The contribution of static and dynamically varying ITDs and IIDs to binaural detection

Jeroen Breebaart and Steven van de Par
IPO Center for Research on User-System Interaction, P.O. Box 513, NL-5600 MB Eindhoven, The Netherlands

Armin Kohlrausch[a)]
IPO Center for Research on User-System Interaction, P.O. Box 513, NL-5600 MB Eindhoven, The Netherlands and Philips Research Laboratories Eindhoven, Prof. Holstlaan 4, NL-5656 AA Eindhoven, The Netherlands

(Received 10 December 1997; accepted for publication 4 May 1999)

This paper investigates the relative contribution of various interaural cues to binaural unmasking in conditions with an interaurally in-phase masker and an out-of-phase signal (MoSπ). By using a modified version of multiplied noise as the masker and a sinusoid as the signal, conditions with only interaural intensity differences (IIDs), only interaural time differences (ITDs), or combinations of the two were realized. In addition, the experimental procedure allowed the presentation of specific combinations of static and dynamically varying interaural differences. In these conditions with multiplied noise as masker, the interaural differences have a bimodal distribution with a minimum at zero IID or ITD. Additionally, by using the sinusoid as masker and the multiplied noise as signal, a unimodal distribution of the interaural differences was realized. Through this variation in the shape of the distributions, the close correspondence between the change in the interaural cross correlation and the size of the interaural differences is no longer found, in contrast to the situation for a Gaussian-noise masker [Domnitz and Colburn, J. Acoust. Soc. Am. **59**, 598–601 (1976)]. When analyzing the mean thresholds across subjects, the experimental results could not be predicted from parameters of the distributions of the interaural differences (the mean, the standard deviation, or the root-mean-square value). A better description of the subjects' performance was given by the change in the interaural correlation, but this measure failed in conditions which produced a static interaural intensity difference. The data could best be described by using the energy of the difference signal as the decision variable, an approach similar to that of the equalization and cancellation model. [S0001-4966(99)03808-4]

PACS numbers: 43.66.Pn, 43.66.Ba, 43.66.Dc [DWG]

INTRODUCTION

Interaural time differences (ITDs) and interaural intensity differences (IIDs) are generally considered to be the primary cues underlying our ability to localize sounds in the horizontal plane. It has been shown that at low frequencies changes in either ITDs or IIDs affect the perceived locus of a sound source (Sayers, 1964; Hafter and Carrier, 1970; Yost, 1981). Besides mediating localization, it has been argued that the sensitivity to ITDs and IIDs of the auditory system is the principle basis of the occurrence of binaural masking level differences (BMLDs) (Jeffress *et al.*, 1962; McFadden *et al.*, 1971; Grantham and Robinson, 1977). When an interaurally out-of-phase sinusoid is added to an in-phase sinusoidal masker of the same frequency, i.e., a tone-on-tone condition, *static* IIDs and/or *static* ITDs are created, depending on the phase angle between masker and signal. These interaural differences result in lower detection thresholds for the out-of-phase signal compared to an in-phase signal (Yost, 1972a). In terms of the signal-to-masker ratio, subjects tend to be more sensitive to signals producing ITDs than to those producing IIDs (Yost, 1972a; Grantham and Robinson, 1977).

Besides sensitivity to static interaural differences, the binaural auditory system is also sensitive to dynamically varying ITDs (Grantham and Wightman, 1978) and IIDs (Grantham and Robinson, 1977; Grantham, 1984). As a consequence, BMLDs occur for stimuli with dynamically varying interaural differences. When an interaurally out-of-phase sinusoidal signal is added to an in-phase noise masker with the same (center) frequency, the detection threshold may be up to 25 dB lower than for an in-phase sinusoidal signal (Hirsh, 1948; Zurek and Durlach, 1987; Breebaart *et al.*, 1998). For such stimuli, both dynamically varying IIDs and ITDs are present (Zurek, 1991). Experiments which allow the separation of the sensitivity to IIDs and ITDs in a detection task with noise maskers were published by van de Par and Kohlrausch (1998b). They found that for multiplied-noise maskers, the thresholds for stimuli producing only IIDs or only ITDs are very similar.

These ''classical'' paradigms used in the investigation of the BMLD phenomenon with static and dynamically varying interaural differences exploited different perceptual phenomena. For the experiments that are performed with noise

[a)]Electronic mail: kohlraus@ipo.tue.nl

maskers, the average values of the IIDs and ITDs for a masker plus signal are zero, while the variances of these parameters are nonzero. The addition of an out-of-phase signal to a diotic noise masker (i.e., the production of time-varying interaural differences) is usually perceived as a widening of the sound image. For tone-on-tone masking conditions, however, a static interaural cue is introduced and detection is based on a change in the lateralization of the sound source. One notion which suggests that these situations differ from each other is that the binaural system is known to be sluggish, as has been shown by several studies (Perrott and Musicant, 1977; Grantham and Wightman, 1978, 1979; Grantham, 1984; Kollmeier and Gilkey, 1990; Holube, 1993; Holube *et al.*, 1998). These studies show that if the rate at which interaural cues fluctuate increases, the magnitude of the interaural differences at threshold increases also. It is often assumed that this reduction in sensitivity is the result of a longer time constant for the evaluation of binaural cues compared to the constant for monaural cues (Kollmeier and Gilkey, 1990; Culling and Summerfield, 1998). Another demonstration suggesting that the detection of static and dynamically varying interaural differences is different was given by Bernstein and Trahiotis (1997). They showed that roving of static IIDs and ITDs does not influence the detection of dynamically varying interaural differences, indicating that binaural detection of dynamically varying cues does not necessarily depend upon changes in laterality.

One of the proposed statistics for predicting binaural thresholds is the size of the change in the *mean* value of the interaural difference between the signal and no-signal intervals of the detection task. For example, studies by Webster (1951), Yost (1972a), Hafter (1971), and Zwicker and Henning (1985) argued that binaural masked thresholds could be described in terms of just-noticeable differences (jnd's) of the IID and ITD. For stimuli for which the mean interaural difference does not change by adding a test signal (e.g., in an $MoS\pi$ condition with Gaussian noise), it is often assumed that changes in the *width* (e.g., the standard deviation) of the distribution are used as a cue for detection (Zurek and Durlach, 1987; Zurek, 1991). The parameters of the distributions of the interaural differences are generally considered to be important properties for binaural detection. It is unknown, however, how the sensitivity for stimuli producing combinations of static and dynamically varying interaural differences can be described in terms of these parameters.

An attempt to describe the combined sensitivity to static and dynamically varying interaural differences was made by Grantham and Robinson (1977). They measured thresholds for stimuli producing static cues as well as dynamically varying cues.[1] They found that the thresholds for signals producing static cues only were very similar to thresholds for stimuli producing a fixed combination of static and dynamic cues. They discussed the data in terms of the mean interaural differences at threshold, which were very similar for the two conditions. Such an analysis does, however, ignore the contribution of dynamically varying cues for detection in those conditions where these cues are available in addition to static cues.

In the present study $MoS\pi$ stimuli will be used which contain either IIDs, ITDs, or combinations of both cues for which the ratio between the static and dynamic component will be varied over a wide range. This allows one to perform a critical assessment of whether detection data can be cast within a framework based on the IIDs and ITDs. A second point of interest of this study is related to an alternative theory that has become very popular for describing binaural detection which relies on the cross correlation of the signals arriving at both ears (cf. Osman, 1971; Colburn, 1977; Lindemann, 1986; Gaik, 1993; van de Par and Kohlrausch, 1995; Stern and Shear, 1996; van de Par and Kohlrausch, 1998a). In these models it is assumed that the change in the interaural correlation resulting from the addition of a signal to a masker is used as a decision variable. In fact, Domnitz and Colburn (1976) argued that for an interaurally out-of-phase tonal signal masked by a diotic Gaussian noise, a model based on the interaural correlation and a model based on the distribution of the interaural differences will yield essentially the same predictions of detection. Thus, theories based on the cross correlation are equivalent to models based on the *width* of the probability distribution functions of the interaural differences, as long as Gaussian-noise maskers and sinusoidal signals are used. However, this equivalence is not necessarily true in general. In the discussion it will be shown that the theories discussed above do not predict similar patterns of data for the stimuli used in the present experiments. Specifically, by producing stimuli with unimodal and bimodal distributions of the interaural cues, we can make a critical comparison between theories based on the IIDs and ITDs and theories based on the interaural cross correlation. Such a comparison is impossible for those $MoS\pi$ studies which employ Gaussian-noise maskers and sinusoidal signals.

In summary, this study has a twofold purpose. On the one hand, it intends to collect more data with stimuli producing combinations of static and dynamically varying cues. On the other hand, we wanted to collect data with stimuli producing different shapes of the distributions of the interaural differences. Specifically, the employed procedure enables the production of stimuli with both unimodal and bimodal distributions of the interaural differences. These data may supply considerable insight into how detection thresholds for combinations of static and dynamic cues can be described.

I. MULTIPLIED NOISE

Because of its specific properties, multiplied noise allows control of the fine-structure phase between a noise masker and a sinusoidal signal. As already mentioned by Jeffress and McFadden (1968), control of this phase angle allows the interaural phase and intensity difference between the signals arriving at both ears in an $MoS\pi$ condition to be specified. Multiplied noise is generated by multiplying a high-frequency sinusoidal carrier by a low-pass noise. The multiplication by the low-pass noise results in a band-pass noise with a center frequency that is equal to the frequency of the carrier and which has a symmetric spectrum that is twice the bandwidth of the initial low-pass noise. For our experiments, we modified this procedure by first adding a dc

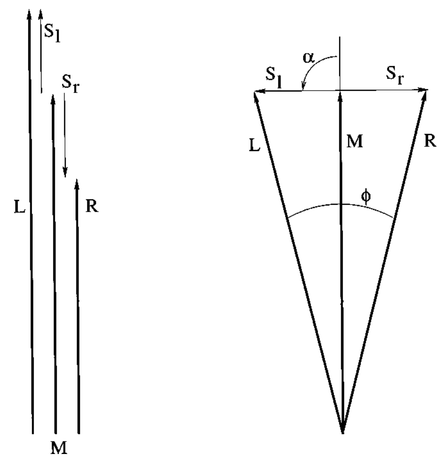

FIG. 1. Vector diagrams illustrating the addition of an interaurally out-of-phase signal (S_l and S_r) to an in-phase masker (M) for $\alpha=0$ (left panel) and $\alpha=\pi/2$ (right panel).

