and gating window) were randomized.

A total of ten normal-hearing listeners participated and were tested individually in sound-attenuating booths. Signals were generated digitally at a sampling frequency of 44.1 kHz. They were converted from digital to analogue signals and via an external sound card (RME Fireface 400, Haimhausen, Germany) and presented via Sennheiser HD650 headphones that were calibrated using Bruel & Kjaer artificial ear type 4153 and driven in phase.

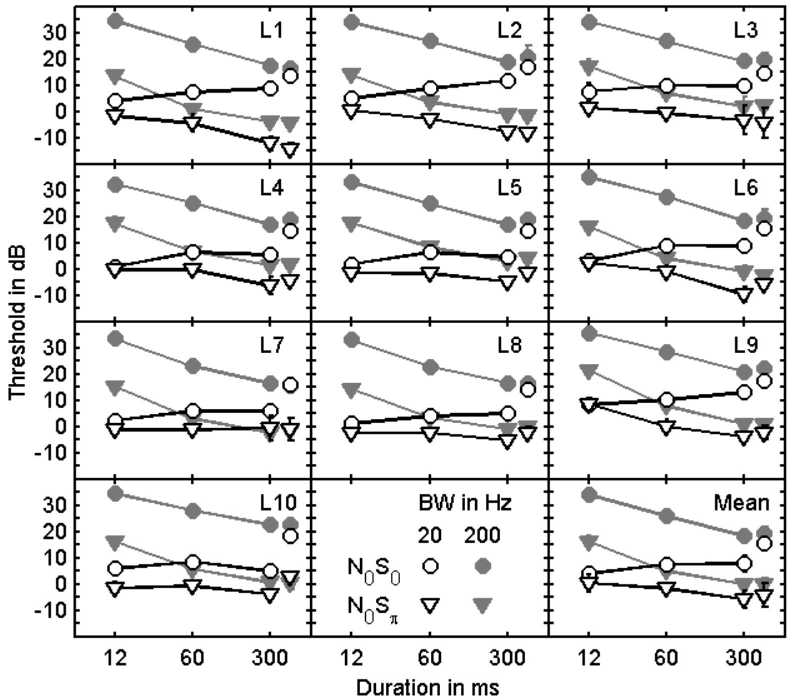

Fig. 1: *Thresholds as a function of signal duration for a 250-Hz signal embedded in a bandpass-filtered noise centered on the signal frequency. N_0S_0 and N_0S_π thresholds are shown with circles and downward pointing triangles, respectively. Errorbars indicate plus and minus one standard deviation. They are only shown if they are larger than the marker (indicating the threshold). Gray-filled symbols indicate data for a masker bandwidth BW of 200 Hz and black open symbols those for a 20-Hz wide masker. Thresholds values are expressed as levels in dB relative to the masker spectrum level (50 dB). Thresholds connected to each other with a solid line are those where the signal had the same ramp duration of 6 ms. The far right (disconnected) thresholds are obtained for a 300-ms signal with 50-ms ramps at signal on- and offset. The four rows present individual data per panel. In addition, the middle and right-most panel of the bottom row show the symbol legend and mean data (average across listeners), respectively.*

3. Results and discussion

Figure 1 shows thresholds as a function of the signal duration, expressed relative to the masker spectrum level (50 dB). Except for the bottom middle and right-most panels, each panel shows individual data. The middle and right-most panel of the bottom row show the symbol legend and mean data (average across listeners) respectively. Different symbols indicate different conditions as shown in the legend. Per panel, data points connected with a solid line indicate thresholds for signal durations with 6-ms ramps, the unconnected data points on the far right of each panel indicate thresholds for a 300-ms signal with 50-ms ramps. For better readability, these latter data points are shifted slightly to the right.

For all listeners, N_0S_0 and N_0S_π thresholds for the 200-Hz wide masker (gray symbols) decrease as signal duration increases. On average, for the 200-Hz masker, the threshold for both N_0S_0 and N_0S_π conditions decreases by 16 dB, when the signal duration is increased from 12 to 300 ms. For the 20-Hz wide masker, the pattern of results differed considerably from those for the 200-Hz wide masker. For the 20-Hz masker, in general, N_0S_π thresholds for signals with 6-ms ramps (connected symbols of downward-pointing open triangles in Fig. 1) slightly decrease as signal duration increases but the decrease is less pronounced than for the corresponding data with the 200-Hz wide masker. For listener L7, signal duration hardly affects thresholds for the signals with 6-ms ramps. For all listeners, the slope of the N_0S_π threshold curve with a 20-Hz masker is less steep than for the corresponding threshold curve for the 200-Hz wide masker (connected symbols downward-pointing filled gray triangles in Fig. 1). The same trend is observed in the average data (bottom right panel).

Increasing the ramp duration for the 300-ms signal from 6 ms to 50 ms in the presence of a 20-Hz masker results in an increase in N_0S_π threshold for some listeners (L4-L6, L8-L10) and a slight decrease or no change for others (L1-L3, L7). On average, the difference between the N_0S_π thresholds for the 300-ms signals with 6-ms and 50-ms ramps is 1.5 dB.

