ABSTRACT

Differences in interaural phase configuration between a target and a masker can lead to substantial binaural unmasking. This effect is decreased for masking noises with an interaural time difference (ITD). Adding a second noise with an opposing ITD in most cases further reduces binaural unmasking. Thus far, modeling of these detection thresholds required both a mechanism for internal ITD compensation and an increased binaural bandwidth. An alternative explanation for the reduction is that unmasking is impaired by the lower interaural coherence in off-frequency regions caused by the second masker (Marquardt and McAlpine, 2009, JASA pp. EL177 - EL182). Based on this hypothesis, the current work proposes a quantitative multi-channel model using monaurally derived peripheral filter bandwidths and an across-channel incoherence interference mechanism. This mechanism differs from wider filters since it has no effect when the masker coherence is constant across frequency bands. Combined with a monaural energy discrimination pathway, the model predicts the differences between a single delayed noise and two opposingly delayed noises, as well as four other data sets. It helps resolve the inconsistency explaining some data sets requires wide filters while others require narrow filters.

1 Introduction

The detection of a pure tone in noise is facilitated by differences in the interaural phase between tone and noise (Hirsh, 1948). The improvement in the detection threshold compared to the diotic case is referred to as the binaural masking level difference (BMLD). The maximum BMLD is observed when detecting an antiphase pure tone target ($\pi$) in an in-phase noise masker ($N_0$). Adding an interaural time difference (ITD) to the masker has been observed to reduce the BMLD (Langford and Jeffress, 1964). A particularly simple case is when the noise and the target tone have exactly opposite interaural phase differences. In this case, detection thresholds increase gradually and monotonically with increasing noise ITD (Rabiner et al., 1966). The increase can be simulated accurately by exploiting changes in the cross-correlation coefficient of left and right signal after using a filter with an equivalent rectangular bandwidth (ERB) of 60... 85 Hz at a center frequency of 500 Hz (Rabiner et al., 1966; Dietz et al., 2021). This bandwidth range resembles the established estimate of the human peripheral filter bandwidth obtained from monaural psychoacoustic experiments at this frequency which is 79 Hz (Glasberg and Moore, 1990) and referred to as standard filter bandwidth in the following.

Another explanation uses an array of different internal delays, known as delay lines (van der Heijden and Trahiotis, 1999; Stern and Colburn, 1978; Bernstein and Trahiotis, 2018, 2020). Jeffress (1948) suggested that the binaural system
Figure 1: a) Cross-correlogram of delayed noise (SDN) with ITD = 2 ms. White and black areas represent maxima and minima of the cross-correlation functions, respectively. The white box highlights the 500 Hz frequency channel while the gray box highlights a channel centered at 625 Hz. b) Interaural cross-correlogram as in (a) but for opposingly delayed noises (ODN). c) Interaural coherence $|\gamma|$ as a function of noise ITD for SDN (blue lines) and ODN (gray lines) for two underlying filter bandwidths. d) Continuous lines: Normalized cross-power spectral density (CPSD) at ITD = 2 ms as a function of frequency, $C(\omega)$, as derived in Eq. 11 et seq.; Bars: Interaural coherence $|\gamma|$ of the signals after peripheral Gammatone filtering. e) Thresholds of $S_\pi$ detection in SDN and ODN as a function of ITD from van der Heijden and Trahiotis (1999). The dashed lines symbolize the coherence-decline-induced threshold increase determined by a binaural bandwidth of ERB = 79 Hz (lower line) and ERB = 130 Hz (upper line). As denoted by the arrows, the data can be explained in two ways: (1: dotted downward arrow) The ODN thresholds are determined by the cross-correlation function at 500 Hz and a binaural bandwidth $\geq$ 130 Hz. A delay line causes the lower SDN thresholds. (2: solid upward arrow) The SDN thresholds are determined by the ITD-dependent coherence as derived from an ERB of 79 Hz. Off-frequency incoherence in ODN causes higher ODN thresholds.

has the ability to compensate for the external ITD. The compensation accuracy or efficiency has been assumed to decrease with masker ITD in order to model the decreasing BMLD (Stern and Colburn, 1978; van der Heijden and Trahiotis, 1999; Bernstein and Trahiotis, 2017).

van der Heijden and Trahiotis (1999) generated a new stimulus which they termed double-delayed noise (diamonds in Fig. 1e) by adding two noises, one with a positive and one with a negative ITD. We refer to this as opposingly delayed noises (ODN). They found detection thresholds in ODN to be substantially higher than in “regular” delayed
noise termed "single-delayed noise", SDN. Since internal delays can only compensate for the ITD of one noise, ODN limits the usefulness of the putative delay lines. Thus, van der Heijden and Trahiotis (1999) attributed the additional unmasking in SDN, compared to ODN, to the delay lines. So far, only models based on delay lines have precisely accounted for both SDN and ODN detection thresholds. The SDN-ODN detection threshold difference is therefore used as psychoacoustic evidence for long delay lines (Stern et al., 2019). The difference was in fact used to derive the length and potency of the delay line system (van der Heijden and Trahiotis, 1999).