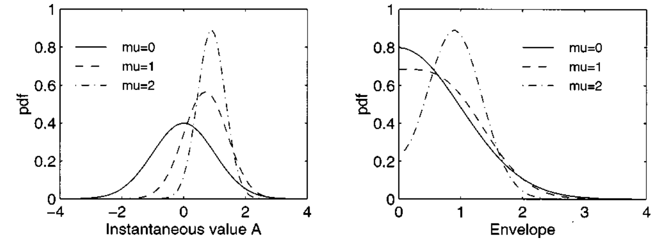

FIG. 2. Probability density functions of the instantaneous value of a Gaussian noise with a constant rms value of 1 (left panel) and the resulting multiplied-noise envelope (right panel). The three curves indicate different values of the static component of 0 (solid line), 1 (dashed line), and 2 (dash-dotted line).

value to the Gaussian low-pass noise before multiplication with the carrier. The effect of using a noise with a nonzero mean is explained in the following section.

A. Multiplied noise as a masker

For the following description we assume an interaurally in-phase multiplied-noise masker and an interaurally out-of-phase sinusoidal signal (i.e., an MoSπ condition). An additional parameter is the phase angle α between the fine structures of noise and sinusoidal signal. If the frequency and phase of the signal that is added to the left ear are equal to those of the masker ($\alpha=0$), we can form a vector diagram of the stimulus as shown in the left panel of Fig. 1. Here, the vector **M** (the masker) rotates with a constant speed (the frequency of the carrier), while its length (i.e., the envelope of the multiplied noise) varies according to the instantaneous-value distribution of the low-pass noise. $\mathbf{S}_l$ and $\mathbf{S}_r$ denote the tonal signals added to the left and right ear, respectively, while **L** and **R** denote the total signals arriving at the left and right ears. Clearly, the vectors **L** and **R** differ only in length, thus only IIDs are present for this stimulus configuration.

If the fine-structure phase of the signal lags the fine-structure phase of the carrier by $\pi/2$ (i.e., $\alpha=\pi/2$), as shown in the right panel of Fig. 1, the resulting vectors **L** and **R** have the same length. However, **R** lags **L** by ϕ. Thus, only ITDs are produced. In a similar way, by adjusting the phase angle α to $\pi/4$ or $3\pi/4$, combinations of IIDs and ITDs can be produced.

Because the instantaneous value of the low-pass noise changes dynamically, the envelope of the multiplied noise constantly changes with a rate of fluctuation dependent on the bandwidth of the low-pass noise. The effect of the addition of a dc component to the low-pass noise before multiplication with the carrier can be visualized as follows. If no dc component is added, the instantaneous value of the low-pass noise has a Gaussian probability density function (PDF) with a zero mean and rms$=1$, as shown in the left panel of Fig. 2 by the solid line. If the instantaneous value of the low-pass noise is positive, and an Sπ signal with $\alpha=\pi/2$ is added to the multiplied-noise masker (see the right panel in Fig. 1), the fine-structure phase of the right ear lags the fine-structure phase of the left ear by ϕ. If, however, the instantaneous value of the low-pass noise is negative, and the same signal is added, the fine-structure phase of the left ear lags the fine-structure phase of the right ear by ϕ. Thus, the interaural phase difference has changed its sign. Due to symmetry around zero in the instantaneous-value probability density function of the low-pass noise, the probability for a certain positive interaural difference equals the probability for a negative interaural difference of the same amount. Therefore, the distribution of the interaural difference is symmetric with a mean of zero.

The static component μ is defined as the magnitude of the dc component added to the low-pass noise with a rms value of 1 and zero mean. For $\mu>0$, the mean of the low-pass noise shifts to a nonzero value (dashed and dash-dotted line of Fig. 2, for $\mu=1$ and $\mu=2$, respectively). If the rms value of the noise plus dc is held constant (i.e., set to 1), the width of the instantaneous-value probability density function of the low-pass noise becomes narrower with increasing μ.

The resulting envelope probability distribution of the multiplied noise is shown in the right panel of Fig. 2. For $\mu=0$ (solid line), the distribution function is half-Gaussian, while for increasing μ, the distribution becomes narrower; for μ approaching infinity, the envelope has a mean of one and a variance of zero.

The decreasing variance of the envelope probability distribution with increasing static component has a strong effect on the behavior of the interaural differences that occur when an Sπ signal is added. If, at a certain time, the noise envelope is large, the phase lag in the above example is relatively small. Adding the signal to a small masker envelope, however, results in a large interaural phase lag. Thus, the width of the masker envelope probability distribution determines the range over which the interaural phase difference fluctuates. A wide distribution implies large fluctuations in the interaural difference, while a very narrow distribution implies only small fluctuations. Because an increase of the static component results in a narrower envelope probability density function, the range over which the interaural difference fluctuates becomes smaller. Consequently, the dynamically varying part of the interaural difference decreases.

We also showed that for a zero mean of the low-pass noise, the overall probability of a positive interaural difference equals the probability of a negative interaural difference of the same magnitude. If a static component is introduced,

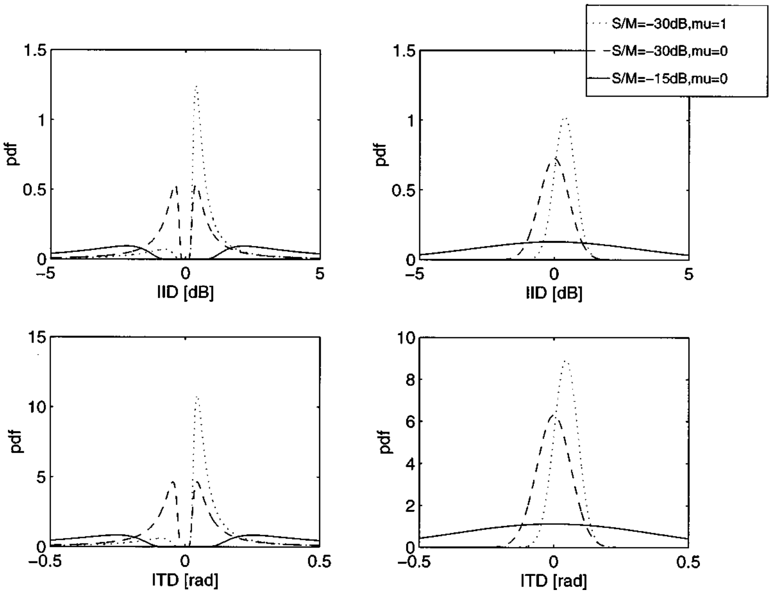

FIG. 3. Probability density functions for the interaural intensity difference for $\alpha=0$ (upper panels) and for the interaural phase difference for $\alpha=\pi/2$ (lower panels). Left panels: multiplied-noise masker, sinusoidal signal. Right panels: sinusoidal masker, multiplied-noise signal. Solid line: S/M$=-15$ dB, $\mu=0$. Dashed line: S/M $=-30$ dB, $\mu=0$. Dotted line: S/M$=-30$ dB, $\mu=1$.

however, the low-pass noise has a nonzero mean. Hence the probability of a positive interaural difference will be larger than the probability of a negative interaural difference. Consequently, an increase of the static component results in an increase in the mean interaural difference.

In summary, an increase of the static component of the multiplied-noise masker results for the MoSπ condition in an increase of the *mean* of the interaural difference and a decrease of the *range of fluctuations*. Thus, by controlling the value of the static component, binaural stimuli containing different combinations of static and time-varying interaural differences can be created in an MoSπ condition.

B. Multiplied noise as a signal

We now consider the situation where the roles of the multiplied noise and the sinusoid are reversed. The masker consists of an in-phase sinusoid, and the signal consists of an interaurally out-of-phase multiplied noise with a carrier having the same frequency as the sinusoidal masker. If the phase lag between the left-ear carrier and masker is zero ($\alpha=0$), this stimulus produces only IIDs. For $\alpha=\pi/2$, only ITDs are present. A phase lag of $\alpha=\pi/4$ results in IIDs and ITDs favoring the same ear, while a phase lag of $\alpha=3\pi/4$ results in IIDs and ITDs pointing in opposite directions. Again, by adding a static component to the low-pass noise, a mixture of static and dynamically varying interaural differences is achieved.

Two important differences exist between the stimulus described here (with a multiplied-noise *signal*) and the stimulus described in Sec. I A (with a multiplied-noise *masker*): (1) in the present condition, the envelope of the masker is flat, and besides interaural differences, the signal also produces fluctuations in the envelope of the waveforms arriving at both ears, and (2) an *increase* in the multiplied-noise signal envelope results in an *increase* in the interaural difference, while the opposite is true for the case with a multiplied-noise masker envelope. This reversed relation between multiplied-noise envelope and interaural difference has a strong effect on the probability density functions of the interaural differences that occur. This aspect will be discussed in the next section.

