Effects of non-simultaneous masking on the binaural masking level difference

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The present study sought to clarify the role of non-simultaneous masking in the binaural masking level difference for maskers that fluctuate in level. In the first experiment the signal was a brief 500-Hz tone, and the masker was a bandpass noise (100–2000 Hz), with the initial and final 200-ms bursts presented at 40-dB spectrum level and the inter-burst gap presented at 20-dB spectrum level. Temporal windows were fitted to thresholds measured for a range of gap durations and signal positions within the gap. In the second experiment, individual differences in out of phase (No π) thresholds were compared for a brief signal in a gapped bandpass masker, a brief signal in a steady bandpass masker, and a long signal in a narrowband (50-Hz-wide) noise masker. The third experiment measured brief tone detection thresholds in forward, simultaneous, and backward masking conditions for a 50- and for a 1900-Hz-wide noise masker centered on the 500-Hz signal frequency. Results are consistent with comparable temporal resolution in the in phase (NoSo) and No π conditions and no effect of temporal resolution on individual observers' ability to utilize binaural cues in narrowband noise. The large masking release observed for a narrowband noise masker may be due to binaural masking release from non-simultaneous, informational masking.

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I. INTRODUCTION

Under many stimulus conditions, signal detection thresholds in a diotic masker are lower if the signal is out of phase (No π) than if it is in phase (NoSo) across ears. This difference is an example of the binaural masking level difference (MLD; [Hirsh, 1948b](#)). Several lines of research indicate that the MLD obtained with a low-frequency pure tone centered in a narrowband noise masker is dominated by binaural cues present during envelope minima in the inherent amplitude modulation of the masker ([Grose and Hall, 1998](#); [Buss et al., 2003, 2007](#)). For example, the MLD for a brief, 500-Hz signal centered in a 50-Hz-wide Gaussian noise masker is larger if the signal coincides with a masker envelope minimum than an envelope maximum ([Buss et al., 2003, 2007](#)). There are large individual differences in the ability to make use of binaural cues in narrowband noise masker conditions ([Bernstein et al., 1998](#)), but No π thresholds are on the order of 10 dB lower for signals presented in masker envelope minima than maxima ([Buss et al., 2007](#)).

The finding of lower No π thresholds for brief, low-frequency signals in envelope minima than maxima is broadly consistent with a model developed by Bernstein, Trahiotis, and colleagues ([Bernstein and Trahiotis, 1996, 1999](#); [Bernstein et al., 1999](#)). In that model, detection is based on the normalized interaural correlation following a simplified model of peripheral encoding. [Buss et al. \(2003, 2007\)](#) adapted this model to the detection of brief signals by including a stage of binaural temporal integration, wherein

changes in interaural correlation as a function of time are smoothed via convolution with a temporal window. This type of binaural integration has a relatively uniform effect on No π threshold estimates for signals coincident with masker envelope minima and maxima because the masker temporally surrounding the signal is diotic regardless of envelope amplitude. One factor not explicitly considered in this model is monaural temporal resolution, in which the effects of forward and backward masking could increase thresholds in both NoSo and No π conditions. Such non-simultaneous masking might be especially important to consider in the case of a brief signal coincident with a masker envelope minimum, where forward masking, in particular, could significantly reduce the fidelity with which signal information is represented in the auditory periphery.

The effect of non-simultaneous masking on the ability to process binaural cues has usually been studied by measuring threshold for a brief π signal presented immediately before or after presentation of an No masker burst or between a pair of No masker bursts, such that the signal is presented during an epoch of quiet. Under these stimulus conditions, several studies have demonstrated forward masking ([Yama, 1992](#)), backward masking ([Dolan and Trahiotis, 1972](#)), or both ([Small et al., 1972](#); [Berg and Yost, 1976](#); [Yost and Walton, 1977](#); [Zwicker and Zwicker, 1984](#)). That is, π thresholds can be elevated by an No masker even if there is no temporal overlap between these stimuli, analogous to non-simultaneous masking effects observed with monaural and diotic stimuli.