However, two problems exist with establishing the psychoacoustically derived delay line length or internal delay distribution function. First, measured delays in binaural neurons of mammals are short compared to the respective period duration (McAlpine et al., 2001; Joris et al., 2006) and thus too short to fulfill the lengths requirements of delay line models (Thompson et al., 2006; Marquardt and McAlpine, 2009; Stern et al., 2019).

Second, if the delay-line models use their internal delays to account for SDN thresholds while correlation coefficient-based models (Rabiner et al., 1966; Dietz et al., 2021; Encke and Dietz, 2021) are equally precise for SDN without delay lines, the two model types must differ by something else: filter bandwidth. van der Heijden and Trahiotis (1999) started off with ODN to determine the filter bandwidth. They could best fit their ODN thresholds with filters of various shapes and an ERB of 130 to 180 Hz at 500 Hz center frequency. This is expectedly larger than what models without delay lines, such as Encke and Dietz (2021), required for SDN. The two versions cannot both be correct. Thus, either the SDN-threshold-based filter bandwidth is confounded by not considering delay lines or the ODN-based filter bandwidth fit by van der Heijden and Trahiotis (1999) is confounded by something else. For the latter, Marquardt and McAlpine (2009) offered a possible explanation. They identified the interaural coherence to be lower in certain off-frequency regions in ODN but not in SDN. They argued that the higher detection thresholds in ODN could also originate from some detrimental off-frequency impact related to the low coherence rather than from a wider filter bandwidth per se (upward arrow in Fig. 1e). If this is true, both SDN and ODN thresholds can potentially be predicted using the same standard filter bandwidth. Fig. 1, panels a), b) and d), show that the cross-power spectral density is constant across frequency in SDN but spectrally modulated in ODN (see Appendix for derivation).

Leaving aside the first physiologic argument, there are two options to account for the SDN-ODN difference. (1) wider filters combined with delay lines (downward arrow in Fig. 1e) or (2) filters with standard peripheral bandwidths and a detrimental off-frequency impact (upward arrow in Fig. 1e). However, recent data of SDN thresholds measured for different noise bandwidths can only be accurately simulated with filters falling into the standard peripheral bandwidth category (Bernstein and Trahiotis, 2020; Dietz et al., 2021), causing a logical impasse for the wider-filters assumption even within the psychoacoustic domain and for SDN alone.

The aim of this study is thus to develop a model that accounts for SDN and ODN thresholds at the same time, using a standard filter bandwidth and – consequently – without long delay lines but with off-frequency impact. Specifically, we suggest an across-frequency incoherence interference mechanism which is inspired by binaural interference (Bernstein and Trahiotis, 1995) and modulation detection interference (Yost and Sheft, 1989; Oxenham and Dau, 2001). This makes sure that the same "hardware" causes different detection thresholds for maskers with different amounts of off-frequency IPD fluctuations. The here developed mechanism will be described in Section 2 and used to predict critical binaural detection data in Section 3.

Even beside the discussion concerning delay lines in humans and other mammals, the width of filters has caused an unresolved contradiction in the binaural literature that filters need to be narrow to account for some and broad to account for other data (see Verhey and van de Par, 2020 for a review). Generally speaking, detection thresholds in spectrally simpler maskers can be simulated using a standard peripheral filter bandwidth (Breebaart et al., 2001b), whereas more complex maskers appear to be processed by wider filters or alternative across-frequency processes (Kolarik and Culling, 2010). We therefore evaluated our model with data from five different studies in three groups:

1. van der Heijden and Trahiotis (1999) combined all key aspects required to revisit Marquardt and McAlpine’s hypothesis: (a) The SDN thresholds are planned to be determined by the decay of $|\gamma|$ with a 79 Hz-wide Gammatone filter. (b) The ODN thresholds supposedly will, despite the same 79 Hz on-frequency filter, be elevated by the across-channel incoherence interference. The most importantdatapoints to judge this are at those ITDs where the on-frequency coherence of SDN and ODN is the same, but thresholds differ. For $S_0$ detection this is the case at ITD = 1 ms and 3 ms, for $S_\pi$ detection at ITD = 2 ms and 4 ms.

2. Marquardt and McAlpine (2009) not only presented the above-mentioned hypothesis but also detection thresholds. There, SDN and ODN maskers are spectrally surrounded by bands that each have a different, constant IPD. Due to the different signs they either do or do not cause interaural incoherence at the transitions. Their reported differences impose a challenge for single-channel models that use a constant filter bandwidth.