C. Probability density functions of the interaural cues

For a given phase angle α between sinusoid and masker carrier, a certain static component μ and a fixed signal-to-masker ratio S/M, the probability densities of the resulting IIDs and ITDs can be calculated as shown in Appendix A. In Fig. 3, the probability density functions for the interaural intensity difference are given for three values of μ and S/M for the two conditions that the masker consists of multiplied noise (left panels) and that the signal consists of multiplied noise (right panels). The upper panels show the IID probability density function for $\alpha=0$ (i.e., only IIDs), the lower panels show the ITD probability density function for $\alpha=\pi/2$ (i.e., only ITDs). The solid line represents no static component ($\mu=0$) and a signal-to-masker ratio of -15 dB, the dashed line represents $\mu=0$ and S/M$=-30$ dB, while the dotted line represents S/M$=-30$ dB but with a static component of $\mu=1$. Clearly, for $\mu=0$, the probability density functions are symmetric around zero. Furthermore, a smaller S/M ratio results in narrower distributions. Finally, we see that if the *masker* consists of multiplied noise and $\mu=0$, the probability density function has a *minimum* at zero (the distribution is bimodal), while for a multiplied noise *signal*, the probability density function shows a *maximum* at zero (the distribution is unimodal).

II. METHOD

A. Procedure

A three-interval three-alternative forced-choice procedure with adaptive signal-level adjustment was used to determine masked thresholds. Three masker intervals of 400-ms duration were separated by pauses of 300 ms. The subject's task was to indicate which of the three intervals contained the 300-ms interaurally out-of-phase signal. This signal was temporally centered in the masker. Feedback was provided to the subject after each trial. In some experiments, the reference intervals contained an Mo masker alone, while in other experiments, an MoSo stimulus (i.e., both masker and signal interaurally in phase) was used. The rationale for these different procedures is explained in the next section.

The signal level was adjusted according to a two-down one-up rule (Levitt, 1971). The initial step size for adjusting the level was 8 dB. After each second reversal of the level track, the step size was halved until it reached 1 dB. The run was then continued for another eight reversals. From the level of these eight reversals, the median was calculated and used as a threshold value. At least four threshold values were obtained and averaged for each parameter setting and subject.

B. Stimuli

All stimuli were generated digitally and converted to analog signals with a two-channel, 16-bit D/A converter at a sampling rate of 32 kHz with no external filtering other than by the headphones. The maskers were presented to the subjects over Beyerdynamic DT990 headphones at a sound pressure level of 65 dB. The multiplied-noise samples were obtained by a random selection of a segment from a 2000-ms low-pass noise buffer with an appropriate dc component and a multiplication with a sinusoidal carrier. The low-pass noise buffer was created in the frequency domain by selecting the frequency range from a 2000-ms white-noise buffer after a Fourier transform. After an inverse Fourier transform, the addition of a dc component and rescaling the signal to the desired rms value, the noise buffer was obtained. All thresholds were determined at 500-Hz center frequency. In order to avoid spectral splatter, the signals and maskers were gated with 50-ms raised-cosine ramps. Thresholds are expressed as the signal-to-masker power ratio in decibels.

Thresholds were obtained by measuring the detectability of an interaurally out-of-phase signal in an in-phase masker (MoSπ) in the following four experiments:

(1) The masker consisted of in-phase multiplied noise, while the signal consisted of an interaurally out-of-phase sinusoid. In this experiment, the reference intervals contained only an Mo masker. Thresholds were obtained as a function of the static component (μ=0, 0.5, 1, 1.5, and 2) for α=0 and $\alpha=\pi/2$ and masker bandwidths of 10 and 80 Hz. The rationale for this experiment was to investigate binaural masked thresholds for combinations of static and dynamic interaural differences, for bimodal distributions of the interaural cues. Two bandwidths were applied; a narrow one in order to produce slowly varying interaural differences and a bandwidth corresponding to the equivalent rectangular bandwidth at 500 Hz (Glasberg and Moore, 1990), producing interaural cues which fluctuate faster. In this way the influence of the rate of fluctuations is investigated.

(2) The masker consisted of an in-phase sinusoid, while the signal consisted of interaurally out-of-phase multiplied noise. Thresholds were obtained for the same parameter settings as in experiment 1. This experiment served to study thresholds for unimodal distributions of the interaural differences. The reference intervals consisted of in-phase sinusoids combined with in-phase multiplied noise (i.e., MoSo). Thus, the task was to discriminate between MoSo and MoSπ, so that the subjects could not use the fluctuations in the envelope produced by the signal as a cue for detection.

(3) The masker consisted of an in-phase sinusoid, while the signal consisted of interaurally out-of-phase multiplied noise. For similar reasons as in experiment 2, the reference intervals consisted of in-phase sinusoids combined with in-phase multiplied noise. Thresholds were obtained as a function of the bandwidth (10, 20, 80, 160, 320, and 640 Hz) of the noise for μ=0 and α=0 and $\alpha=\pi/2$. This experiment served to check for possible effects of off-frequency listening in experiment 2. Because the noise bandwidth is larger than the bandwidth of the masker (the sinusoid), an auditory filter that is tuned to a frequency just above or below the masker frequency receives relatively more noise (signal) intensity than masker intensity. Furthermore, this difference increases with increasing signal bandwidth. It is therefore expected that for signal bandwidths beyond the critical band, off-frequency listening will result in lower thresholds compared with the case of a signal of subcritical bandwidth. If off-frequency listening influences the results in experiment 2, the parameters of the distributions of the interaural differences cannot be compared between experiments 1 and 2, since peripheral filtering would alter these parameters significantly. To investigate at which signal bandwidth this effect starts to play a role, we determined the bandwidth dependence of the thresholds for this stimulus configuration.

(4) Similar to experiment 1, the masker consisted of an in-phase multiplied noise, while the signal consisted of an interaurally out-of-phase sinusoid. The reference intervals contained an Mo masker alone. In this experiment, thresholds were obtained as a function of the fine-structure phase angle between masker and signal for α=0 (only IIDs), $\pi/4$ (IIDs and ITDs which favor the same ear), $\pi/2$ (only ITDs), and $3\pi/4$ (IIDs and ITDs pointing in opposite directions). No static component was present (μ=0). The masker had a bandwidth of 10 or 80 Hz. In addition, an in-phase sinusoid was used as a masker. This experiment served to investigate the effect of the phase angle α, for both dynamically varying and static interaural differences.

Table I shows a summary of the experimental conditions that were used.

III. RESULTS

A. Experiment 1: Multiplied noise as masker

In Fig. 4, the four lower panels show the detection thresholds for four subjects as a function of the static component for experiment 1. The upper panel shows the mean thresholds. The filled symbols denote the IID conditions (α =0), the open symbols denote the ITD conditions ($\alpha=\pi/2$). The upward triangles correspond to a masker bandwidth of

TABLE I. Table showing the experimental variables of experiments 1–4.

Experiment No.	Masker type	Signal type	Noise bandwidth (Hz)	Static component	α	Reference intervals
1	Multiplied noise	Sinusoid	10, 80	0, 0.5, 1, 1.5, 2	0, $\pi/2$	Mo
2	Sinusoid	Multiplied noise	10, 80	0, 0.5, 1, 1.5, 2	0, $\pi/2$	MoSo
3	Sinusoid	Multiplied noise	10, 20, 40, 80, 160, 320, 640	0	0, $\pi/2$	MoSo
4	Multiplied noise	Sinusoid	10, 80	0, infinity	0, $\pi/4$, $\pi/2$, $3\pi/4$	Mo

80 Hz, the downward triangles to 10 Hz. Most of the thresholds are in the range of -30 to -20 dB. Generally, we see that the mean thresholds (upper panel) show only small differences across bandwidth or physical nature of the cue (i.e., IIDs versus ITDs). Within subjects, however, some systematic differences are present. Subjects MV and JB show higher thresholds for the 80-Hz conditions than for the 10-Hz conditions, while for subject MD, the 80-Hz IID thresholds are lower than the 10-Hz IID data. Although within and across subjects thresholds vary by about 10 dB, the mean data do not show effects of that magnitude.

B. Experiment 2: Multiplied noise as signal

In Fig. 5, the detection thresholds for experiment 2 are shown as a function of the static component. The format is the same as in Fig. 4. The 80-Hz ITD data (open upward triangles) are systematically 4 to 5 dB lower than thresholds for the other stimulus configurations (especially for subjects MD and MV). For these subjects, the thresholds show an increase of up to 6 dB with increasing static component for the 80-Hz ITD condition. The other conditions show approximately constant thresholds for the mean data, independent of bandwidth and physical nature of the interaural cue.

Because of the small differences that were found in these two experiments, a multifactor analysis of variance (MANOVA) was performed for the results shown in Figs. 4 and 5 to determine the significance of the different experimental variables used in the experiments. The factors that were taken into account were (1) the multiplied-noise bandwidth, (2) the masker-signal phase angle α, (3) the static component μ, and (4) the masker type (multiplied noise as masker or signal). The p-values for the effects that were significant at a 5% level are shown in Table II.

Thus, significant factors are

(1) the masker-signal phase angle α: a change from $\alpha=0$ to $\pi/2$ results in a mean decrease in thresholds of 1.4 dB;

(2) the static component μ: an increase from $\mu=0$ to 2 results in an increase of the thresholds by 3 dB;

(3) the masker type: on average, conditions with a multiplied-noise masker have 2.2 dB lower thresholds than conditions with a multiplied-noise signal.

