# A comparison of detection and lateralization of interaurally time-delayed signals in the presence of diotic masking noise

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# A COMPARISON OF DETECTION AND LATERALIZATION OF INTERAURALLY TIME-DELAYED SIGNALS IN THE PRESENCE OF DIOTIC MASKING NOISE

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## ABSTRACT
Detection of a signal in the presence of diotic masking noise is much better when the signal differs in terms of its interaural parameters from the masking noise. Besides contributing to the detectability of a signal, interaural time delays (ITDs) also allow the listener to lateralize the signal. In this study, we investigate how detection and lateralization of time-delayed signals are affected by the diotic masking noise. All stimuli covered a spectral range from 250 to 850 Hz. The interaurally time-delayed signals consisted either of noise, or a tone-complex with 20 Hz intercomponent spacing. ITDs were 0.1 or 0.6 msec. Results show that detection performance is strongly dependent on the ITD with a 10 dB increase in threshold going from 0.6 to 0.1 msec ITD. Interestingly, lateralization thresholds, although being higher than detection thresholds, are much less dependent on ITD; only a few dB change in threshold is observed. An additional ITD adjustment experiment was performed where the ITD of a tone complex in isolation had to be adjusted to an ITD tone-complex presented in diotic and roving-ITD masking noise. Listeners were able to perform this adjustment reliably suggesting that in the noise, the tone complex effectively functions as a segregated object.

## INTRODUCTION
In many daily settings, sound sources are not occurring in isolation, but are rather heard against a background of competing sounds. It is of interest to learn how the binaural system contributes to auditory perception in these situations. Studies on binaural masking have shown that the *detection* of the presence of a target sound can be considerably improved when the target is presented with different interaural parameters than the masking sound. Detection thresholds can be as much as 25 dB lower when listening with two ears instead of one ear only [6, 3].

The largest binaural advantage of 25 dB is typically obtained with diotic maskers and interaurally out-of-phase targets ($N_0S_\pi$) that are narrowband and the cue for detection of the target is often described as a spatial image widening. Such a cue differs considerably from the percept that is associated with the target heard in isolation. It is therefore important to make a distinction between *detecting* that some target signal is present and being able to *discriminate* between two target signals because it requires to perceive some of the characteristics of the target signal.

In an earlier study [4], we determined threshold levels for which interaurally out-of-phase harmonic tone complexes with fundamental frequencies in the range from 20 to 80 Hz, and interaurally out-of-phase noise signals could be discriminated in the presence of a diotic noise masker. We found that discrimination thresholds were about 4 dB higher than $N_0S_\pi$ detection thresholds for the individual targets. These discrimination thresholds were clearly lower than the monaural detection threshold, which indicates that listeners were able to discriminate the two targets binaurally at a signal-to-noise ratio for which the targets were not detectable based on monaural hearing. This suggests that the binaural internal representation is rich enough to allow discrimination between the different temporal structures of the target noise and the target tone complex. The good performance was only observed for wide band maskers and targets and only possible when the two target signals had a clearly different temporal structure. For narrow band maskers, hardly any binaural advantage was found and also for random-phase tone complexes, discrimination thresholds were high.

In a more recent study [5] we investigated whether the binaural display provides sufficient information to hear the lateralization based on Interaural Time Delays (ITDs) of a harmonic tone complex target signal that is presented simultaneously with a noise signal. The experiment was designed such that the two signals covered the same spectral range and that the long term cross correlation function of the combined signals always peaked at zero. Due to the peakedness of the tone complex, the ITD of the tone complex dominated the stimulus at its peaks, while at other moments the ITD of the noise dominated the stimulus. Thus, in order to be able to hear the lateralization of the target, the listener had to rely on processing of the dynamically changing pattern of ITDs and somehow link these to the target.

As in the previous study investigating the discrimination between different target signals based on binaural interaction [4], the more recent lateralization study [5] showed that also lateralization was only possible for wide band targets and maskers and also required that the temporal structures of target and masker were sufficiently different.

Two questions could not be answered in the previous lateralization study. Lateralization thresholds were measured at a signal-to-noise ratio of zero dB. Therefore it is not known what the lowest signal-to-noise ratio is at which listeners can hear the lateralization of the target. The first experiment will determine signal-to-noise ratios for which lateralization is still possible.

A second question is whether listeners can also determine the lateralization *extent* of the target signal. If listeners are able to hear the lateralization extent of a target in the presence of a noise masker, this would be support for the idea that target and masker are indeed perceptually segragated. This question will be adressed in the second experiment.