3. Sondhi and Guttmann (1966), Holube et al. (1998) and Kolarik and Culling (2010) reported detection thresholds of an $S_\pi$ tone centered in an in-phase noise that is spectrally surrounded by antiphase noise. These simulations
are included for an additional discussion about the proposed standard-filter-plus-off-frequency-impact concept, since larger binaural bandwidths have previously been derived based on such data.

2 Description of the Model

Fig. 2 shows the processing stages of the proposed model. It is designed as a numerical multi-channel model through all stages, but these were here realized and tailored to predict binaural-detection data with a 500 Hz pure-tone target. The model builds on the analytical single-channel model approach of Encke and Dietz (2021). It furthermore includes an across-frequency incoherence interference mechanism. It consists of a multi-channel binaural processing pathway and a monaural pathway. Both pathways compare multiple tokens of the processed representation of the condition-specific masker only to the representation of signal plus masker. This comparison has been suggested to mimic a subject’s strategy of comparing a stimulus to a learned reference template (Dau et al., 1996, 1997; Jepsen et al., 2008; Breebaart et al., 2001a; Bernstein and Trahiotis, 2017). Based on these comparisons, both pathways deliver a sensitivity index ($d'$). An optimal combination of the pathways’ estimates gives the overall $d'$ estimate of the model (Green and Swets, 1966; Biberger and Ewert, 2016).

![Diagram of Processing Stages](image_url)

Figure 2: Processing stages of the proposed model. See main text for details.

2.1 Peripheral Processing

The left and right input signals were processed with a fourth-order Gammatone filterbank that represents basilar-membrane bandpass filtering. The filterbank implementation by Hohmann (2002) was employed with a spacing of five filters per ERB in the range of 67 Hz to 1000 Hz. The grid was defined by centering one filter at 500 Hz. This filter had an ERB of 79 Hz (Glasberg and Moore, 1990) and was indexed with $k = 0$. 

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4
To focus on the impact of the spectral masker properties discussed above, the present implementation did not include any other peripheral processing such as low-pass filtering, power-law compression or half-wave rectification. Only Gaussian noise was used as masker, and only 500-Hz tones as targets.

2.2 Binaural Pathway

The correlation coefficient $\gamma(\tau = 0) = \gamma$ was derived from the analytical, i.e. complex-valued left and right signals $l(t)$ and $r(t)$ in the frequency channel $k$, provided by the Gammatone filterbank:

$$\gamma_k = \frac{\sum_{t} l_k(t) r_k(t)}{\sqrt{\sum_{t} |l_k(t)|^2 |r_k(t)|^2}}$$

(1)

where $\bar{\gamma}$ marks the temporal mean. This results in one complex correlation coefficient per frequency channel, averaged over the whole stimulus duration. The complex-valued correlation coefficient was used because it conveniently combines information about both the mean IPD as $\arg\{\gamma\}$ and about the amount of IPD fluctuations in the form of interaural coherence $|\gamma|$. While the Introduction mentioned a mismatch between mammalian physiology and delay line models, it should be noted that the seemingly abstract use of complex-valued correlation is identical to two real-valued correlations with a 90° phase offset. Such two orthogonal correlators exist in the form of the average left- and right hemispheric binaural neuron in mammals (McAlpine et al., 2001; Joris et al., 2006). The physiologic relation of $\gamma$ is explained in more detail in Encke and Dietz (2021).

As pointed out in the Introduction, the novelty of the present model is the interference of IPD fluctuations across frequency channels. The term incoherence interference describes purely detrimental effects, meaning only channels with lower coherence affect their neighborhood, but not the other way around. This process is implemented as a restricted across-channel weighted average of the coherence $|\gamma|_k$: The $|\gamma|_k$ are limited such that they can no more exceed the on-frequency $|\gamma|$, thus referred to as $|\gamma|_{k,\text{lim}}$. A weighted average of $|\gamma|_{k,\text{lim}}$ therefore means that only channels with lower coherence, or stronger IPD fluctuations, affect the on-frequency coherence, i.e. interference of IPD fluctuations:

$$|\gamma|_w = \sum_{m} \sum_{-m} w(k) |\gamma|_{k,\text{lim}}$$

(2)

$w(k)$ symbolizes a function that weights the contribution of a channel $k$ to the resulting $|\gamma|_w$. The employed weighting function has an exponential decay described by

$$w(k) = e^{-|k|/(b \sigma_w)}.$$  

(3)

$\sigma_w$ represents the decay parameter, normalized by the number of filters per ERB, $b$. The double-exponential decay shape was chosen by empirical trials. While the exact shape of the window was not crucial, we did not obtain more precise simulations with other shapes.