Although it is clear that non-simultaneous masking has some effect on sensitivity in No π conditions, there is a lack of consensus regarding the relative magnitude and time

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course of non-simultaneous masking in analogous NoS π and NoSo conditions. Some studies have concluded that the threshold for an S π signal presented with an No noise is closely related to the magnitude of the associated NoSo threshold, regardless of whether the signal is presented in forward, simultaneous, or backward masking conditions (Small *et al.*, 1972; Zwicker and Zwicker, 1984). That is, the amount of binaural masking release is proportional to the amount of baseline masking in both simultaneous and non-simultaneous masking conditions. Not all data are consistent with this conclusion, however. Berg and Yost (1976) found that whereas forward masking was comparable in NoSo and NoS π conditions, there was less backward masking in NoS π than in NoSo conditions. Kohlrausch and Fassel (1997) reported steeper recovery from forward masking in NoSo than in NoS π conditions, results they interpreted as showing that the MLD is limited to short signal/masker delays (also see Hanna *et al.*, 1982). Complicating the picture further, Yost and Walton (1977) reported that the masking observed under conditions of combined forward and backward masking was reduced in binaural as compared to monaural listening conditions. These studies used a wide range of different stimulus parameters—including click and tonal signals, different masker bandwidths and durations, and even frozen noise in one case—and the factor or factors responsible for the discrepant conclusions regarding the importance of non-simultaneous masking for NoS π detection are unclear.

The present study sought to clarify the role of non-simultaneous masking in the MLD for a 500-Hz tone in a narrowband noise masker. Under these conditions NoS π thresholds have been shown to depend on cues coincident with masker envelope minima, introducing the possibility that individual differences in temporal resolution affect the magnitude of the MLD. As noted above, the results of previous studies on forward and backward masking in NoS π and NoSo conditions are inconsistent, and all considered detection of a signal in the absence of simultaneous masking. Whereas signal cues coincident with an envelope minimum of a narrowband noise masker may be affected by *non-simultaneous* masking associated with the surrounding masker envelope peaks, use of these cues may also be limited by *simultaneous* masking arising from energy in the masker envelope minimum, at least in conditions considered to date (Grose and Hall, 1998; Buss *et al.*, 2003, 2007). The presence of both simultaneous and non-simultaneous masking could be significant for reasons having to do with the preservation of stimulus phase information. Kohlrausch and Fassel (1997) argued that the use of interaural phase cues requires neural representation of masker phase during the signal presentation. Phase is preserved in the peripheral representation of the masker for a short period of time following stimulus offset due to ringing at the periphery (Shailer and Moore, 1987). For longer delays, however, phase information is thought to decay. The degradation of phase information for relatively long signal/masker delays could be significantly reduced by the presence of a lower level simultaneous masker in the gap between non-simultaneous masker bursts. This consideration, in conjunction with the inconsistencies in the literature noted above, prompted us to revisit the effects of non-simultaneous

masking in NoSo and NoS π detection thresholds under conditions of combined simultaneous and non-simultaneous masking.

The approach taken here for characterizing the temporal resolution with which signals are encoded in NoSo and NoS π conditions was modeled on the gapped-masker paradigm developed by Moore, Plack, and colleagues (Moore *et al.*, 1988; Plack and Moore, 1990). This method was based on the notched-noise method developed by Patterson for characterizing auditory frequency selectivity (Patterson, 1976; Patterson and Nimmo-Smith, 1980). The basic approach is to measure detection thresholds for a brief tone in a temporal gap between two maskers. Parametrically varying the duration of the gap results in an estimate of the resolution with which that gap is represented in the auditory system, and placing the signal asymmetrically within the gap (either early or late with respect to the temporal center) provides information about the symmetry of the temporal window. For a 500-Hz signal and a 50-dB spectrum level masker, this method produces an estimate of the monaural temporal window that is slightly asymmetric, indicating more forward than backward masking, and typically has an equivalent rectangular duration (ERD) of 7.9 ms (Moore *et al.*, 1988).