## EXPERIMENT I: LATERALIZATION THRESHOLDS

In order to determine the threshold signal-to-noise ratios at which a target can be lateralized in the presence of a noise masker, lateralization thresholds were measured for two target ITDs, 0.6 and 0.1 ms. Besides determining lateralization thresholds, also ITD detection thresholds ($N_0S_\tau$) for the time delayed targets were measured as a well as diotic detection thresholds ($N_0S_0$).

### Method and Stimuli

For the lateralization threshold measurements, a 3-Interval Forced Choice (3-IFC) procedure was used where target levels were adapted with a 2-down 1-up adaptive tracking procedure. Initial step sizes were 8 dB, after each second reversal, the step-size was halved until it was 1 dB. For this step-size, an additional 8 reversals were measured which were used to determine the median which served as the threshold value. For each condition, 4 thresholds were determined and averaged to serve as the value reported in this paper.

In the 3-IFC procedure for measuring lateralization thresholds, reference intervals contained a target with an ITD leading in the left ear, while the test interval had a target ITD leading in the right ear. Almost the same procedure was used to measure ITD detection thresholds ($N_0S_\tau$), except that now the two reference intervals only contained the noise masker. For the diotic detection threshold ($N_0S_0$), also only the test interval contained the target, but now it was a diotic target.

Both target and maskers were 600-Hz wide and centered around 550 Hz. Diotic Gaussian-noise maskers were used at a presentation level of 65 dB SPL. Targets were either Gaussian noise or harmonic tone complexes with an inter-component spacing of 20 Hz covering the specified spectral range. Starting phases of the sinusoidal components were in sine phase. Two ITD values were used for the targets, 0.6 and 0.1 ms. Both masker and target had a duration of 400 ms and had raised-cosine on- and offset ramps of 30 ms.

In Fig. 1 the results of the first experiment are shown. As can be seen, thresholds are highest for the $N_0S_0$ condition, while for $N_0S_\tau$ considerably lower thresholds are obtained. The lower thresholds in the latter condition are in line with the idea that interaural differences resulting from the addition of the interaurally time delayed signal improve the detectability of the target. As can be seen thresholds are considerably lower (around 10 dB) for an ITD of 0.6 ms as compared to an ITD of 0.1 ms, consistent with the idea that a larger ITD in the target signal results in stronger interaural differences in the target-plus-masker signal, making detection easier.

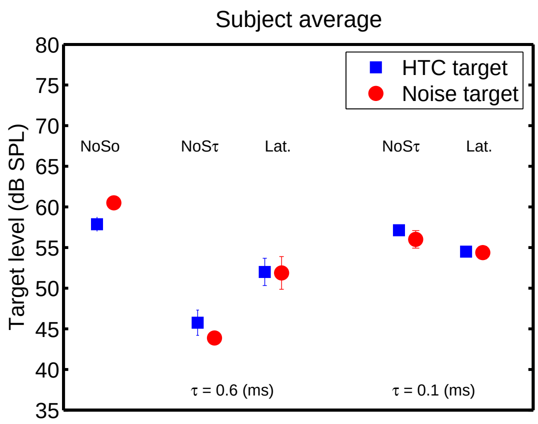


Figure 1: Average thresholds for three subjects for harmonic tone complex (squares) and noise (circles) targets. $N_0S_0$ and $N_0S_\tau$ represent detection thresholds for diotic and interaurally time delayed targets, respectively. "Lat." respresents lateralization thresholds for interaurally time delayed targets. Two conditions with ITDs of 0.6 ms (left side) and 0.1 ms (right side) are shown. Error bars indicate averages of within-subject standard deviations.

Lateralization thresholds for an ITD of 0.6 ms are considerably higher than the corresponding detection thresholds. Apparently, it is much easier to hear the presence of an interaurally delayed target than hearing its laterality. Interestingly, for an ITD of 0.1 ms, lateralization thresholds are only marginally higher (2 to 3 dB) than for an ITD of 0.6 ms. A possible explanation for the relatively high lateralization thresholds is the phase interaction between masker and target. When the situation is considered that the masker is much higher in level than the target and we observe the stimulus at the output of a narrow-band auditory filter, the stimulus interaural phase resulting from the target ITD is inverted in sign when target and masker are momentarily in opposite phase. This phase inversion occurs about half the time. Therefore, the average lateralization of the target plus masker is zero. Only when the target is of sufficient level as compared to the masker, the average localization will point in the direction of the target ITD. In line with this explanation, lateralization detection performance depends rather on the signal-to-noise ratio than on the target ITD.