Significant interactions are

(1) the multiplied-noise bandwidth combined with α: an increase from 10- to 80-Hz bandwidth results in a decrease

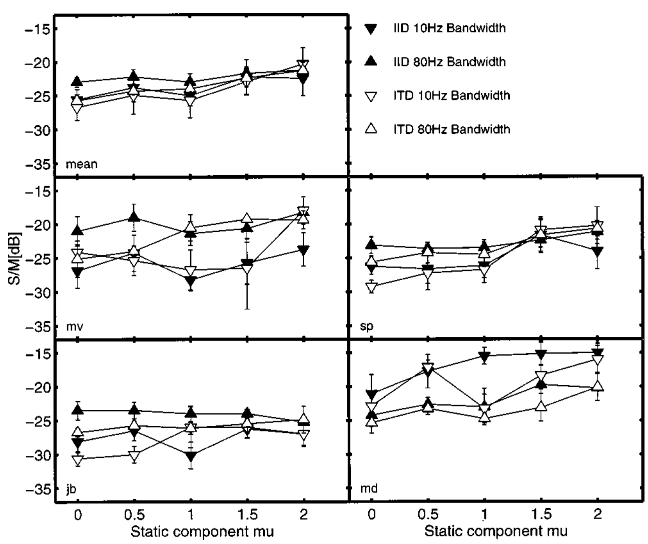

FIG. 4. Detection thresholds for an out-of-phase sinusoidal signal added to an in-phase multiplied-noise masker for $\alpha=0$, 10-Hz bandwidth (filled downward triangles); $\alpha=0$, 80-Hz bandwidth (filled upward triangles); $\alpha=\pi/2$, 10-Hz bandwidth (open downward triangles); and $\alpha=\pi/2$, 80-Hz bandwidth (open upward triangles). The four lower panels show thresholds for individual subjects, the upper panel represents the mean across four subjects. Error bars for the individual plots denote the standard error of the mean based on four trials of the same condition. The error bars in the upper panel denote the standard error of the mean across the mean data from the four subjects.

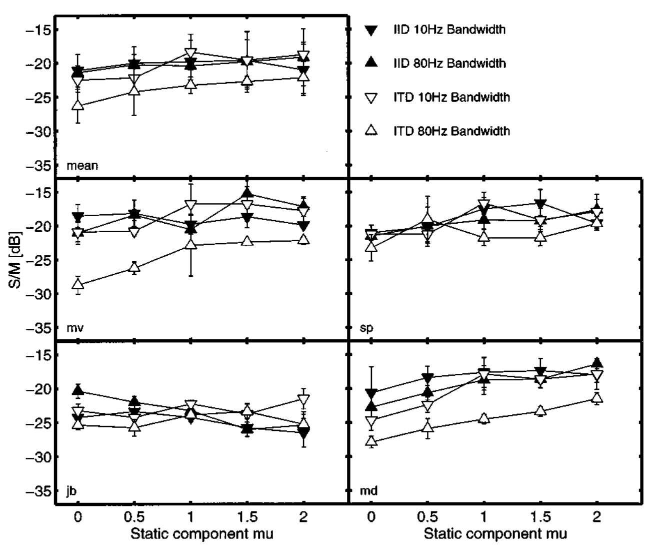

FIG. 5. Detection thresholds for an out-of-phase multiplied-noise signal added to a diotic sinusoidal masker as a function of the dc component μ. Same format as Fig. 4.

TABLE II. Factors and their significance levels according to a multifactor analysis of variance of the data shown in Figs. 4 and 5. Only those factors (upper three) and interactions (lower two) which are significant at a 5% level are given.

Effect	p value
Phase angle α	0.011 20
Static component	0.000 73
Masker type	0.000 01
Noise bandwidth and α	0.024 24
Noise bandwidth and masker type	0.006 42

of the thresholds by 5 dB for the ITD-only conditions, while the IID-only conditions are similar;

(2) the multiplied-noise bandwidth combined with the masker type: the above interaction is only seen for a multiplied-noise signal. For a multiplied-noise masker, the thresholds for $\alpha=0$ and $\alpha=\pi/2$ remain similar with changes in the masker bandwidth.

C. Experiment 3: Bandwidth dependence of a multiplied-noise signal

In this experiment, thresholds were determined as a function of the bandwidth of a multiplied-noise test signal added to a sinusoidal masker. Figure 6 shows the detection thresholds as a function of the bandwidth of the multiplied noise for $\alpha=0$ (IIDs, filled triangles) and $\alpha=\pi/2$ (ITDs, open triangles). Both for the ITD, and IID conditions, the thresholds remain approximately constant for bandwidths up to a bandwidth of 80 to 160 Hz, while for wider bandwidths, the thresholds decrease with a slope of 7 dB/oct of signal bandwidth. The measure of 80 Hz of the auditory filter bandwidth agrees with the monaural equivalent rectangular bandwidth estimates of 79 Hz at 500 Hz center frequency from Glasberg and Moore (1990). Furthermore, we see that, on average, the ITD thresholds are approximately 5 dB lower than the IID

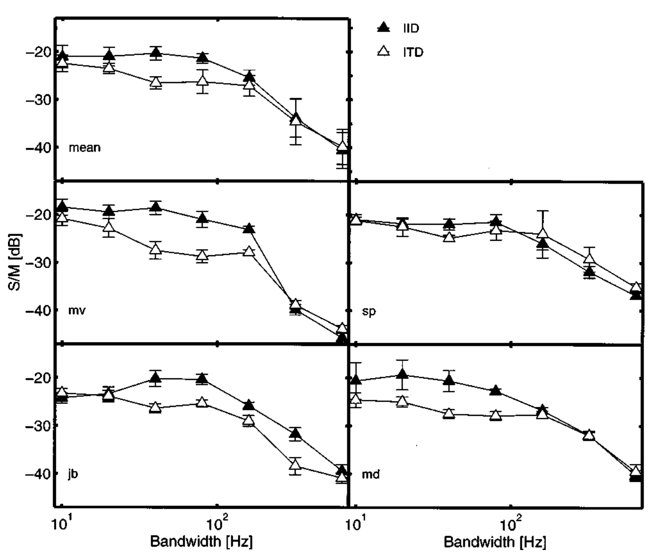

FIG. 6. Detection thresholds for an interaurally out-of-phase multiplied noise signal added to an in-phase sinusoidal masker as a function of the bandwidth of the noise for $\alpha=0$ (filled triangles) and $\alpha=\pi/2$ (open triangles). The upper panel shows the mean thresholds.

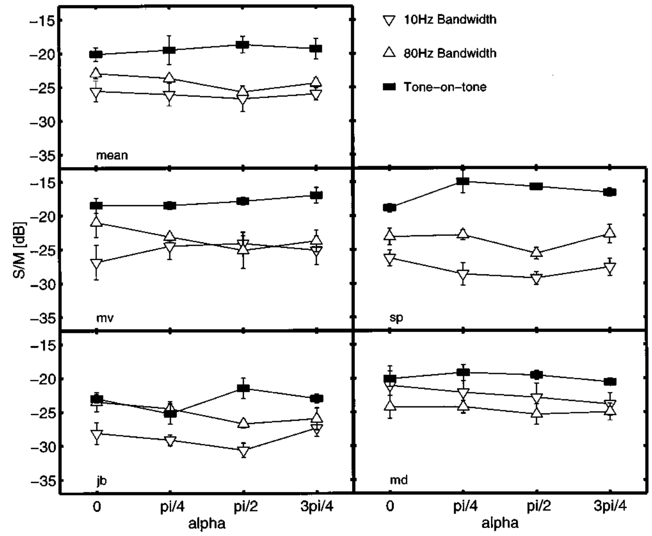

FIG. 7. Detection thresholds for an interaurally out-of-phase sinusoid added to an in-phase sinusoid (squares), a 10-Hz-wide multiplied noise (downward triangles), and an 80-Hz-wide multiplied noise (upward triangles) as a function of the fine-structure phase angle between signal and masker carrier. The lower four panels show thresholds for four subjects, the upper panel shows the mean thresholds.

thresholds for intermediate bandwidths (i.e., 40 and 80 Hz), which is consistent with the data from experiment 2.

D. Experiment 4: Dependence on α

Figure 7 shows thresholds for experiment 4 as a function of the phase angle between masker carrier and signal. The lower four panels show thresholds of four individual subjects, the upper panel shows the mean thresholds. The downward triangles refer to a masker bandwidth of 10 Hz, the upward triangles refer to a masker bandwidth of 80 Hz and the squares to the tone-on-tone condition. The latter has almost always the highest thresholds being 3 to 7 dB higher than thresholds for the noise maskers. Furthermore, a small decrease in thresholds is observed if α is increased from 0 to $\pi/2$ for the 80-Hz-wide condition. For the 10-Hz-wide and the tone-on-tone conditions, the thresholds are independent of α.

IV. DISCUSSION

A. Effect of α

If the overall means of the data presented in Figs. 4 and 5 are considered, the IID thresholds are on average 1.4 dB higher than the ITD thresholds. This value is roughly in line with the observed 3 dB found by van de Par and Kohlrausch (1998b). Furthermore, the data shown in Fig. 7 show a minor influence of the masker-signal phase α, for both static and dynamically varying interaural differences. Many studies have been published which present differences between ITD-only and IID-only conditions varying between -8 and $+6.5$ dB (Jeffress *et al.*, 1956; Hafter *et al.*, 1969; Wightman, 1969; Jeffress and McFadden, 1971; McFadden *et al.*, 1971; Wightman, 1971; Yost, 1972b; Yost *et al.*, 1974; Robinson *et al.*, 1974). Only one study reports differences that deviate from these data with differences of up to 16 dB (Grantham and Robinson, 1977). We therefore conclude that our results are well within the range of other data, although there does not exist much consistency about the influence of α on detection thresholds.

If the thresholds for $\alpha=\pi/4$ and $\alpha=3\pi/4$ are compared, only small threshold differences of less than 3 dB are found. Grantham and Robinson (1977) reported differences varying between -5 and $+8$ dB across different subjects. Also studies of Robinson *et al.* (1974) and Hafter *et al.* (1969) report differences within that range.

Corresponding to results from other studies (cf. McFadden *et al.*, 1971; Jeffress and McFadden, 1971; Grantham and Robinson, 1977), large differences exist across subjects when the effect of α is concerned. Some subjects seem to be more sensitive to signals producing ITDs, and some to IIDs. Thus, one general model can never account for these interindividual differences. But since we are comparing theories and trying to model the general trend, we focus on the mean data knowing that individual differences are not taken into account.