In the present adaptation of the gapped-masker paradigm, instead of turning the masker completely off during the inter-burst gap, the masker was reduced in level by 20 dB. This 20-dB level reduction is large enough to measure the temporal resolution in both NoSo and NoS π conditions, while maintaining simultaneous masking. Further, 20 dB represents the effective masker level reduction available to a listener in the previous narrowband MLD studies of Buss *et al.* (2003, 2007). The reasoning here is as follows. In those studies the masker was a 50-Hz-wide band of Gaussian noise, and the signal was a brief tone burst, gated on and off with 15-ms raised-cosine ramps. That signal was presented temporally centered on either the lowest masker envelope minimum or the highest maximum of a 409-ms sample. In the design stage of the present experiment, a set of 100 masker samples was generated, following the procedures described by Buss *et al.* (2003, 2007). For each sample the masker level was computed using a 7.9-ms rectangular window centered on the epoch of the masker when the signal would have been presented (i.e., the envelope minimum or maximum); this duration was chosen because it corresponds to the monaural temporal window duration estimated by Moore *et al.* (1988). With these procedures, the median masker level was 19.3 dB lower in the masker envelope minima than maxima. To the extent that the monaural temporal window characterizes limits of the peripheral encoding of the signal, we would expect the fidelity of binaural processing to be subject to at least as much temporal integration as monaural processing. Therefore we reasoned that a 20-dB change in masker level is representative of the effective level fluctuation of a 50-Hz-wide narrowband noise masker. The effect of masker level on the MLD for static stimuli will be addressed with supplemental data in the Discussion section.

In a previous binaural study based on the gapped-masker paradigm, Culling and Summerfield (1998) measured thresholds for a brief 500-Hz signal. The masker was

composed of two interaurally uncorrelated noise bursts and an intermediate segment of diotic noise, with masker amplitude held constant irrespective of interaural correlation. Thresholds were measured for S_o and S_π signals as a function of the duration of the intermediate No noise segment. Results of that study were interpreted as showing a “sluggish” response to changes in the binaural configuration of the masker (see also: [Grantham and Wightman, 1978](#); [Kollmeier and Gilkey, 1990](#); [Holube et al., 1998](#)). One important distinction between the approach taken in the present study and that of Culling and Summerfield is that the masker is diotic in all conditions of the present paradigm, with level changes defining the gap rather than changes in the binaural configuration of the masker.

Temporal windows for a 20-dB reduction in masker level were measured in the first experiment. In the second experiment, individual observers’ thresholds for a brief tone in a steady or a gapped masker were compared with thresholds for a long tone in a narrowband noise masker. This comparison tested the hypothesis that individual differences in temporal resolution underlie individual differences in NoS_π thresholds with a narrowband masker. The final experiment evaluated the effect of masker bandwidth on simultaneous and non-simultaneous masking in NoS_o and NoS_π conditions, and results are interpreted as reflecting the contribution of informational masking to the MLD with narrowband noise maskers.

II. GENERAL METHODS

A. Observers

All observers were adults with normal hearing, defined as 20 dB hearing level (HL) or lower at octave frequencies 250–8000 Hz ([ANSI, 2004](#)). No observer reported a history of ear disease or hearing problems.

B. Stimuli

Signals were 500-Hz pure tones, gated on and off with raised-cosine ramps. The durations of signals and associated ramps are specified separately for each experiment. The starting phase of the signal was random, and the interaural correlation was either 1.0 (S_o) or -1.0 (S_π). Maskers were diotic (No) bandpass filtered noise samples. These were generated in the frequency domain by defining the real and imaginary components within the masker passband using random draws from a Gaussian distribution, and the results were then transformed into the time domain. This procedure generates a noise sample that can be played continuously without discontinuities. The masker gating and duration are specified separately for each experiment. In all three experiments stimuli were presented at a sampling rate of 12 077 Hz.