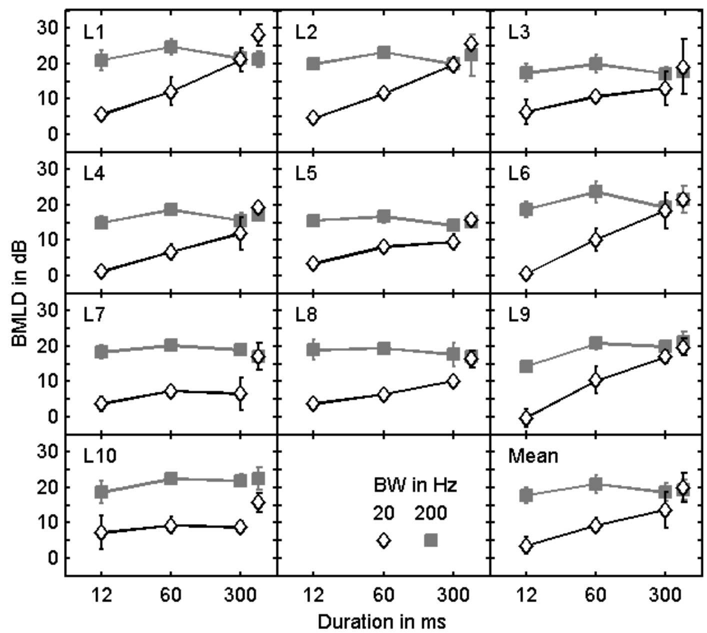

Fig. 2: *The difference in thresholds for the two interaural conditions, i.e., the BMLD. Different symbols indicate different masker bandwidths: 20 Hz (open diamonds) and 200 Hz (filled gray squares). Errorbars indicate the plus and minus one standard deviation. As in Fig.1, the four rows present individual data per panel. In addition, the middle and right-most panel of the bottom row show the symbol legend and mean data (average across listeners), respectively.*

For all listeners, N_0S_0 thresholds for the 20-Hz wide masker (open circles) increase as the signal duration is increased from 12 ms to 60 ms. Some listeners (L2, L9) also show a threshold increase as signal duration is increased from 60 ms to 300 ms (with 6-ms ramps) but for most listeners these two thresholds are similar. On average, the 12-ms N_0S_0 threshold is 3.5 dB lower than the 60-ms N_0S_0 threshold and the same threshold of 58 dB SPL is obtained for the 60-ms and 300-ms signals with the same ramp duration. Increasing the ramp duration raises individual thresholds for all listeners. On average, for the 20-Hz masker, N_0S_0 thresholds for the 300-ms signal with 50-ms ramps are 8 dB higher than those for the 300-ms signal with 6-ms ramps.

Figure 2 shows the individual and average BMLD data for the ten listeners. Kohlrausch (1990) concluded on the basis of his own data and data in the literature, that “shortening the test signal has only a minor influence on the BMLD, if the masker duration is not changed.” For a 200-Hz signal and a broadband masker, Kohlrausch (1990) measured about the same BMLD for 20 and 250 ms signals (and a masker duration of 500 ms), when the data were averaged across the two listeners who participated in the experiment. The present data for the 200-Hz wide masker is in agreement with this finding: Since about the same slope of the average threshold curves for the 200-Hz wide masker (see gray symbols in bottom right panel of Fig.1) was measured for the N_0S_0 and N_0S_π conditions, the average BMLD hardly depends on the signal duration (gray symbols in bottom right panel of Fig. 2). In general, this is also observed in the individual data. Two subjects show a slight decrease in BMLD as signal duration is decreased from 60 to 12 ms. None of the listeners of the present study showed a slight increase in BMLD for shorter signals observed in some previous studies (e.g., Bernstein and Trahiotis, 1998, for 500 Hz). An increase in ramp duration leads to a subtle increase of the BMLD for the 200-Hz wide masker for most listeners (L2-L6, L9-L10). The other listeners show a slight decrease in BMLD. On average, the ramp duration does not affect the BMLD for the 200-Hz wide masker (difference < 1 dB). In contrast, both signal parameters (overall duration and ramp duration) affects the BMLD for the 20-Hz wide masker. For this masker width, the BMLD tends to increase as signal duration increases and is larger for the 300-ms signal with 50-ms ramps than for the 300-ms signal with 6-ms ramps. The average difference in BMLD for these two signals and a masker bandwidth of 20 Hz is 6 dB.