If binaural detection were based on changes in laterality resulting from a combined time-intensity image, different thresholds would be expected for $\alpha=\pi/4$ and $\alpha=3\pi/4$. For $\alpha=\pi/4$, the interaural differences in time and intensity point in the same direction and the combined image would be lateralized more than for each cue separately, while for $\alpha=3\pi/4$, the ITDs and IIDs would (at least) partially cancel each other. The very similar threshold values suggest that detection is not based on changes in laterality resulting from a combined time-intensity image.

B. Binaural sluggishness

Several studies have provided evidence that the binaural auditory system is sluggish. We can classify these studies into two categories. The first category comprises experiments that determine the ability of human observers to detect interaural differences against a reference signal that contains no interaural differences. For example, if observers have to discriminate a binaural amplitude-modulated noise in which the modulating sinusoid is interaurally in-phase, from the same amplitude-modulated noise in which the modulator is interaurally out-of-phase, a substantial increase in the modulation depth at threshold is observed if the modulation frequency is increased from 0 to 50 Hz (Grantham, 1984). Similar results were found for dynamically varying ITDs (Grantham and Wightman, 1978). However, the time constant of processing dynamically varying ITDs seems to be longer than for IIDs. Estimates for these constants are approximately 200 and 50 ms, respectively (Grantham, 1984). Also many binaural masking conditions like $MoS\pi$ fall into this category of detection against a monaural reference signal (Zurek and Durlach, 1987). The second category comprises binaural detection experiments in which the masker has a time-varying correlation (cf. Grantham and Wightman, 1979; Kollmeier and Gilkey, 1990; Culling and Summerheld, 1998). These studies show that modulation rates of interaural correlation as low as 4 Hz result in large increases in detection thresholds.

The experiments performed in our study clearly belong to the first group, because the correlation of the masker is always one. The fact that our results do not show any difference between the 10- and 80-Hz-wide conditions runs counter to an expectation based on binaural sluggishness. If one tries to characterize the rate at which the interaural differences change from leading to lagging in each ear, one could take the expected number of zero-crossings of the low-pass noise used in generating the multiplied noise. Roughly, if the low-pass noise changes its sign, the resulting interaural difference in an $MoS\pi$ condition also changes its sign. Thus, the number of zero-crossings represents the number of changes per second in lateralization pointing to the left or right ear. For a 10-Hz-wide noise, the expected number of lateralization changes amounts to 5.8 per second, while for the conditions at 80-Hz bandwidth, the expected number is 46.2 (Rice, 1959). On the basis of the expected number of zero-crossings, assuming that the binaural system is sluggish in its processing of binaural cues, a difference in detection thresholds is expected between conditions at 10- and 80-Hz bandwidth. Furthermore, assuming that the time constant for processing ITDs is longer than for IIDs (Grantham, 1984), the ITD-only thresholds should be higher than than the IID-only thresholds for the 80-Hz-wide condition. The MANOVA analysis shows that the bandwidth of the multiplied noise is not a significant factor, indicating that the thresholds between the 10- and the 80-Hz-wide conditions are similar. Furthermore, the data do not show the expected difference between the IID-only and the ITD-only conditions for a bandwidth of 80 Hz. Thus, effects of sluggishness, although expected, were not found in this study.

C. Off-frequency listening

For bandwidths beyond 80 Hz using a multiplied-noise signal, the thresholds decrease with increasing bandwidth (see Fig. 6). This is probably caused by the fact that the signal bandwidth exceeds the equivalent rectangular bandwidth of the auditory filters. Thus, the signal-to-masker ratio within an auditory filter tuned to a frequency just below or just above the masker frequency will be larger than for an on-frequency filter, resulting in lower detection thresholds if off-frequency filters can be used for detection. These off-frequency effects start to play a role for a signal bandwidth of 160 Hz. This indicates that for the results of experiment 2, where the maximum employed bandwidth was 80 Hz, off-frequency listening is not likely to influence detection thresholds. Hence, the externally presented interaural differences are very similar to the differences after peripheral filtering for all experiments. Therefore, we can validly compare the parameters of the distributions of the interaural differences at threshold across experiments with multiplied noise as masker and as signal.

One noteworthy effect seen in the data which is a significant factor according to our statistical assessment is that the ITD-only thresholds for a multiplied-noise signal decrease by 5 dB when the bandwidth is increased from 10 to 80 Hz, while for a multiplied-noise masker, this decrease does not occur. It is not clear what causes this effect.

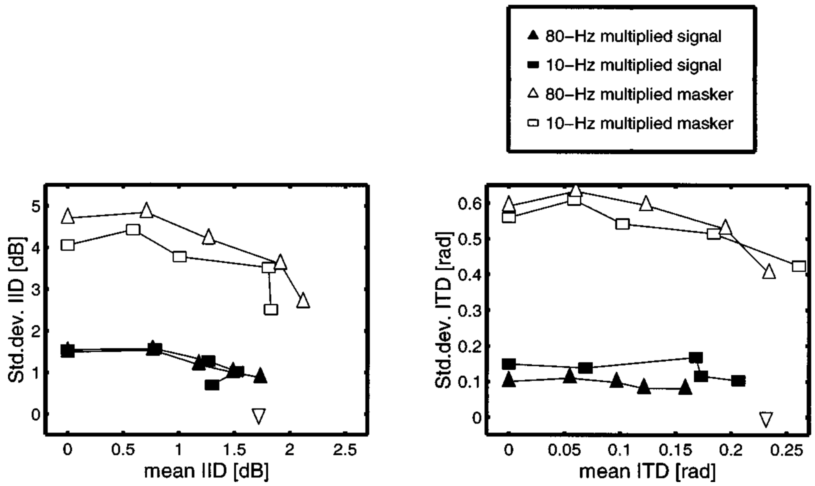

FIG. 8. Mean and standard deviation of the interaural cues at threshold level at 10-Hz bandwidth (squares) and 80-Hz bandwidth (upward triangles). The open symbols represent data for a diotic multiplied-noise masker (experiment 1), the filled symbols represent data for an interaurally out-of-phase multiplied noise signal (experiment 2). The downward triangles represent the data for the tone-on-tone conditions (experiment 4). The left panels shows data for the IID-only conditions, the right panel shows data for the ITD-only conditions.

D. Models based on the evaluation of IIDs and ITDs

In this section we analyze the contribution of static and dynamic cues to binaural detection. For this purpose we consider the mean, the standard deviation, and the rms of the probability density functions for IIDs and ITDs at threshold for the mean data shown in Figs. 4 and 5. The left panel of Fig. 8 shows the standard deviations of the probability density functions for IID-only conditions as a function of the mean IID, while the right panel shows the standard deviations of the ITD functions as a function of the mean ITD for the ITD-only conditions. The open symbols represent thresholds from experiment 1, the filled symbols represent thresholds from experiment 2. The squares represent the 10-Hz-wide noise, the upward triangles the 80-Hz-wide noise, and the downward triangles the tone-on-tone conditions. The data at the left side in each panel represent $\mu=0$, while from left to right, the static component increases. With increasing static component, the mean of the interaural difference at threshold level increases also, while the standard deviation shows a minor decrease.

Clearly, the mean interaural differences at $\mu=2$ for the conditions with multiplied noise (upward triangles and squares at the right side of each panel) are very similar to the tone-on-tone conditions (downward triangles). Furthermore, we see that points for 10-Hz bandwidth lie very close to points for 80-Hz bandwidth. This is expected, because these conditions have very similar detection thresholds. Because the mean and standard deviation of the interaural difference are independent of the bandwidth of the signals, similar thresholds result in similar statistics of the interaural differences.

The standard deviations for experiment 2 (filled symbols) are approximately four times smaller than for experiment 1 (open symbols). To end up with a similar standard deviation for IIDs at threshold for experiment 2 as in experiment 1, the signal-to-masker ratio must amount to -11 dB for $\mu=0$. However, the data show a threshold of -21 dB. Thus, the standard deviations of the interaural differences cannot be used to correctly predict binaural masked thresholds for both experiments.[2]

The only data available in the literature using comparable stimuli are those published by Grantham and Robinson (1977). Similar to our procedure, they used a noise stimulus with a certain dc offset and multiplied this noise with a sinusoidal carrier. The resulting bandpass noise (120 Hz wide) was used as a masker in an MoSπ condition. They did not vary the dc offset, however, but fixed it to a value that corresponds to $\mu=2.05$ in our framework. In addition, they in-

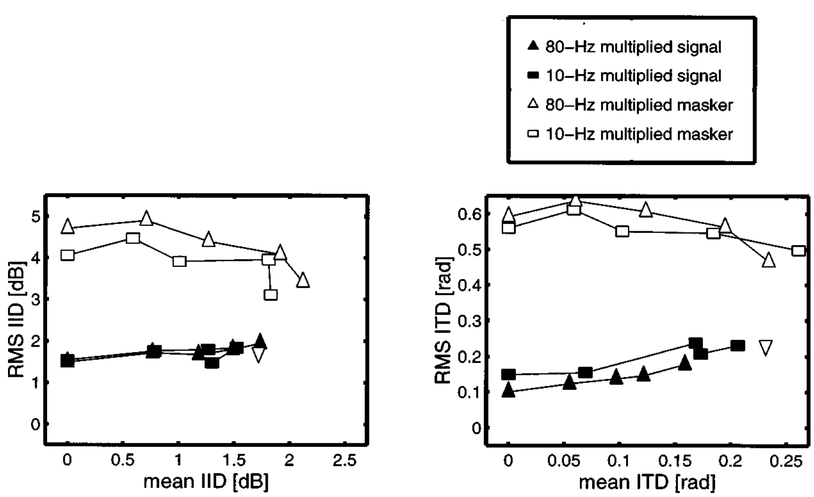

FIG. 9. Mean and rms value of the interaural cues at threshold level in the same format as Fig. 8.

cluded the tone-on-tone conditions in their experiment. Because of the fact that their IID data are relatively high and their ITD data are relatively low compared to our results, we focus on the relative difference between the conditions with noise maskers and tonal maskers. For IIDs only, Grantham and Robinson (1977) found a mean IID at threshold of 3.2 and 3.1 dB for tonal and noise maskers, respectively. For ITD-only conditions, these values amounted to 0.080 and 0.106 rad, respectively. Thus, in correspondence with our data, the mean interaural differences for the tonal masker are slightly lower than for the noise masker for $\alpha=\pi/2$. From our analysis based on PDFs, it is clear that the close correspondence between the mean values of the interaural cues found by Grantham and Robinson relies on their specific choice of μ. Had they chosen a lower value, then they probably would have found larger discrepancies: for $\mu=0$, the mean interaural cue is equal to zero at threshold, while for large values of μ, mean interaural differences of up to 4 dB or 0.1 rad may be found at threshold. Thus, the mean interaural difference cannot account for the complete set of data either.