C. Procedures

Testing took place in a double-walled soundproof booth. Stimuli were generated in MATLAB, played out of a real-time processor (RP2, TDT), routed through a headphone buffer (HB7, TDT), and presented over deeply inserted earphones (ER2, Etymotic). Stimuli were presented using a three-interval,

three-alternative forced-choice design. Listening intervals were visually indicated using lights mounted on a handheld response box. In most conditions the listening interval was significantly longer than the signal presentation, and in all conditions the temporal position of the signal was fixed relative to the listening interval within a block of trials. Whereas the duration of the listening interval differed in the three experiments, as specified below, the inter-stimulus interval was 500 ms in all cases. Observers indicated their responses by pressing one of three buttons on the response box. Correct answer feedback was provided after every response.

Detection thresholds were estimated using a three-down one-up adaptive procedure which converges on 79% correct ([Levitt, 1971](#)). Initial signal level adjustments were made in steps of 4 dB, and this step-size was reduced to 2 dB after the second track reversal. A track continued until a total of eight track reversals had been obtained. Threshold estimates were the mean signal level at the last six track reversals. Three such estimates were obtained in each condition, with a fourth estimate taken in cases where the first three spanned a range of 3 dB or more. A fourth estimate was required in 29% (Exp. 1), 37% (Exp. 2), and 39% (Exp. 3) of blocks. The final threshold for each observer in each condition was the average of the three or four estimates obtained. Observers were tested in one-hour sessions, with a brief break offered at the half-hour point. A criterion value of $\alpha = 0.05$ was adopted for statistical analyses, and tests were two-tailed except where specified otherwise.

III. EXPERIMENT 1: EFFECT OF BRIEF REDUCTIONS IN MASKER LEVEL FOR NoS_o AND NoS_π

The goal of the first experiment was to characterize the role of forward and backward masking in the ability to make use of binaural cues present in a masker envelope minimum. A gapped-masker paradigm was used to estimate the temporal windows in NoS_o and NoS_π conditions. Results of this procedure have been used previously to characterize the energetic masking exerted by masker envelope peaks surrounding a signal presented in quiet, with detection based on monaural cues ([Moore et al., 1988](#); [Plack and Moore, 1990](#); [Holube et al., 1998](#)). The present study adapted this approach to examine the effects of reducing masker level by 20 dB on sensitivity in NoS_o and NoS_π conditions.

A. Methods

1. Observers

There were seven observers, aged 18–54 (mean of 29 yr). All observers in this group had extensive listening experience in previous psychoacoustic studies, including prior experiments on binaural processing, and were considered “good listeners” based on those previous data.

2. Stimuli

The masker was a diotic (No) Gaussian noise, bandpass filtered from 100 to 2000 Hz. The masker amplitude was scaled to produce two bursts, each with a 200-ms steady state and a variable inter-burst gap duration. The onsets and

offsets of these bursts were shaped with 2-ms raised-cosine ramps, including transitions in and out of the inter-burst gap. During the bursts the masker had a 40-dB spectrum level, and during the inter-burst gap that was reduced to 20-dB spectrum level. In addition to the gapped-masker conditions, thresholds were also measured with a steady 400-ms masker presented at either 40- or 20-dB spectrum level.

