THE INFLUENCE OF INTERAURAL PHASE UNCERTAINTY ON BINAURAL SIGNAL DETECTION

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ABSTRACT

This study investigates whether binaural signal detection is improved by the listener's a priori knowledge about the interaural phase relations. We measure binaural masked thresholds and vary the interaural phase of masker and test signal randomly within the same measurement. A comparison of the results with experiments applying a fixed binaural configuration shows no significant differences. The results allow an examination of different model predictions in relation to the simultaneous processing of signals with distinct interaural phase relations.

INTRODUCTION

Speech perception in background noise is to a large extent dependent on the function of the binaural hearing system. This fact can be tested qualitatively by occlusion of one ear in a typical "cocktail-party" situation and, more exactly, by listening tests in a defined acoustical condition. A quantitative measure of the noise reducing ability is given by the Binaural Masking Level Difference (BMLD), the threshold difference between monaural and binaural signal presentation. Binaural thresholds depend on the interaural parameters (time and level differences) of the background (masking noise) and the test stimulus. Similar to monaural experiments, only the interaural parameters within a limited frequency range around the test frequency contribute to the masking /1/.

The experiments in this study investigate a specific binaural aspect of signal detection. This aspect shall be explained by a short discussion of two models for binaural signal processing proposed by Durlach /2/ and Colburn /3,4/.

In the Equalization and Cancellation (EC) theory /2/, binaural unmasking is explained by mathematical operations, which are performed on the acoustical inputs to both ears in order to reduce the intensity of the masking signal. In a first "Equalization" step the maskers from the left and the right ear are adjusted to each other by internal transformations of amplitude (by attenuation) and time (by delay). These transformations are accompanied by errors, described as amplitude and time jitter. Therefore, the subtraction of the two adjusted masking signals in the second step does not totally cancel the masker intensity. For most interaural phase relations, however, this binaural processing leads to an increased signal-to-noise ratio, which is directly related to the lower binaural masked thresholds. The transformations are performed on the peripherally bandpass filtered signals within a critical band. In the description of the theory, it remains unclear whether this system is able to apply distinct transformations simultaneously.

The "auditory-nerve-based model" from Colburn /3,4/ differs from the EC-theory by including a detailed description of the peripheral transduction process from acoustical waveforms to neural activity. In the central part of the model, the synchronous neural activity is measured for pairs of fibres from the left and right acoustic pathway having identical best frequency f_i and a specific internal time delay τ_i. This part of the model can be described as a two-dimensional pattern of coincidence detectors with internal delay τ and best frequency f as the two dimensions. For a fixed frequency f_i, the coincidence values along the τ-axis represent an estimate of the cross-correlation function of the input to the right and the left ear within the frequency channel i. From the activity within this two dimensional pattern a decision variable is derived, which can be used to calculate binaural masked thresholds /4/. As all coincidence detectors analyze the input signals simultaneously, different internal delays (corresponding to different Equalization transformations in the EC-theory) can be applied even within the same frequency channel simultaneously.

The experiments described in this paper were performed to test the differences between the two models in this point. We used a binaural masking noise with distinct interaural phase relations in different frequency regions. Thus, according to the EC-theory, the optimal binaural processing strategy had to be different for different test signal frequencies. By introducing uncertainty about the test signal frequency and phase, we could test whether a priori knowledge of the interaural phase relations is advantageous for the listeners, as it would be predicted by the EC-theory.

METHOD

Apparatus

The experimental setup for measuring binaural masked thresholds is shown in Fig.1. The experiments were controlled by a 16 bit microcomputer TI 980A, which also generated the sinusoidal test stimuli. They were converted to analog signals by means of a 2 channel 12 bit D/A-converter at a sampling rate of 5 kHz, low pass filtered at 1 kHz and attenuated. The dichotic noise masker had a steep transition of the interaural phase difference from 0 to π at 500 Hz. This masker was generated digitally and stored on magnetic tape. Computer controlled gate switches were used to turn the noise on and off at the appropriate instants of time. The masker was low pass filtered at 2.5 kHz and presented at an overall level of 75 dB SPL. Masker and test signal were added with the appropriate interaural phase relations and presented to the subject over headphone (Sennheiser HD 44) in a sound insulated booth.

Threshold Procedure

Binaural masked thresholds were determined with an adaptive 3 Interval Forced Choice (3 IFC) procedure. The 500 ms noise masker was presented in three sequential intervals separated by short breaks of 100 ms. In one randomly chosen interval, the test signal was added to the temporal center of the masker. In the main experiment, the test signal had a duration of 20 ms including 5 ms linear ramps. After each trial (a group of three intervals), the subject had to specify the number of the interval containing the probe tone. The level of the test signal was changed adaptively following a two-down-one-up rule /5/. After two subsequent correct responses, the level was decreased by 1 dB, after each incorrect response, it was increased by the same amount. In the beginning of the measurement, the level was lowered after each correct response until the subject first failed to specify the correct interval. The threshold value was finally calculated by averaging the signal level of the 15 trials that followed the second lower turning point of the signal level. Each data point in the figures is based on at least four such measurements. Five subjects aged 23 to 30 years participated in the experiments.