For a low masker coherence, or at the practically irrelevant case of a positive SNR, adding a target with an IPD of $\pi$ relative to the masker can swap the mean IPD from the masker to that of the target. In specific cases, the masker alone and masker plus target can have the same coherence, but differ in their mean IPD and thus in their correlation. Thus, the interaural coherence $|\gamma|$ is not sufficient as a decision variable. Instead, $\gamma$, including both coherence and the mean IPD, is required. Therefore, the original mean IPD is now reintroduced to the coherence after the limitation and interference stage, so that the model can operate on the complex correlation coefficient as suggested by Encke and Dietz (2021).

$$\gamma_w = |\gamma|_w e^{\arg\{\gamma_w\}}$$

(4)

Unity-limited measures such as coherence or correlation can be Fisher $z$, i.e. atanh-transformed for the purpose of variance normalization (McNemar, 1969; Just and Bamler, 1994, as often applied in psychophysics, e.g., Lüddemann et al., 2007; Bernstein and Trahiotis, 2017). As in Encke and Dietz (2021), $\gamma_w$ is multiplied by a model parameter $\hat{\rho} < 1$ to avoid an infinite sensitivity to deviations from a coherence of one. This is equivalent to adding uncorrelated noise to the two input signals. The decision variable of the binaural pathway is thus

$$\zeta = z[\hat{\rho} |\gamma_w|]$$

(5)

where $z[\cdot]$ is the Fisher $z$-transform applied to the modulus of $|\gamma_w|$ while leaving the argument unchanged.

In the signal detection stage, the $d'$ is obtained based on the difference between the ensemble averages of the representations of the target signal plus noise, $\zeta_{N+S}$, and the representations of the noise alone, $\zeta_N$:

$$d'_b = \frac{|\zeta_{N+S} - \zeta_N|}{\sigma_b}$$

(6)

The internal noise $\sigma_b$ defines the sensitivity of the binaural model pathway (Dietz et al., 2021).
2.3 Monaural Pathway

For the monaural pathway, the power $P$ of the on-frequency filter channel was evaluated. It is half the squared mean of the envelope across the whole signal duration (Biberger and Ewert, 2016). The envelope is the modulus of the complex-valued filter output:

$$P = \frac{|u_0(t)|^2}{2}.$$  \hspace{1cm} (7)

In the stimuli employed in this study, the power is identical in the left and right channels, thus it is sufficient to evaluate only one side.

For a signal-induced power change $\Delta P = P_{N+S} - P_N$, the processing accuracy is limited by a level-dependent internal noise with a Gaussian distribution of amplitudes and a standard deviation of $\sigma_m$. Thus, the sensitivity of the monaural pathway is equivalent to

$$d'_m = \frac{\Delta P / P_{\text{avg}}}{\sigma_m},$$  \hspace{1cm} (8)

where $P_{\text{avg}}$ represents the average power between $P_{N+S}$ and $P_N$.

2.4 Detector

The sensitivity indices of the binaural, $d'_b$, and monaural pathway, $d'_m$, were combined assuming two independent information channels (Green and Swets, 1966; Biberger and Ewert, 2016)

$$d'_{b+m} = \sqrt{d'^2_b + d'^2_m},$$  \hspace{1cm} (9)

The $d'$ that corresponds to the experiment-specific detection thresholds was obtained via table-lookup (Numerical evaluation in Hacker and Ratcliff, 1979). This depends on the number of intervals, as well as the specific staircase procedure used in the simulated experiments. For each condition, the model was evaluated for a range of target levels. This delivered the psychometric function. The predicted detection threshold was obtained from a straight line fitted to the logarithmic $d'$. The model parameters were manually adjusted in order to optimize the prediction accuracy. The resulting parameter values are given in Table 1.

3 Predictions of Binaural-Detection Datasets

In all experiments, a 500 Hz $S_\pi$ or $S_0$ tone was to be detected in a broadband Gaussian noise masker. Figures 3, 4 and 5 show the experimental data denoted by symbols, the predictions of the proposed model including incoherence interference as continuous lines, as well as predictions of the single-channel version which means without incoherence interference, as dotted lines. Three types of binaural-detection experiments were simulated, as described in detail in the following subsections. Table 1 summarizes the parameter values used to simulate the experimental conditions. It further lists the non-adjusted coefficient of determination ($R^2$, interpretable as the proportion of variance in the data explained by the model) and the root-mean-square error (RMSE) of the simulations both with and without the proposed incoherence interference.

| Experiment                        | Signal | Variable | $\hat{\rho}$ | $\sigma_b$ | $\sigma_w$ | $\sigma_m$ | $R^2$   | $R^2$   | RMSE / dB | $R^2$   | RMSE / dB |
|-----------------------------------|--------|----------|--------------|------------|------------|------------|---------|---------|-----------|---------|-----------|
| van der Heijden and Trahiotis (1999) | $\pi$  | ITD      | 0.91         | 0.20       | 0.50       | 0.40       | 0.94    | 0.85    | 0.78      | 1.45    |           |
| Marquardt and McAlpine (2009)     | 0      | BW       | 0.86         | 0.17       | 0.65       | 0.40       | 0.96    | 0.86    | 0.57      | 1.38    |           |
| Kolarik and Culling (2010)        | 0      | BW       | 0.91         | 0.20       | 0.50       | 0.40       | 0.97    | 0.67    | -0.62     | 1.97    |           |