The signal was a 500-Hz tone, either diotic (So) or out of phase at the two ears ($S\pi$), gated on and off with 10-ms raised-cosine ramps and no steady state. In the steady masker conditions the signal was temporally centered in the 400-ms masker. In the gapped-masker conditions the timing of the signal was defined based on the interval between the half-rise point of the 2-ms masker ramp and the temporal center of the signal. The signal/masker interval prior to presentation of the signal is defined as t_1 and that following the signal as t_2 . When the signal was centered in the gap, both t_1 and t_2 were 10, 20, 50, 100, or 200 ms. When the signal was not in the temporal center of the gap, either t_1 or t_2 was increased by 20 ms relative to these standard intervals. In asymmetric signal conditions, the signal/masker interval duration is reported as the smaller of the two intervals. When $t_1 = t_2$, total gap duration was twice the signal/masker interval. When $t_1 < t_2$ or $t_1 > t_2$, the total gap was twice the minimum signal/masker interval plus 20 ms. Figure 1 shows an example stimulus, with $t_1 > t_2$ and a minimum signal/masker interval of 20 ms; the total gap duration in this example is 60 ms.

There were two steady maskers and 15 gapped maskers, with five signal/masker intervals and three symmetry conditions ($t_1 = t_2$, $t_1 < t_2$, and $t_1 > t_2$). Thresholds were measured for both So and $S\pi$ signals in all maskers for a total of 34 conditions. A random sample of noise was generated prior to each listening interval. Stimuli were presented such that the signal, when present, occurred in the temporal center of the 1-s listening interval.

3. Procedures

Stimuli were presented in a three-alternative forced-choice design, and signal detection thresholds were estimated using a three-down one-up adaptive procedure which converges on 79% correct. All threshold estimates for a particular condition were obtained in sequence, but the order of

FIG. 1. An example stimulus is shown, illustrating the relative timing of the signal (black) and masker (gray) for the gapped-masker condition with $t_1 > t_2$ and minimum signal/masker interval of 20 ms. Values of t are defined as the interval between the 3-dB down point of the masker and the temporal center of the signal, with t_1 defining the interval prior to the signal and t_2 the interval following the signal. When $t_1 < t_2$ or $t_1 > t_2$, their values differed by 20 ms.

FIG. 2. Mean thresholds are plotted as a function of the minimum signal/masker interval, in milliseconds. Symbols indicate mean data, and lines show double rounded-exponential data fits. The symbol and line styles reflect masker condition, as defined in the legend. Data for the NoSo conditions are shown in the top panel, and those for the NoS π conditions are shown in the bottom panel. The median standard error of the mean across thresholds ($n = 7$) appears in the lower right of each panel.

conditions was randomized independently for each observer. Refer to the General Methods section for more details.

B. Results

The results were very similar across the seven observers, so only the mean data will be presented. Thresholds are plotted in Fig. 2 as a function of the minimum signal/masker interval. The results for NoSo and NoS π conditions are shown in the top and bottom panels, respectively. Symbols indicate the stimulus masker level and positioning of the signal within the inter-burst gap, as defined in the legend. The thresholds associated with a signal/masker interval of zero are those measured with a 400-ms steady masker, presented at either 40-dB spectrum level (open circles) or 20-dB spectrum level (filled circles). Thresholds in the NoS π conditions were about 15 dB lower than those in the associated NoSo conditions, but otherwise the pattern of results was similar. Thresholds were highest in the steady 40-dB masker, and they fell with introduction of a masker gap. Increasing the signal/masker interval tended to lower thresholds, and thresholds tended to be lower when $t_1 > t_2$. Both of these trends were most evident at short signal/masker intervals.

1. Temporal window analysis

Modeling temporal resolution with a temporal window typically assumes that excitation at any point of time can be estimated based on the convolution of the instantaneous power of the stimulus and the temporal window [Eq. (1), below]. This convolution is performed twice, once with the masker alone and once with the signal plus masker, supporting an estimate of the signal-to-noise ratio (SNR) as a function of time. Thresholds in each stimulus condition can then

be estimated as the signal level required to attain a criterion peak SNR. Since there are no restrictions on the temporal position of the SNR peak, this method incorporates off-time listening when it is advantageous.