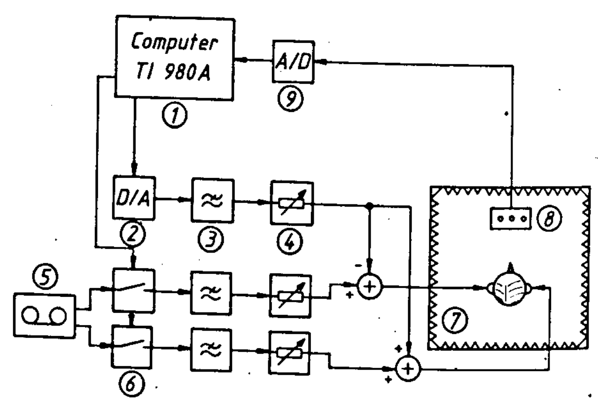


Fig.1: Experimental setup: (1) 16 bit microcomputer TI 980A; (2) 12 bit D/A converter; (3) low pass filter Krohn + Hite, 48 dB/octave; (4) manual attenuators; (5) two channel white noise, stored on magnetic tape; (6) computer controlled gates; (7) sound insulated booth; (8) response box; (9) 12 bit A/D converter.

Frequency and phase uncertainty

To introduce uncertainty about the test signal frequency and the test signal phase, the threshold procedure was modified in the following way: Within one measurement, the thresholds for two different test signals were determined using the adaptive 3 IFC procedure. For each trial, one of the two signals was randomly chosen with probability 1/2. The two signals differed in frequency and interaural phase difference. The frequencies of each pair of signals were chosen symmetrically around 500 Hz, e.g. 450 and 550 Hz or 200 and 800 Hz. The phase difference was always opposite to the noise phase difference at that frequency, e.g. π for the lower test frequency and 0 for the higher test frequency. Thus, the subject had no prior knowledge about the frequency and interaural phase of the test signal in the next trial. The level adjustment for either test frequency followed the algorithm described above and the measurement was completed if for both signals the number of 15 trials was reached.

EXPERIMENTS

Influence of test signal duration on the BMLD

In the first experiment we investigate the BMLD pattern for the masker with frequency varying interaural phase difference. To define the interaural conditions of our experiments, we use the notation common in binaural psychoacoustics: N and S describe noise masker and (test) signal respectively, the interaural phase differences are given by indices (0 indicates in-phase, π antiphase presentation). In addition, we introduce the notation $N_{0\pi}$ for the masker with phase difference 0 below 500 Hz and phase difference π above 500 Hz. By inverting one channel of this masker, the components below 500 Hz are in antiphase and the components above 500 Hz in phase ($N_{\pi 0}$).

In Fig.2, we demonstrate the effect of the interaural phase step of the masker for a 250 ms S_π test signal. Open and closed symbols respresent the BMLD values for $N_{0\pi}$ and $N_{\pi 0}$ masker respectively. The continuous line gives the values for a masker with fixed phase difference of 0 at all frequencies (N_0). The step of the interaural masker phase strongly influences the binaural thresholds between

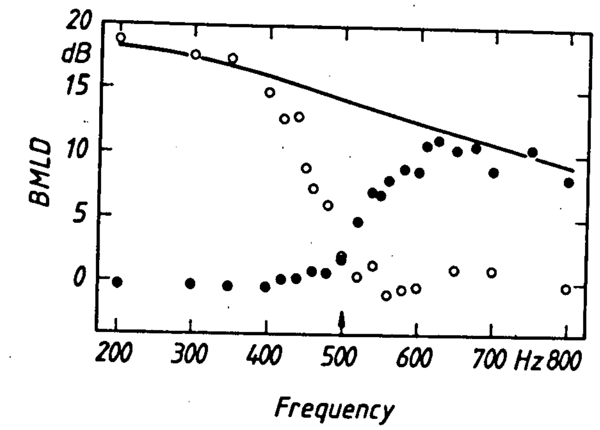


Fig.2: BMLD of a 250 ms test signal in the configurations $N_{0\pi}S_\pi$ (o) and $N_{\pi 0}S_\pi$ (•). The continuous line shows the N_0S_π BMLD. The arrow marks the transition of the interaural phase difference of the masker at 500 Hz. One subject.