The attentive reader may have noticed that the lateralization thresholds for an ITD of 0.1 ms are lower than the corresponding detection thresholds. This seems to be counterintuitive because, when a signal cannot be detected, one would not expect a listener to be able to lateralize it. These thresholds can, however, not be directly compared. For the $N_0S_\tau$ detection threshold, the test interval is lateralized to the right, while the reference intervals are diotic, i.e. centered in the middle. For the lateralization threshold measurement, the reference intervals contain the target with opposite ITD as compared to the test interval. Thus the change in lateralization is twice as large, and thresholds turn out to be somewhat lower. The reason for presenting the target to both the test and the reference intervals with equal but opposing ITDs, is to make sure that monaural cues or changes in correlation by itself cannot be used to select the test interval.

A comparison between the two target types, harmonic tone complex and noise, did not show large differences. The initial reason for including these two target types was that they have very different temporal structures. As a consequence, a temporally peaked tone complex target will dominate during short temporal intervals over the masker signal. During these intervals the target ITD will be better represented in the peripheral auditory system than would be the case for a more constant amplitude noise target. As a consequence the tone complex target could have been easier to lateralize. Possibly, the short durations of the intervals where the tone-complex target dominates results in an increase in uncertainty of the ITD values observed during these intervals due to inherent stimulus variability which counters the advantage that is obtained from the better signal-to-noise ratio when the target peaks.

## EXPERIMENT II: LATERALIZATION MATCHING

The previous experiment measured the lowest target-to-masker ratio at which listeners could determine to what side the target was lateralized. In the design of the first experiment this could be resulting from a change in the long term cross correlation function. Our previous study [5] suggested that listeners were able to segregate and lateralize a harmonic tone complex that was presented simultaneously with a noise signal. For this stimulus, segregation and lateralization could be based on the temporal envelope peaks of the tone complex that would temporally dominate over the noise signal to provide intervals were the ITD of the tone complex could be read out. Based on these results and on those of the previous experiment, it is not clear, however, whether the listeners could correctly determine the extent to which the harmonic tone complex target was lateralized when presented simultaneously with a noise target.

For noise targets with simultaneous on- and offsets it is not expected that the target can be segregated from the masker. For tone complex targets, however, listeners may be able to segregate the target from the masker based on their different temporal structure and correctly hear the extent of target lateralization (cf. [5]). The ability of listeners to do this would support the hypothesis that concurrent sounds can be separated and localized based on differences in temporal envelope structure.

### Method and Stimuli

In order to determine whether listeners could correctly hear the target lateralization extent in the presence of noise, listeners participated in a lateralization matching experiment. Within each trial, three intervals were presented. The first and third interval contained the noise plus target harmonic tone complex (HTC) each at a level of 65 dB SPL leading to an overall level of 68 dB SPL in the first and third interval. The target HTC had an ITD that was the same in both intervals. In the second interval, an HTC was presented in isolation at 65 dB SPL for which the ITD could be adjusted by the listener. After each presentation of these three intervals, the listeners could indicate whether the adjustable HTC presented in isolation (second interval) needed to be moved to the left or right in order to better match the target HTC lateralization in the first and third interval.

The ITD of the adjustable HTC was adapted iteratively by repeatedly presenting the three-interval trials keeping the target ITD constant. Initially, ITDs were adjusted with 80 $\mu$s steps. After each second reversal, the step size was halved until a step size of 10 $\mu$s was reached. Another 4 reversals were measured using this step size. The median value of these reversals served as the adjusted ITD. For each listener and condition, two adjustment measurements were done. Target ITDs were -0.4, -0.3, -0.2, -0,1, 0, 0.1, 0.2, 0.3, 0.4 ms. The other stimulus parameters such as bandwidth and center frequency were the same as in the previous experiment.

Two conditions were used for the noise (masker) signal; a diotic condition, and a roving-ITD condition with ITDs uniformly distributed from -1 to 1 ms. The roving masker ITD was constant within a trial, but varied randomly across trials.