Table 1: Summary of the simulated experiments and predictions. Columns 1 - 3: Simulated experiment, IPD of the used target signal, independent variable. Columns 4 - 7: Used model parameters: $\hat{\rho} < 1$: Maximum coherence (internal noise); $\sigma_b$: Standard deviation of the internal noise to determine the absolute performance of the binaural pathway; $\sigma_w$: Slope parameter of the double-exponential across-channel interaction window (normalized by the number of filters per ERB); $\sigma_m$: Standard deviation of the level-dependent internal noise to determine the accuity of the monaural pathway; Columns 8 - 11: Accuracy of the predictions with and without incoherence interference: Coefficient of determination ($R^2$, interpretable as the proportion of the variance in the data explained by the model); root-mean-square errors (RMSE) of the predictions.
3.1 van der Heijden & Trahiotis 1999

In this arguably most central experiment, detection thresholds of an $S_0$ target tone (Fig. 3, upper panel) as well as of an $S_\pi$ tone (Fig. 3, lower panel) were measured as a function of the interaural masker ITD in steps of 0.125 ms. The bandwidth of the masker was 900 Hz. As outlined in the Introduction, the ODN consisted of two superimposed noises with opposite ITD. The experiment performed by van der Heijden and Trahiotis (1999) employed a four-interval, two-alternative forced choice task (4I-2AFC, first and fourth intervals always contained only the masker and served as queuing intervals). Their adaptive 2-down 1-up stair case procedure estimated the 70.7% correct-response threshold. This is equivalent to a $d'$ of 0.78 at threshold. Thus, as described in section 2.4 the model determined the threshold in the form of the signal level producing this $d'$. The continuous lines in Fig. 3 show the simulations of the presented model, including the across-channel incoherence interference. From visual inspection, the simulations captured all effects from the experimental thresholds and the critical threshold differences between SDN and ODN at all ITDs under both conditions. Specifically, the critical threshold differences of 3.5 dB at ITD = 1 ms in the $S_0$ condition and 4 dB ITD = 2 ms in the $S_\pi$ condition are precisely accounted for. This good correspondence is also reflected in the around 90% explained variance under both conditions, and RMS errors of less than 1 dB. The dashed lines show simulations without the across-channel incoherence interference (single-channel model, cf. Encke and Dietz, 2021) but all other model parameters unchanged. This shows that a large amount of the threshold differences is already explained by differences in the on-frequency coherence. In much the same way as ODN coherence oscillates as a function of analysis frequency (Fig. 1d), it also fluctuates as a function of the masker ITD (Fig. 1c). Particularly at ITD = 0.5 ms, ODN is incoherent in the 500-Hz band, whereas SDN is almost fully coherent. This, and not the across-frequency process, causes the difference in the simulated thresholds at this ITD. The across-frequency process only comes into play at those ITDs where the coherence at 500 Hz (on-frequency) is nearly identical in SDN and ODN (upper panel: ITD = 1 ms and 3 ms; lower panel: ITD = 2 ms and 4 ms).

![Graphical representation](image-url)
3.2 Marquardt & McAlpine 2009

The masker of this experiment contained SDN and ODN centered at the frequency of the $S_0$ target tone with a constant ITD = 1 ms in the inner band. The inner band was spectrally surrounded by bands that each had a constant IPD of $\pi/2$ and $-\pi/2$, or vice versa. Thresholds are given as a function of the inner-band bandwidth. The resulting phase transitions between inner and flanking bands have been hypothesized to impair the detection if they cause a frequency region of low interaural coherence. The lower and upper frequency limits of the composite stimuli are 50 Hz and 950 Hz, respectively. The two-interval-two-alternative-forced choice task with a 3-down 1-up procedure that was used estimated the thresholds to be 79.4 % correct. This corresponds to $d' = 1.14$ at the threshold predicted by the model. In Fig. 4, detection thresholds of the $S_0$ tone are shown as a function of the bandwidth of the inner band. Again, the model predicted all critical characteristics of the data. These are the 3 dB difference between SDN and ODN at the full inner-band bandwidth (same as ITD = 1 ms in the $S_0$ condition in van der Heijden and Trahiotis, 1999), the elevated SDN thresholds in the $[-\pi/2, SDN, +\pi/2]$ compared to the $[+\pi/2, SDN, -\pi/2]$ condition and the 3 dB BMLD where the inner-band bandwidth is zero. Without the incoherence interference, the predictions cannot distinguish between the different conditions of the experiment. They deviate more from the mean than the data, resulting in a negative $R^2$.