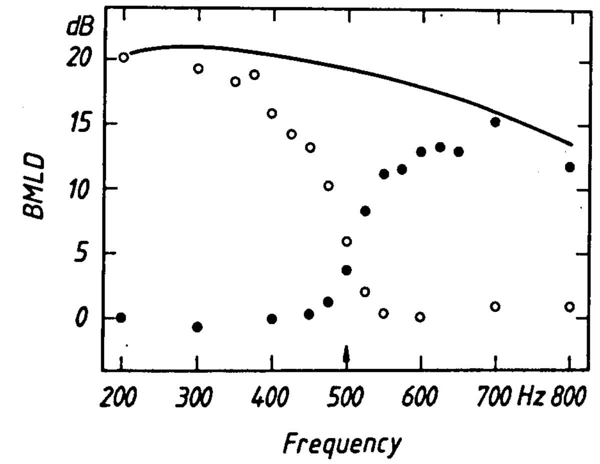


Fig.3: Same as Fig.2 for a 20 ms test signal.

400 and 650 Hz. A detailed analysis of this BMLD pattern leads to the conclusion that the masker cross-correlation averaged over the critical band at the test frequency is the crucial factor in this experiment /1/. As this correlation variies between +1 and -1 for test frequencies close to 500 Hz, the BMLD of the test signal also variies by about 15 dB. At test frequencies well apart from 500 Hz, no

influence of the phase transition is observed and the $N_{0\pi}$ and $N_{\pi 0}$ maskers have the same effect as the N_0 masker.

In order to test the influence of test signal duration in this detection task, we repeated the same experiment with a 20 ms tone (Fig.3). The slope of the data in this figure is the same as for the 250 ms test signal in Fig.2. The slight increase of the BMLD for the shorter test signal confirms the observations in other binaural configurations /6,7/. The broadening of the transition range may be due to the widening of the test signal spectrum.

Generally, the presence of two spectral masker ranges with different interaural phase relations which would require different processing strategies in the view of the EC theory, does not hamper the binaural system. Even for a short test signal of 20 ms, the maximal amount of binaural unmasking is reached at test frequencies well apart from 500 Hz.

Influence of frequency uncertainty on diotic masked thresholds

In the previous experiment, the test signal always was presented at a constant frequency within one measurement block. To determine the importance of this a priori information, we introduced uncertainty concerning the test frequency by the algorithm described above. Both test signals and the masker were presented in phase (N_0S_0 condition).

In Fig.4, the results for uncertain frequency presentation (•) are compared to threshold values for fixed frequeny (o). The uncertainty has only a slight influence on the masked thresholds, the averaged difference between the two experimental conditions amounts to 1 dB.

In this experiment, the subjects are obviously able to concentrate on different frequency regions simultaneously without strong reduction in sensitivity. If the number of alternative frequencies is further increased, a monotonous rise of the thresholds is observed /8/.

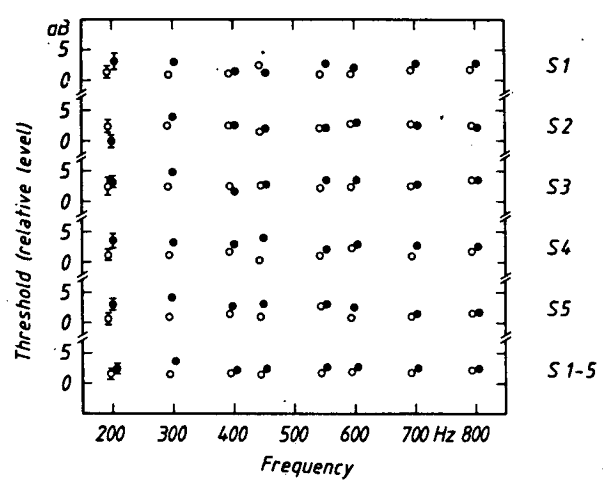
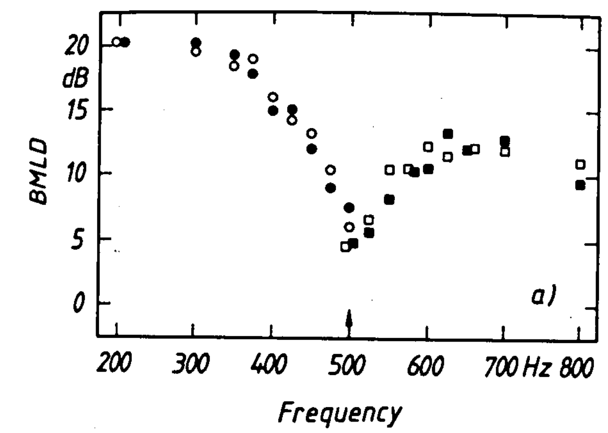