A straightforward way to combine the sensitivity for static and dynamically varying interaural differences is to consider the rms value of the interaural differences. Figure 9 shows the rms values of the interaural cues of the mean data of experiments 1 and 2 as a function of the mean interaural cues. The format is the same as in Fig. 8. Within one experiment, the rms value remains fairly constant, although there is a tendency for the rms to decrease with increasing mean for the data with a multiplied-noise masker and to increase for the multiplied-noise signal. However, we can reject the rms as a valuable detection variable because for this measure, too, the values of the two experiments differ by a factor 2 to 4.

E. Models based on the interaural correlation

Another detection statistic that is often proposed to account for binaural masked thresholds is the interaural correlation. Domnitz and Colburn (1976) argued that for an out-of-phase sinusoidal signal combined with a diotic Gaussian-noise masker, models based on the PDFs of the interaural differences and models based on the interaural correlation

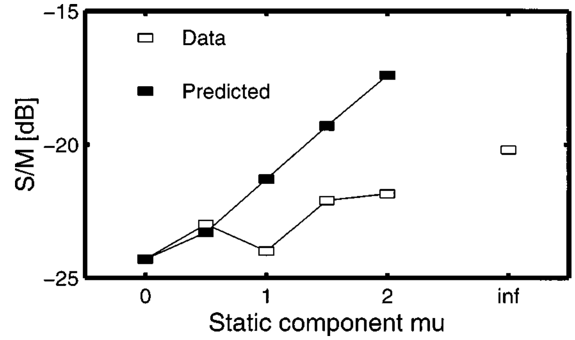

FIG. 10. Predicted values according to a simple interaural correlation model (filled symbols) and experimental data (open symbols) for an MoSπ condition with a multiplied-noise masker and $\alpha=0$ as a function of the static component.

are equivalent. We will now explore whether this statement also holds for our stimuli. For a diotic masker alone, the interaural correlation equals +1. The interaural correlation for the masker plus signal is given by (Durlach *et al.*, 1986):

$$\rho=\frac{1-\langle S^2\rangle/\langle M^2\rangle}{1+\langle S^2\rangle/\langle M^2\rangle}, \tag{1}$$

where $\langle S^2\rangle/\langle M^2\rangle$ denotes the signal-to-masker power ratio. This equation holds provided that masker and signal are statistically independent. For our stimuli, this is true provided that $\mu=0$ or $\alpha=\pi/2$. Thus, the correlation is only dependent on the signal-to-masker ratio and does not depend on the physical nature of the interaural difference (i.e., IIDs or ITDs). Furthermore, the correlation is not dependent on the shape of the PDFs of the interaural differences. Therefore, contrary to models based on the PDF of the interaural cues, a model based on the cross correlation will yield *equal* thresholds for experiments 1 and 2, on the condition that $\mu=0$ or $\alpha=\pi/2$ (i.e., masker and signal uncorrelated). This implies that the statement from Domnitz and Colburn (1976) cannot be generalized to our stimuli and that with our stimuli a valuable way to distinguish between cross-correlation models and binaural-cue-based models is available.

Equation (1) is, however, not applicable under conditions where $\alpha\neq\pi/2$ and $\mu>0$. For $\alpha=0$, the interaural correlation can be written as (see Appendix B)

$$\rho=\frac{\langle M^2\rangle-\langle S^2\rangle}{\sqrt{(\langle M^2\rangle+\langle S^2\rangle+\langle 2SM\mu\rangle/\sqrt{1+\mu^2})(\langle M^2\rangle+\langle S^2\rangle-\langle 2SM\mu\rangle/\sqrt{1+\mu^2})}}. \tag{2}$$

From the above equation, we see that the static component has a strong influence on the interaural correlation of an MoSπ stimulus. We therefore computed the predictions according to a simple interaural correlation model for an MoSπ condition with a multiplied-noise masker as a function of the static component μ. The overall mean signal-to-masker ratio at threshold for $\alpha=0$ and $\mu=0$ in our experiments was −24.3 dB, resulting in an interaural correlation of 0.9926. We therefore used a *decorrelation* of 0.0074 as a just noticeable difference (jnd) in the interaural correlation. From this correlation jnd, we computed the signal-to-masker ratios that produce the same amount of decorrelation as a function of the static component μ. The computed thresholds are shown by the filled squares in Fig. 10. The open symbols represent the mean experimental data from experiment 1 for $\alpha=0$. Clearly, the predicted values based on the change in the in-

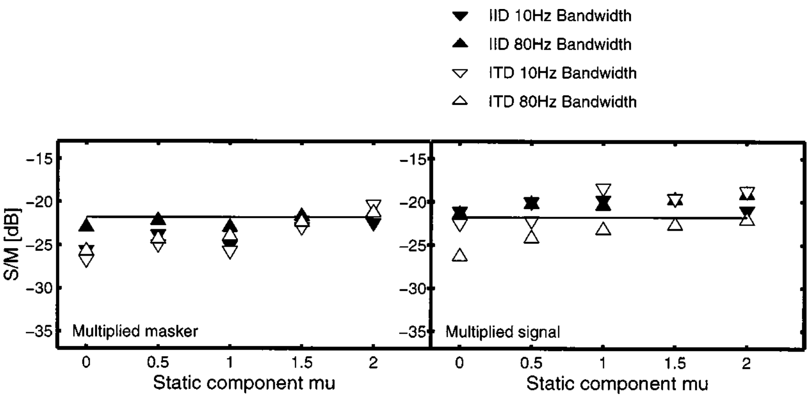

FIG. 11. Predicted values of experiments 1 and 2 according to an EC-like model (solid line) and experimental data (symbols, in the same format as in Fig. 4) for an MoSπ condition with a multiplied-noise masker (left panel) and a multiplied-noise signal (right panel) as a function of the static component.

teraural correlation show a large increase in threshold with increasing static component. This results from the insensitivity of the interaural correlation to static interaural intensity differences. This strong increase was not found in our experimental data, implying that a simple cross-correlation model without extensions for static interaural intensity differences cannot account for the data.

F. A new model

The question arises which other detection statistic can be used to characterize our data. Because the experimental data show approximately similar thresholds across all the experimental conditions, we propose that a model based on the *difference intensity* of the signals arriving at both ears could be a valid detection statistic. We define difference intensity as the intensity in the stimulus obtained when the waveforms to the two ears are equalized and differenced. This approach is related to Durlach's EC-theory (Durlach, 1963), but the two are not equivalent: the EC-theory predicts BMLDs, while this approach describes binaural thresholds directly. Such an approach also differs from a cross-correlation model for stimuli containing static IIDs. For tone-on-tone conditions with $\alpha=0$ (i.e., only static IIDs are present), a cross-correlation model fails to detect the static IID, while the present approach is sensitive to this cue, as will be explained below.

In our approach, an internal interaural delay and an internal interaural intensity difference are determined which tend to equalize the masking signal arriving at the two ears. These parameters can be obtained from the masker-alone intervals. For the signal interval, the *masker* is equalized and subsequently eliminated by a cancelation process. For signals producing interaural intensity differences, the amount of signal remaining after the described equalization process increases with an increasing interaural intensity difference; hence, static IIDs can be detected. For MoSπ stimuli, the masker-elimination process is simply performed by subtracting the waveforms at both ears, computing the power of the remaining signal and using this as a decision variable. If the signals arriving at the left and the right ears are denoted by $L(t)$ and $R(t)$, respectively, the difference intensity D is defined as

$$D=\int_0^T (L(t)-R(t))^2\,dt. \qquad (3)$$

Here, T denotes the interval length. In fact, for an MoSπ condition, D is exactly equal to four times the energy of the out-of-phase signal. Hence a model based on this processing scheme would give equal thresholds for all subcritical conditions (i.e., with a noise bandwidth of 80 Hz or less), because the difference intensity D is directly proportional to the signal intensity. For all MoSπ conditions as presented in this study, the only limiting factor in the detection process will be the internal errors, since the masker can be cancelled completely. The magnitude of this internal error can, in principle, be set to any (fixed) value. We can therefore simply derive predictions for the experiments 1, 2, and 4. We adjusted this value to result in a signal-to-masker threshold value of -22 dB. The predictions according to this model are shown in Figs. 11 and 12. Figure 11 shows the thresholds for experiments 1 and 2 (left and right panels, respectively) in the same format as Fig. 4. The solid line represents the model predictions. Figure 12 shows the mean data of Fig. 7 (experiment 4) combined with the model predictions (solid line). We did not simulate the data for experiment 3, because modeling off-frequency effects needs a much more complicated model. We are in the process of describing such a model, but it is far beyond the scope of this paper to include it here.

The predictions match the experimental data quite well. There are, however, some differences between data and model predictions, which can be summarized as follows:

(i) The slight increase of thresholds with increasing static component (see Fig. 11) is not present in the model simulations.