![Figure 4: Experimental data from Marquardt and McAlpine (2009) (symbols) and model predictions (lines). Detection thresholds are given as function of the inner-band bandwidth. The inner band contains delayed noise (triangles) or opposingly delayed noises (diamonds and bullets) with a fixed ITD = 1 ms while the flanking bands have a constant phase shift of $+\pi/2$ (upward triangle and diamond) and $-\pi/2$, or vice versa (downward triangle and bullet). Continuous and dashed lines again show predictions with and without across-frequency incoherence interference, respectively.](image)

3.3 Experiments on the operating bandwidth in binaural detection

Several studies investigated the operating bandwidth in binaural detection using maskers that contains two flanking bands which differ in their interaural configuration from the inner band (Sondhi and Guttman, 1966; Holube et al., 1998; Kolarik and Culling, 2010). The masking noise is diotic ($N_0$) in the inner band and antiphase ($N_2$) in the flanking bands. Detection thresholds of an $S_0$ target tone were again measured as a function of the inner-band bandwidth. Results are expressed as the difference between thresholds in the flanked condition and the threshold without an inner band, i.e. $N_2 S_0$. In Fig. 5, the circles mark the threshold differences reported by Kolarik and Culling (2010, centered condition), which represent averages across their three participants. The triangles show individual thresholds of the two participants in the study by Holube et al. (1998, rectangular condition). The gray diamonds show the data from Sondhi and Guttman (1966). Our model predictions were oriented on the 2-down 1-up 2I-2AFC paradigm employed in Kolarik and Culling (2010), equivalent to $d' = 0.78$ at threshold. The black continuous line shows the model predictions with the same parameter settings as used to predict the $S_0$ detection thresholds in van der Heijden and Trahiotis (1999, Fig. 3b). The dotted black line shows model predictions without the across-channel incoherence interference, so that detection was purely determined by the ERB = 79 Hz Gammatone filter centered at 500 Hz. Despite the large deviations between and within experiments, the model predictions involving the incoherence interference captured the shape of the decreasing thresholds with increasing inner-band bandwidth.

![Figure 5: Model predictions and experimental data for the operating bandwidth in binaural detection. The black continuous line shows the model predictions with the same parameter settings as used to predict the $S_0$ detection thresholds in van der Heijden and Trahiotis (1999, Fig. 3b). The dotted black line shows model predictions without the across-channel incoherence interference, so that detection was purely determined by the ERB = 79 Hz Gammatone filter centered at 500 Hz. Despite the large deviations between and within experiments, the model predictions involving the incoherence interference captured the shape of the decreasing thresholds with increasing inner-band bandwidth.](image)
4 Discussion

As long as the masker coherence is fairly constant across frequency bands, experiments on binaural detection can be explained purely on the basis of the coherence $|\gamma|$ defined by a 79 Hz wide Gammatone filter at $f_c = 500$ Hz (Rabiner et al., 1966; Encke and Dietz, 2021). This includes fully coherent broadband noise maskers (Hirsh, 1948; van de Par and Kohlrausch, 1999), mixtures of correlated and uncorrelated noise (Robinson and Jeffress, 1963; Pollack and Trittipoe, 1959; Bernstein and Trahiotis, 2014), and experiments where the interaural coherence of the masker is reduced by an ITD (Langford and Jeffress, 1964; Rabiner et al., 1966; Bernstein and Trahiotis, 2020). However, the on-frequency coherence does not account for thresholds obtained with maskers where these properties change substantially across filter bands. Specifically, the single-channel model version as proposed in Encke and Dietz (2021) is neither able to predict all of the threshold differences between SDN and ODN nor experiments like Marquardt and McAlpine (2009) and Kolarik and Culling (2010) that involve IPD transitions in the masker spectrum (see dashed lines in Figs. 3, 4, 5.

Marquardt and McAlpine (2009) hypothesized across-channel processing in the binaural system to explain the reduced binaural benefit under such conditions. Here, we extended the analytical model by Encke and Dietz (2021) to a multi-channel numerical signal-processing model with interference of IPD fluctuations. With across-frequency interference only caused by IPD fluctuations, i.e. by off-frequency incoherence, the proposed model differs from approaches assuming wider binaural filters (e.g. van der Heijden and Trahiotis, 1999; Kolarik and Culling, 2010). For stimuli with spectrally constant coherence and masker-target phase relations, like SDN and all conditions simulated by Encke and Dietz (2021), the incoherence interference has no effect and the model operates on the standard filter bandwidths of its peripheral filterbank. Modeling an interference process, our approach also differs from the symbolic model suggested by Marquardt and McAlpine (2009), which sums interaural cues after binaural interaction and, with their implementation, is also different from wider filters. Their across-frequency processing still causes a stronger damping of binaural sensitivity with increasing masker ITD, which is not seen in the data.