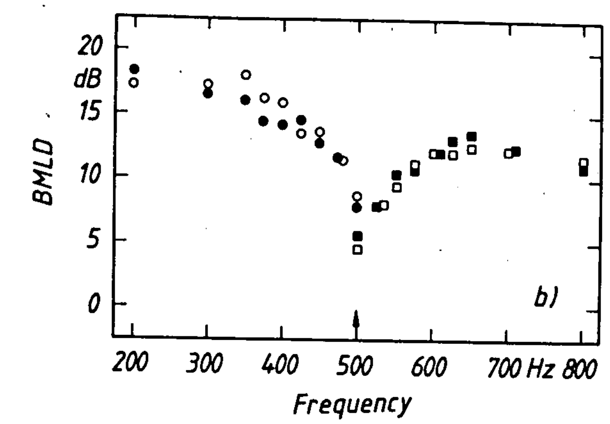
Fig.4: Binaural masked thresholds of a 20 ms test signal in the diotic configuration N_0S_0. o fixed test signal frequency, • uncertain (one out of two) test signal frequency. Values for 5 listeners and their means.

Frequency and phase uncertainty in a dichotic detection task

In the following experiment, we apply the uncertain frequency algorithm to a dichotic condition. In this case, the frequency uncertainty is accompanied by an uncertainty about the optimal binaural processing strategy. The masking noise is in phase at frequencies below 500 Hz and in antiphase at frequencies above 500 Hz ($N_{0\pi}$). The low-frequency test signal was interaurally inverted (S_π), the high-frequency signal was in phase (S_0). Thus, the two test frequencies correspond to the two different binaural conditions N_0S_π (low-frequency stimulus) and $N_\pi S_0$ (high-frequency stimulus). For comparison, we determined the binaural thresholds for fixed test frequency in the same binaural conditions.

Fig.5 shows the results of three listeners for fixed (o,□) and randomly chosen (•,■) test signals. For all subjects, there is no significant difference in the threshold values of the two measurements. Additional experiments in other binaural conditions confirmed this result: The binaural unmasking process is not influenced by uncertainty about the interaural phase of masker and test signal.





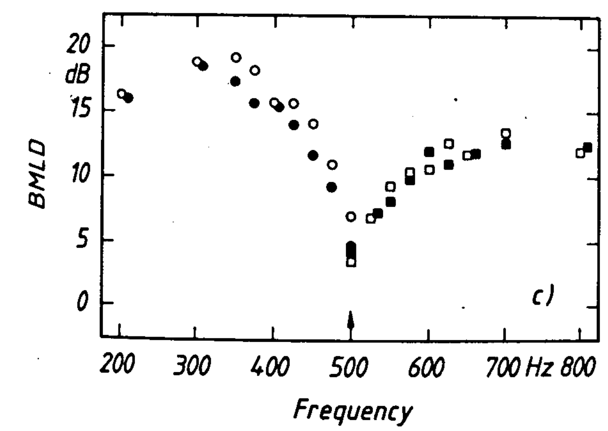


Fig.5: BMLD of a 20 ms test signal as a function of frequency. Masker $N_{0\pi}$, test signal at frequencies below 500 Hz S_π (o,•), at frequencies above 500 Hz S_0 (□,■). Open symbols: Fixed test signal frequency. Closed symbols: Uncertain test signal frequency. a) to c): 3 subjects.

DISCUSSION

The results presented in Fig.5 emphasize the following conclusions: The detectability of short test signals presented randomly in different critical bands with different interaural phase relations is as good as for fixed signal parameters. As we assume that an adjustment of the optimal processing strategy is not possible within the short test signal duration, one could argue that the ear uses a priori information about the different binaural conditions. This a priori knowledge could be aquired in the beginning of the measurement, as the two test signals are presented clearly audible. It could be stored as different processing strategies for the two frequency regions of interest.

However, this way of reconciling our experimental results with the ideas of the EC theory does not hold if the two signals are presented within the same critical band. For the test signal pair 500 Hz S_π/ 500 Hz S_0, the optimal strategy has to be subtraction of the two channels (for the S_π signal) and addition for the S_0 signal. Thus, different strategies are necessary according to the test signal phase. As the binaural system reaches a significant BMLD in this condition, it must be able to apply different transformations instantaneously within the same critical band.

This outcome of the experiments is much more compatible with cross-correlation models of binaural interaction /3,4,9-11/. In these models each binaural stimulus leads to a specific two-dimensional excitation pattern (cf. introduction). Test signals with different interaural phase relations excite different places along the τ-axis. Uncertainty about test signal frequency and phase results in uncertainty about the exact place of excitation within this cross-correlation pattern. Our results emphasize that uncertainty about interaural phase (one dimension within the cross-correlation pattern) has the same (negligible) effect as uncertainty about test signal frequency (the other dimension, cf. Fig.4). In the same way as in monaural hearing the listener can concentrate on different frequencies simultaneously, he seems to be able to concentrate on different interaural delays in binaural hearing. Therefore, the a priori information about the interaural parameters does not further improve the detection of binaurally presented signals.

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