(ii) The fact that the thresholds for a multiplied-noise

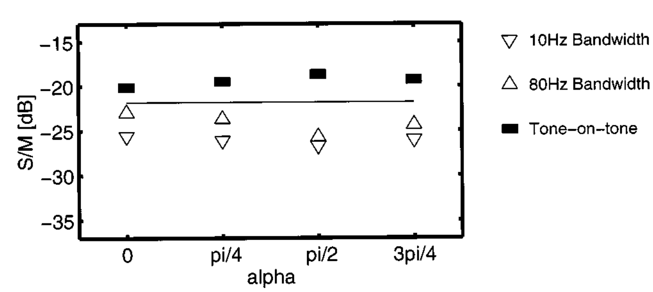

FIG. 12. Predicted values of experiment 4 according to an EC-like model (solid line) and experimental data (symbols, same format as in Fig. 7) for an MoSπ condition as a function of the masker-signal phase difference α.

masker are on average 2.2 dB lower than the data for a multiplied-noise signal is not represented in the model predictions.

(iii) The fact that the tone-on-tone conditions (filled symbols in Fig. 12) give higher thresholds than the multiplied-noise maskers (open symbols in Fig. 12) cannot be understood by this simple model.

(iv) The model's performance is independent of the masker-signal phase difference α, while the experimental data show an overall difference of 1.4 dB if α is changed from 0 to $\pi/2$.

However, some of these effects can be understood by considering the presence of nonlinearities in the peripheral auditory system. For example, we can qualitatively account for the fact that the ITD thresholds are 1.4 dB lower than the IID thresholds by assuming that peripheral compression at the level of the basilar membrane has an effect on binaural masked thresholds. This issue was already discussed by van de Par and Kohlrausch (1998c, 1999). Following their hypothesis, basilar membrane compression results in a decrease of the IIDs in the internal representation and has no effect on ITDs, resulting in higher IID thresholds if the difference intensity is used as a decision variable. Peripheral compression also has a strong effect on binaural masked thresholds with different masker-envelope statistics (van de Par and Kohlrausch, 1998b). Compression reduces interaural intensity differences most strongly for high envelope values. Because a sinusoidal masker has no valleys in the envelope and multiplied noise has many valleys in its envelope, it is expected that IID thresholds for a sinusoidal masker (see Fig. 5) are higher than for a multiplied noise masker (see Fig. 4), in line with the observed overall difference of 2.2 dB. This rationale also holds for the increase in thresholds with an increase of the static component. As described in Sec. I A, the static component has a strong influence on the envelope statistics of the stimuli, resulting in fewer valleys in the envelope if the static component is increased.

However, an EC-like model fails to account for the tone-on-tone data shown in Fig. 12. Here, the tone-on-tone conditions show distinctively higher thresholds than the conditions with a multiplied-noise masker, while an EC-like model without peripheral compression predicts equal thresholds. The inclusion of peripheral compression might account for the fact that the IID tone-on-tone thresholds are higher than the conditions with noise maskers. It is more difficult, however, to see how compression can explain the difference in threshold between tonal and noise maskers with ITDs only.

In summary, the binaural masked thresholds for MoSπ stimuli in the present study seem to be best described by a peripheral preprocessing stage followed by a differencing device that calculates the difference intensity of the signals from the left and right ears and uses this output as a detection variable. Although such an approach cannot account for all data presented here, it provides better predictions than a model based on the probability distributions of the interaural differences or a cross-correlation model *per se*.

ACKNOWLEDGMENTS

We would like to thank A. Houtsma, the associate editor D. W. Grantham, Q. Summerfield, and one anonymous reviewer for helpful comments on the manuscript. The investigations were (in part) supported by the Research Council for Earth and Lifesciences (ALW) with financial aid from the Netherlands Organization for Scientific Research (NWO).

APPENDIX A: DERIVATION OF THE DISTRIBUTIONS OF INTERAURAL DIFFERENCES

1. ITD probability density for a multiplied-noise masker

Figure 1 shows a vector diagram illustrating an interaurally out-of-phase signal $\mathbf{S}_l$ and $\mathbf{S}_r$, a noise masker $\mathbf{M}$, and the resulting signals $\mathbf{L}$ and $\mathbf{R}$ presented at the two ears. The phase angle between masker and signal fine structures is denoted by α, the phase angle between $\mathbf{L}$ and $\mathbf{R}$ by ϕ (with $-\pi<\phi\leqslant\pi$). For the interaural phase ϕ, a convenient expression relating the variables was given by Zurek (1991):

$$\phi=\frac{\pi}{2}-\arctan\frac{A\cos\alpha-S}{A\sin\alpha}-\arctan\frac{A\sin\alpha}{S+A\cos\alpha}. \tag{A1}$$

Here, A represents the instantaneous value of the low-pass noise. Note that A is defined as the sum of a dc component μ and a Gaussian noise with mean zero and rms=1, which is rescaled to have unit power. This results in a probability density function for A given by:

$$p(A)=\sqrt{\frac{1+\mu^2}{2\pi}}\exp\left(-1/2(-\mu+A\sqrt{1+\mu^2})^2\right). \tag{A2}$$

The phase probability density $p(\phi)$ can be written as the product of the probability density for $A(\phi)$, multiplied by the absolute derivative of A to ϕ:

$$p(\phi)=p(A(\phi))\left|\frac{dA(\phi)}{d\phi}\right|. \tag{A3}$$

Equation (A1) gives an expression for $\phi(A)$. However, to derive an expression for $p(\phi)$, an expression for $A(\phi)$ is needed. We have to study two distinct cases. We see from Fig. 1 that for $A\geqslant0$, $\phi\geqslant0$ and that for $A<0$, $\phi<0$. $A(\phi)$ can be derived by inverting Eq. (A1), resulting in a second-order polynomial equation which normally has two roots. However, according to the above restriction, the solution for $A(\phi)$ results in

$$A(\phi)=-S\sin\alpha\tan(\phi-\pi/2)+\beta S\sqrt{\sin^2\alpha\tan^2(\phi-\pi/2)+1}, \tag{A4}$$

where β equals 1 for $\phi\geqslant0$ and -1 otherwise. The derivative of A to ϕ becomes

$$\frac{dA}{d\phi}=\frac{-S\sin\alpha}{\cos^2(\phi-\pi/2)}+\frac{\beta S\sin^2\alpha\tan(\phi-\pi/2)}{\cos^2(\phi-\pi/2)\sqrt{\sin^2\alpha\tan^2(\phi-\pi/2)+1}}. \tag{A5}$$

Now, all parameters for Eq. (A3) are known and $p(\phi)$ can be calculated.

2. IID probability density for a multiplied-noise masker

The probability density function for the IID can be derived in a very similar way as was done for the ITD. The interaural intensity difference λ is defined as

$$\lambda = 20 \log \frac{|R|}{|L|} = 10 \log \frac{A^2+S^2+2AS\cos\alpha}{A^2+S^2-2AS\cos\alpha}. \tag{A6}$$

Inverting the above equation results in

$$A(\lambda) = -S\cos\alpha \frac{1+10^{\lambda/10}}{1-10^{\lambda/10}} + \beta S\sqrt{-1+\left(\frac{1+10^{\lambda/10}}{1-10^{\lambda/10}}\right)^2 \cos^2\alpha}, \tag{A7}$$

for $\lambda \geqslant 0$, $A \geqslant 0$ and $\lambda < 0$, $A < 0$. Therefore, $\beta = 1$ for $\lambda \geqslant 0$ and -1 otherwise. The probability density function for λ is given by

$$p(\lambda) = p(A(\lambda)) \left| \frac{dA(\lambda)}{d\lambda} \right|. \tag{A8}$$

Equations (A2), (A7), and (A8) give all necessary parameters to calculate $p(\lambda)$.

3. ITD and IID probability density for a multiplied-noise signal

When exchanging the role of multiplied noise and sinusoid (i.e., the multiplied noise becomes an interaurally out-of-phase signal), we obtain a new relation between interaural phase ϕ and the instantaneous value of the low-pass noise A:

$$A(\phi) = S\sin\alpha\tan(\phi-\pi/2) + \beta S\sqrt{\sin^2\alpha\tan^2(\phi-\pi/2)+1}. \tag{A9}$$

Again, β equals one for $\phi \geqslant 1$ and -1 otherwise. The probability density function is then given by Eq. (A3), where $A(\phi)$ has to be taken from Eq. (A9).

The IID probability density function is given as in Eq. (A8), however, with

$$A(\lambda) = S\frac{1+10^{\lambda/10}}{1-10^{\lambda/10}}\cos\alpha + \beta S\sqrt{-1+\left(\frac{1+10^{\lambda/10}}{1-10^{\lambda/10}}\right)^2 \cos^2\alpha}, \tag{A10}$$

where $\beta = 1$ for $A \geqslant 0$ and -1 otherwise.

APPENDIX B: INTERAURAL CROSS CORRELATION FOR STIMULI WITH STATIC AND DYNAMICALLY VARYING IIDs

For a multiplied-noise masker combined with a sinusoidal test signal with $\alpha = 0$ in an MoSπ condition, the waveforms arriving at the left and right ears [$L(t)$ and $R(t)$, respectively] are given by

$$L(t) = M\sqrt{2}\frac{N(t)+\mu}{\sqrt{1+\mu^2}}\sin(2\pi ft) + \sqrt{2}S\sin(2\pi ft), \tag{B1}$$

$$R(t) = M\sqrt{2}\frac{N(t)+\mu}{\sqrt{1+\mu^2}}\sin(2\pi ft) - \sqrt{2}S\sin(2\pi ft). \tag{B2}$$

Here, M denotes the rms value of the masker, S the rms value of the signal, $N(t)$ denotes the low-pass noise that is used for generating the multiplied noise, μ denotes the static component, and f is the carrier frequency. The definition of the normalized interaural correlation is

$$\rho = \frac{\langle L.R \rangle}{\sqrt{\langle L^2 \rangle \langle R^2 \rangle}}, \tag{B3}$$

where $\langle . \rangle$ denotes the expected value. Combining Eqs. (B1) to (B3) results in

$$\rho = \frac{\langle M^2 \rangle - \langle S^2 \rangle}{\sqrt{(\langle M^2 \rangle + \langle S^2 \rangle + \langle 2SM\mu \rangle / \sqrt{1+\mu^2})(\langle M^2 \rangle + \langle S^2 \rangle - \langle 2SM\mu \rangle / \sqrt{1+\mu^2})}}. \tag{B4}$$

[1]The measure μ for expressing the relative amount of static and dynamically varying cues, which will be introduced in Sec. I A, was equal to 2.05 for the experiments performed by Grantham and Robinson.