The proposed concept of a detrimental incoherence interference is comparable to modulation detection interference, as shown and discussed by, e.g., Yost and Sheft (1989) and Oxenham and Dau (2001). Similar to the proposed across-channel incoherence interference this is modeled by modulation patterns interacting across channels, while energetic spectral masking properties are spectrally limited by peripheral filters (Piechowiak et al., 2007; Dau et al., 2013). Furthermore, a similar process is thought to underlie binaural interference as observed by, e.g., Bernstein and Trahiotis (1995); Best et al. (2007); McFadden and Pasanen (1976).
The dataset of van der Heijden and Trahiotis (1999) contains both SDN and ODN, and is therefore the critical challenge for binaural detection models. Both van der Heijden and Trahiotis and our model simulate the data very accurately. Therefore, the discussion focuses on consequences and plausibility of the two different concepts.

The bandwidth of the signals immediately prior to binaural interaction dictates the temporal coherence and thus the decline of BMLD with increasing noise ITD in the absence of internal ITD compensation (Langford and Jeffress, 1964; Rabiner et al., 1966; van der Heijden and Trahiotis, 1999; Dietz et al., 2021). To date, two of the arguably most comprehensive datasets of dichotic tone-in-noise detection, van der Heijden and Trahiotis (1999) and Bernstein and Trahiotis (2020), have self-reported mutually exclusive requirements for the binaural bandwidth (ERB = 130...180 Hz vs. ERB ≤ 100 Hz at 500 Hz).

A variety of studies aim to estimate the bandwidth at the binaural input stage by means of dichotic tone-in-noise detection, but no consistent picture emerges. There is, for example, a difference in estimated bandwidth between band-widening and notched-noise BMLD data, and between stimuli with different flanking bands (e.g., Kolarik and Culling, 2010). Particularly this stimulus-type dependence of the "apparent bandwidth" challenges the assumption that all stimuli are processed by the same system. To us, the most reasonable "unifying" explanation is that filter properties arise from the basilar membrane and also the binaural system can make full use of this spectral resolution. The observation that there is less spectral resolution in some cases is then best explained by an across-frequency process for certain stimulus features – but in contrast to wider filters it is not affecting all features. The proposed incoherence interference may be this missing across-frequency process. At least it appears to reduce or even eliminate inconsistencies in estimating the bandwidth from various binaural detection experiments.

Another mechanism which has been proposed in the context of bandwidth estimation is an optimal combination of target detectability across frequency channels. Masking patterns in dichotic band-widening experiments have a knee-point at larger bandwidths than their diotic counterparts (van de Par and Kohlrausch, 1999; Bourbon and Jeffress, 1965). van de Par and Kohlrausch (1999) hypothesized that in narrowband maskers, the similar signal-to-noise ratio (SNR) across frequency channels can be exploited to reduce masking. A model which includes such a mechanism (Breebaart et al., 2001b) accounts for the band-widening masking pattern using standard filter bandwidths (i.e. bandwidths as proposed by Glasberg and Moore, 1990). It also correctly predicts that the knee-point is only shifted to a higher bandwidth if the masker is fully or almost fully correlated (van der Heijden and Trahiotis, 1998).

Most recent binaural models, such as Bernstein and Trahiotis (2017) and Encke and Dietz (2021) already assume a bandwidth as narrow as the peripheral bandwidth. This is also in line with direct measurements of the bandwidth in ITD-sensitive inferior colliculus neurons in cats by Mc Laughlin et al. (2008): For delayed noise, as used by van der Heijden and Trahiotis (1999), they found that damping of the cross-correlation function corresponds to the peripheral bandwidth at the respective center frequency.

With the present implementation, the binaural pathway parameters ($\hat{\rho}$, $\sigma_B$, $\sigma_W$) had to be adjusted slightly between conditions with $S_T$ targets and conditions with $S_D$ targets (see Table 1). This is due to the binaural system’s sensitivity depending on the baseline IPD (Hirsh, 1948). An angular compression of the decision variable space $\{\xi\}$ at large IPDs is a possible model extension. Delay-line models can account for this dependence with a corresponding $p(\tau)$ function which defines the sensitivity of the model as a function of its internal delay. However, they then incorrectly predict better unmasking with $N_{ITD}S_D$ compared to $N_{ITD}S_T$ when $ITD = T/2$ (Breebaart et al., 1999). Simulating the data of Marquardt and McAlpine (2009) required slightly different parameter values because their listeners obtained different thresholds compared to van der Heijden and Trahiotis (1999) for identical stimuli. This may be due to the different number of presented intervals. Identical model parameters were used for the $S_T$-conditions of van der Heijden and Trahiotis (1999) and Kolarik and Culling (2010).