The values of the BMLD were analyzed using a within-subject Analysis Of Variance (ANOVA, Girden, 1992). In order to investigate the effect of masker bandwidth on detectability of signals of different durations the ANOVA was conducted on the values of BMLD with main factors of masker noise bandwidth (20 and 200 Hz) and signal duration (12, 60 and 300 ms). Mauchly's Test of Sphericity was shown to be significant and since the value of Epsilon was < 0.75 (Girden, 1992) the Greenhouse-Geisser correction was applied to adjust the degrees of freedom in the resultant ANOVA. There was a significant effect of noise bandwidth [$F_{(1,9)}$ = 277.78, $p < 0.001$ (two-tailed), with effect size, $\eta^2 = 0.97$], signal duration [$F_{(2,18)}$ = 28.83, $p <$ 0.001 (two-tailed)], with effect size, $\eta^2 = 0.76$], and a significant interaction between noise bandwidth and signal duration [$F_{(2,18)}$ = 22.97, $p < 0.001$ (two-tailed), with effect size, $\eta^2 = 0.72$]. Post hoc paired *t*-tests (Bonferroni corrected) revealed that, for the 20-Hz masker bandwidth, the BMLD progressively increased as signal duration increased. The BMLD was significantly greater for the 60-ms signal compared to the 12-ms signal [$t_{(9)}$ = 6.74, $p < 0.001$ (two-tailed)], for the 300-ms signal compared to the 60-ms signal [$t_{(9)}$ = 4.10, $p < 0.01$ (two-tailed)] and also for the 300-ms signal compared to the 12-ms signal [$t_{(9)}$ = 5.56, $p < 0.01$ (two-tailed)]. For the 200-Hz masker bandwidth, the BMLD was significantly greater for the 60-ms signal compared to the 12-ms signal [$t_{(9)}$ = 4.61, $p < 0.01$ (two-tailed)] and 60-ms signal compared to the 300-ms signal [$t_{(9)}$ = 5.86, $p < 0.01$ (two-tailed)]. The BMLD obtained with the 12-ms or 300-ms signal was similar; there was no significant difference in the BMLD.

In order to investigate the effect of increasing ramp duration (50-ms vs. 6-ms $\cos^2$ ramps) for the 300-ms signal, a within-subject ANOVA was conducted on the values of BMLD with main factors of masker bandwidth (20 and 200 Hz), signal ramp duration (300 ms with 6-ms $\cos^2$ ramps and 300 ms with 50-ms $\cos^2$ ramps). There was a significant effect of signal ramp duration

[$F_{(1,9)}$ = 175.30, $p < 0.001$ (two-tailed), with effect size, $\eta^2 = 0.95$] but no significant effect of masker bandwidth. There was a significant interaction between signal ramp duration and masker bandwidth [$F_{(1,9)}$ = 88.51, $p < 0.01$ (two-tailed), with effect size, $\eta^2 = 0.75$]. Post hoc paired *t*-tests (Bonferroni corrected) revealed that for the 20-Hz masker bandwidth the BMLD was significantly greater when the 300-ms signal was presented with longer 50-ms ramps compared to shorter 6-ms ramps [$t_{(9)}$ = 8.71, $p < 0.001$ (two-tailed)]. For the 200-Hz masker bandwidth there was no significant difference in the BMLD obtained for a 300-ms signal with 6-ms or 50-ms ramps.

For the 12-ms signal, all listeners of the present study showed at least a 10 dB smaller BMLD for the 20-Hz wide masker than for the 200-Hz wide masker. For this signal duration and a long masker, Yasin and Henning (2012) measured a similar large increase in BMLD as masker bandwidth was increased from 20 to 200 Hz. For the 300-ms signal with 50-ms ramps, a subset of listeners (L1, L2, L4) show the opposite effect, i.e., a decrease in BMLD as the masker bandwidth is increased, in agreement with the BMLD results of most other studies using a bandwidening type of experiment (e.g., Hall et al., 1983, van de Par and Kohlrausch, 1999). Thus, both seemingly contradicting results concerning the effect of masker bandwidth on the size of the BMLD can be measured within the same listener. This indicates that the difference between the results with long maskers in Yasin and Henning (2012) and those of previous studies are indeed largely due to differences in the signal parameters. The reason for the effect of duration and signal gating on the size of the BMLD for the narrowband masker of the present study is presumably due to the spectral splatter (see e.g., Wightmann, 1971). Due to the spectral splatter for the short signal duration (and long masker duration) the signal-to-noise ratio is likely to be larger in off-frequency compared to on-frequency critical bands. Masking pattern experiments have shown that the BMLD is strongly reduced when the signal is detected in an off-frequency masking condition (e.g., Zwicker and Henning, 1984). Nitschmann and Verhey (2012) argued that this reduced off-frequency BMLD was due to beating cues that are available for monaural detection (by processing them with a modulation filterbank) but not binaural detection. For the short signal of the present study masked by an on-frequency narrowband masker, modulation cues may also play a role, not as beating cues but as an additional signal envelope cue that may be used for monaural detection in the off-frequency channels. This may also explain the effect of different signal ramp durations at the longest signal duration (short signal ramps may excite the modulation filters in the off-frequency channels).

Interestingly, our average result for the long signal with long ramps seems to indicate that the BMLD is the same for the 20-Hz and 200-Hz wide masker. This is presumably due to the group of listeners that participated in the present study. For the 20-Hz wide masker, they show substantial individual differences in the size of the BMLD for the signal with the longest overall duration and ramp duration. Large individual differences for narrowband maskers have already been reported in the literature (e.g., Buss et al., 2007).

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