[2]In addition, other moments of the PDFs of the interaural differences were evaluated at threshold level. These properties also resulted in significantly larger differences between the thresholds of experiments 1 and 2 than the observed difference of 2.2 dB.

Bernstein, L. R., and Trahiotis, C. (**1997**). ''The effects of randomizing values of interaural disparities on binaural detection and on discrimination of interaural correlation,'' J. Acoust. Soc. Am. **102**, 1113–1120.

Breebaart, J., van de Par, S., and Kohlrausch, A. (**1998**). ''Binaural signal detection with phase-shifted and time-delayed noise maskers,'' J. Acoust. Soc. Am. **103**, 2079–2083.

Colburn, H. S. (**1977**). ''Theory of binaural interaction based on auditory-nerve data. II. Detection of tones in noise,'' J. Acoust. Soc. Am. **61**, 525–533.

Culling, J. F., and Summerfield, Q. (**1998**). ''Measurements of the binaural temporal window using a detection task,'' J. Acoust. Soc. Am. **103**, 3540–3553.

Domnitz, R. H., and Colburn, H. S. (**1976**). ''Analysis of binaural detection models for dependence on interaural target parameters,'' J. Acoust. Soc. Am. **59**, 598–601.

Durlach, N. I. (**1963**). ''Equalization and cancellation theory of binaural masking-level differences,'' J. Acoust. Soc. Am. **35**, 1206–1218.

Durlach, N. I., Gabriel, K. J., Colburn, H. S., and Trahiotis, C. (**1986**). ''Interaural correlation discrimination: II. Relation to binaural unmasking,'' J. Acoust. Soc. Am. **79**, 1548–1557.

Gaik, W. (**1993**). ''Combined evaluation of interaural time and intensity differences: psychoacoustic results and computer modeling,'' J. Acoust. Soc. Am. **94**, 98–110.

Glasberg, B. R., and Moore, B. C. J. (**1990**). ''Derivation of auditory filter shapes from notched-noise data,'' Hearing Res. **47**, 103–138.
Grantham, D. W. (**1984**). ''Discrimination of dynamic interaural intensity differences,'' J. Acoust. Soc. Am. **76**, 71–76.
Grantham, D. W., and Robinson, D. E. (**1977**). ''Role of dynamic cues in monaural and binaural signal detection,'' J. Acoust. Soc. Am. **61**, 542–551.
Grantham, D. W., and Wightman, F. L. (**1978**). ''Detectability of varying interaural temporal differences,'' J. Acoust. Soc. Am. **63**, 511–523.
Grantham, D. W., and Wightman, F. L. (**1979**). ''Detectability of a pulsed tone in the presence of a masker with time-varying interaural correlation,'' J. Acoust. Soc. Am. **65**, 1509–1517.
Hafter, E. R. (**1971**). ''Quantitative evaluation of a lateralization model of masking-level differences,'' J. Acoust. Soc. Am. **50**, 1116–1122.
Hafter, E. R., and Carrier, S. C. (**1970**). ''Masking-level differences obtained with pulsed tonal maskers,'' J. Acoust. Soc. Am. **47**, 1041–1047.
Hafter, E. R., Bourbon, W. T., Blocker, A. S., and Tucker, A. (**1969**). ''A direct comparison between lateralization and detection under conditions of antiphasic masking,'' J. Acoust. Soc. Am. **46**, 1452–1457.
Hirsh, I. (**1948**). ''The influence of interaural phase on interaural summation and inhibition,'' J. Acoust. Soc. Am. **20**, 536–544.
Holube, I. (**1993**). ''Experimente und Modellvorstellungen zur Psychoakustik und zum Sprachverstehen bei Normal- und Schwerhörigen,'' Ph.D. thesis, Georg-August-Universität Göttingen, Göttingen.
Holube, I., Kinkel, M., and Kollmeier, B. (**1998**). ''Binaural and monaural auditory filter bandwidths and time constants in probe tone detection experiments,'' J. Acoust. Soc. Am. **104**, 2412–2425.
Jeffress, L. A., and McFadden, D. (**1968**). ''MLD's and the phase angle, alpha,'' J. Acoust. Soc. Am. **43**, 164.
Jeffress, L. A., and McFadden, D. (**1971**). ''Differences of interaural phase and level in detection and lateralization,'' J. Acoust. Soc. Am. **49**, 1169–1179.
Jeffress, L. A., Blodgett, H. C., and Deatherage, B. H. (**1962**). ''Masking and interaural phase. II. 167 cycles,'' J. Acoust. Soc. Am. **34**, 1124–1126.
Jeffress, L. A., Blodgett, H. C., Sandel, T. T., and Wood, C. L. (**1956**). ''Masking of tonal signals,'' J. Acoust. Soc. Am. **28**, 1416–1426.
Kollmeier, B., and Gilkey, R. H. (**1990**). ''Binaural forward and backward masking: evidence for sluggishness in binaural detection,'' J. Acoust. Soc. Am. **87**, 1709–1719.
Levitt, H. (**1971**). ''Transformed up-down methods in psychoacoustics,'' J. Acoust. Soc. Am. **49**, 467–477.
Lindemann, W. (**1986**). ''Extension of a binaural cross-correlation model by contralateral inhibition. I. Simulation of lateralization for stationary signals,'' J. Acoust. Soc. Am. **80**, 1608–1622.
McFadden, D., Jeffress, L. A., and Ermey, H. L. (**1971**). ''Difference in interaural phase and level in detection and lateralization: 250 Hz,'' J. Acoust. Soc. Am. **50**, 1484–1493.
Osman, E. (**1971**). ''A correlation model of binaural masking level differences,'' J. Acoust. Soc. Am. **50**, 1494–1511.
Perrott, D. R., and Musicant, A. D. (**1977**). ''Minimum auditory movement angle: binaural localization of moving sound sources,'' J. Acoust. Soc. Am. **62**, 1463–1466.
Rice, S. O. (**1959**). *Selected Papers on Noise and Stochastic Processes* (Dover, New York), Chap. Mathematical analysis of random noise.
Robinson, D. E., Langford, T. L., and Yost, W. A. (**1974**). ''Masking of tones by tones and of noise by noise,'' Percept. Psychophys. **15**, 159–167.
Sayers, B. M. (**1964**). ''Acoustic image lateralization judgments with binaural tones,'' J. Acoust. Soc. Am. **36**, 923–926.
Stern, R. M., and Shear, G. D. (**1996**). ''Lateralization and detection of low-frequency binaural stimuli: Effects of distribution of internal delay,'' J. Acoust. Soc. Am. **100**, 2278–2288.
van de Par, S., and Kohlrausch, A. (**1995**). ''Analytical expressions for the envelope correlation of certain narrow-band stimuli,'' J. Acoust. Soc. Am. **98**, 3157–3169.
van de Par, S., and Kohlrausch, A. (**1998a**). ''Analytical expressions for the envelope correlation of narrow-band stimuli used in CMR and BMLD research,'' J. Acoust. Soc. Am. **103**, 3605–3620.
van de Par, S., and Kohlrausch, A. (**1998b**). ''Diotic and dichotic detection using multiplied-noise maskers,'' J. Acoust. Soc. Am. **103**, 2100–2110.
van de Par, S., and Kohlrausch, A. (**1998c**). ''Further evidence for the influence of peripheral compression on binaural detection,'' in *Proceedings of the Joint Acoustical Society of America Meeting and the International Congress on Acoustics*, Seattle, June 1998, pp. 853–854.
van de Par, S., and Kohlrausch, A. (**1999**). ''The influence of basilar-membrane compression on binaural detection,'' J. Acoust. Soc. Am. (submitted for publication).
Webster, F. A. (**1951**). ''The influence of interaural phase on masked thresholds. I. The role of interaural time-deviation,'' J. Acoust. Soc. Am. **23**, 452–462.
Wightman, F. (**1969**). ''Binaural masking with sine-wave maskers,'' J. Acoust. Soc. Am. **45**, 71–78.
Wightman, F. (**1971**). ''Detection of binaural tones as a function of masker bandwidth,'' J. Acoust. Soc. Am. **50**, 623–636.
Yost, W. A. (**1972a**). ''Tone-in-tone masking for three binaural listening conditions,'' J. Acoust. Soc. Am. **52**, 1234–1237.
Yost, W. A. (**1972b**). ''Weber's fraction for the intensity of pure tones presented binaurally,'' Percept. Psychophys. **11**, 61–64.
Yost, W. A. (**1981**). ''Lateral position of sinusoids presented with interaural intensive and temporal differences,'' J. Acoust. Soc. Am. **70**, 397–409.
Yost, W. A., Nielsen, D. W., Tanis, D. C., and Bergert, B. (**1974**). ''Tone-on-tone binaural masking with an antiphasic masker,'' Percept. Psychophys. **15**, 233–237.
Zurek, P. M. (**1991**). ''Probability distributions of interaural phase and level differences in binaural detection stimuli,'' J. Acoust. Soc. Am. **90**, 1927–1932.
Zurek, P. M., and Durlach, N. I. (**1987**). ''Masker-bandwidth dependence in homophasic and antiphasic tone detection,'' J. Acoust. Soc. Am. **81**, 459–464.
Zwicker, E., and Henning, G. B. (**1985**). ''The four factors leading to binaural masking-level differences,'' Hearing Res. **19**, 29–47.