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1The most comprehensive simulation of dichotic tone in noise detection thresholds using a cross-correlation-based model is by Bernstein and Trahiotis (2017). It is not expected to simulate the ODN detection thresholds of van der Heijden and Trahiotis (1999) with a good accuracy, because an ERB of at least 130 Hz is necessary. Other ODN stimuli, used experimentally by Bernstein and Trahiotis (2015), were included in the model test battery by Bernstein and Trahiotis (2017). These ODN stimuli, however, differed in several ways from the former. First, the target frequency is 250 Hz, compared to 500 Hz in van der Heijden and Trahiotis (1999) and in all other studies here simulated. Second, instead of fixing the target tone to $S_0$ or $S_T$, the target is delayed by the same amount as one of the two noises, i.e. $(N_{ITD})2ITD(S_T)_{ITD}$. Such an approach is useful for SDN, as it ensures a constant $\pi$ difference between the IPDs of the noise and of the tone. For ODN, however, the IPD of the second noise relative to the tone is offset from $\pi$ by 2xITD. This type of stimulus therefore causes an even more complex ITD-dependence of threshold, which offers no advantage over the ODN from van der Heijden and Trahiotis (1999) for filter estimation. With both definitions, corresponding SDN and ODN stimuli can be generated only if the ITD is an integer or a half-integer multiple of the target period (i.e. $ITD = n/2f$, $n \in \mathbb{N}$). In Bernstein and Trahiotis (2015) (their Figure 1, Panel a) these are the two data points at ITD = 2 and 4 ms. SDN and ODN thresholds are, however, very similar at those points. Third, the masker bandwidth is 50 Hz. For such a masker bandwidth smaller than the peripheral filter width, neither van der Heijden and Trahiotis (1999) nor our model would predict a considerable threshold difference between SDN and ODN at an ITD of 2 and 4 ms, since there are no off-frequency regions of considerably lower coherence.
5 Conclusion

Interaural incoherence interference enables the presented binaural model to simulate detection thresholds both for maskers with a spectrally constant and with a spectrally modulated coherence. Employing auditory filters with monaurally estimated bandwidth Glasberg and Moore (1990), it predicts the reduced unmasking in opposingly-delayed noises (van der Heijden and Trahiotis, 1999) compared to regular delayed noise. The concept can help to resolve the inconsistency that binaural models require filter bandwidths as estimated monaurally for most data sets (Bernstein and Trahiotis, 2017, 2020), but at least 1.6 times wider filters for broadband opposingly delayed noises van der Heijden and Trahiotis (1999) and other spectrally complex maskers Verhey and van de Par (2020).

The main consequence of using a standard filter bandwidth is that the decline of the binaural benefit with masker ITD can be simulated without internal ITD compensation, as first suggested by Langford and Jeffress (1964).

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A Derivation of cross-power spectral density in opposingly-delayed noise

In ODN, two two-channel signals \( u(t) = [u(t) \ u(t + \text{ITD})] \) and \( z(t) = [z(t) \ z(t - \text{ITD})] \) with opposite ITDs, ITD and -ITD, are summed. The cross-power spectral density (CPSD) functions are

\[
S_{UU}(\omega) = 0.5e^{i\text{ITD}\omega}, \\
S_{ZZ}(\omega) = 0.5e^{-i\text{ITD}\omega}.
\]

(10)

The power spectral density is 0.5 \( 1/\text{Hz} \) each, so that the ODN has the same energy as the SDN. Summation of the time signals is equivalent to a summation of their CPSD functions, which leads to

\[
S_{UZ} = S_{UU}(\omega) + S_{ZZ}(\omega) = \cos(\omega \text{ITD}).
\]

(11)

This resulting cosine pattern is determined by the sum of the CPSDs’ phases adding up or canceling each other at different frequencies. This normalized CPSD \( C(\omega) \) represents the coherent energy of the signals as a function of frequency (Gardner, 1992),

\[
C(\omega) = \frac{|S_{UZ}(\omega)|}{\sqrt{S_{UU}(\omega)S_{ZZ}(\omega)}} = |\cos(\omega \text{ITD})|.
\]

(12)

If \( |\gamma(\tau)| \) is based on an ensemble average, then \( C(\omega) = \mathcal{F}\{|\gamma(\tau)|\} \), with \( \mathcal{F}\{\bullet\} \) the fourier transform. As a continuous function of \( \omega \) it gives a coherence for any frequency \( \omega \) representing an infinitesimaly small bandwidth, illustrated as continuous lines in Fig. 1d. The coherence for peripherally filtered, i.e. finite-bandwidth signals is an average of the frequencies’ normalized CPSDs \( C(\omega) \). The coherence decreases with increasing ITD and increasing bandwidth, as illustrated by the bars in Fig. 1d. Two superimposed noises with ITD = ±2 ms are in phase at 500 Hz. At 625 Hz, however, they have IPDs of \( \pi/2 \) and \( -\pi/2 \), respectively. The coherence between left and right signals at 625 Hz is therefore zero.

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