**Results**

In Fig. 2, the results of the lateralization matching experiment are shown. The left panel shows the results for a diotic noise masker for three subjects. Results show that there is a good correspondence between target ITD (horizontal axis) and adjusted ITD (vertical axis). The solid line represents the ideal situation where target and adjusted ITD would be identical. Only for the subject indicated with diamonds, there is a clear deviation from the solid line that seems to be related to difficulties in reliably estimating the lateralization of the target. For the other subjects, there may be some overestimation of the target ITD. In the right panel similar results are shown, but now for a roving-ITD masker. As can be seen also for a roving-ITD masker, listeners are able to match adjustable ITD to the target ITD.

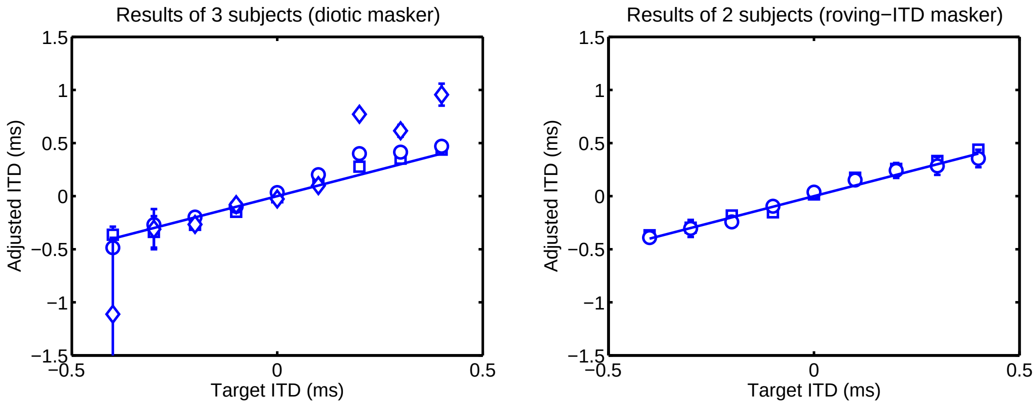


Figure 2: Results of the lateralization matching experiment for diotic noise maskers (left panel) and roving ITD maskers (right panel). The horizontal axis shows the target ITD, the vertical axis shows the adjusted ITD. The solid line represents points for which target and adjusted ITDs are equal.

These results suggest, that listeners are able to separate between the noise lateralization and the HTC lateralization, despite the fact that they are spectrally and temporally overlapping.

**GENERAL DISCUSSION**

The first experiment showed that the ability to hear the lateralization orientation is only present at relatively high target-to-noise ratios and that it does not strongly depend on target ITD. This observation was interpreted to be a consequence of the specific interaction between target and masker phase and as such seems to be more an effect of stimulus uncertainty and not so much a property of binaural hearing.

The ability of listeners to correctly hear the lateralization extent of the target HTC in the presence of a noise masker as measured in experiment II, reveals some interesting properties of the binaural system. Since the noise masker and target are combined at equal SPL, the long term cross correlation such as represented at the output of an auditory filter reveals an ITD that is the average of that of the noise masker and the target HTC. Thus, especially for the condition with the roving ITD noise masker, the long term cross correlation doesn't provide useful information to determine the target lateralization.

Due to the different temporal envelope structures of the noise masker and target, however, the short-term cross correlation will alternately reveal the lateralization of the target HTC and that of the noise depending on which has the highest momentary level. Thus, at the output of the binaural display a temporally changing pattern of ITDs may be represented. When the binaural display is read out at the moment that the target is dominating over the noise masker, it will provide more accurate information about the lateralization of the target. This requires, however, that the binaural display provides sufficient temporal resolution to represent the 20-Hz cycle resulting from the fundamental frequency of the target, and that the display can be read out with sufficient temporal selectivity to synchronize to the temporal envelope of the target signal.

Such a high temporal acuity is not in line with the notion of binaural sluggishness for ITD cues [1] which suggests that listeners can track ITDs only at rates below about 20 Hz. Possibly, the additional monaural envelope information available in our stimuli triggers a more temporally accurate read out of the binaural cues. The results of an earlier study [5] present additional support for the assumption that monaural envelope information may support temporal processing of binaural information.

A similar lateralization adjustment experiment was conducted in the free field by Lorenzi et al. [2]. Although in these experiments, other cues (e.g. interaural level difference cues) may have been involved, the overall results are in line with our findings.

In conclusion, the combination of binaural and monaural processing seems to provide our hearing system with a means to separately hear the lateralization of concurrent and spectrally overlapping stimuli and link the lateralization to the concurrent stimuli based on differences in their temporal envelope patterns. This ability may be highly useful for the capacity to analyze complex auditory scenes.

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