Prior to fitting the temporal window function to the present data, results were examined to assess the assumption of constant SNR at threshold for NoSo and NoS π conditions. For each signal phase the range of masking was determined as the difference between thresholds in the two steady masker conditions, those in which the 400-ms masker was presented at either 20- or 40-dB spectrum level. Mean thresholds in the NoSo conditions differed by 20.6 dB, but thresholds in the NoS π conditions differed by 18.0 dB. Paired *t*-tests on individual observers' thresholds indicated that the change in threshold with a 20-dB reduction in masker level was significantly different from 20 dB for the NoS π ($t_6 = 3.52$, $p = 0.012$) but not for the NoSo ($t_6 = 1.26$, $p = 0.253$) conditions. This is consistent with published data, showing an effect of level on the ability to benefit from the introduction of binaural difference cues (Hirsh, 1948a; Yost, 1988). Whereas the SNR associated with threshold was constant for NoSo conditions, the SNR at threshold for NoS π conditions was higher for the 20- than the 40-dB masker level. As a result, SNR at the output of the temporal window would not be an accurate predictor of threshold for the NoS π condition, and the method for fitting the temporal window had to be modified to take into account the reduced growth of masking in the NoS π condition. The range of masking associated with 20- and 40-dB masker levels was incorporated into the data fitting procedure by linearly scaling the input stimulus function so that its level represented "effective masking" rather than masker level. This step assumes that the growth of masking in NoSo and NoS π for this range of masker levels can be modeled with a pair of lines, with shallower slope for NoS π (see General Discussion section). Compressed instantaneous power was then integrated.

The mean thresholds shown in each panel of Fig. 2 were fitted using a double rounded-exponential function following the procedures of Plack and Moore (1990). Thresholds for both symmetrical and asymmetrical signal conditions for a given signal phase (So or S π) were fitted simultaneously. Each side of the temporal window (W) was defined as

$$W(t) = (1 - \omega) \left(1 + \frac{2t}{Tp} \right) \exp \left(-\frac{2t}{Tp} \right) + \omega \left(1 + \frac{2t}{Ts} \right) \exp \left(-\frac{2t}{Ts} \right). \quad (1)$$

The variable Tp is the time constant associated with the peak, Ts is the time constant associated with the skirt, and ω specifies the transition point between the peak and skirt portions of the function. For these fits, a single value of ω and a fixed Tp/Ts ratio was assumed for both the lagging and leading portions of the window. This allows for asymmetry in the temporal window while preserving the shape, such that one side is a stretched or compressed version of the other. Parameters for the lagging and leading portions of the window are reported

TABLE I. Parameters associated with functions fitted to the mean data of experiment 1 are reported for NoSo and NoS π conditions. Results for double rounded-exponential fits are shown above those for single rounded-exponential fits. The subscripts b and a indicate the time constants associated with weights applied to stimulus events before and after the center point of the window, respectively.

	Time constants (ms)				ω (dB)	R^2
	Tp_b	Tp_a	Ts_b	Ts_a		
NoSo	10.2	0.1	17 095.9	86.6	-31.5	0.97
	10.8	0.2				0.90
NoS π	9.2	3.7	82.8	33.3	-23.6	0.99
	10.4	4.8				0.90

with the subscripts b and a , as these parameters define weights for stimulus events occurring before and after the temporal center of the window, respectively. A second set of fits was performed setting ω to 0, eliminating the skirt portion of the double rounded-exponential function. The MATLAB function *fminsearch* was used to perform these fits.

Parameters defining the best-fitting temporal windows are reported in Table I. Results for the mean NoSo data are shown at the top of the table and those for the mean NoS π data are shown at the bottom. In all cases, time constants associated with the lagging edge of the temporal window (Tp_b and Ts_b) were larger than time constants associated with the leading edge of the temporal window (Tp_a and Ts_a). This reflects the fact that masker energy occurring before presentation of the signal contributed more to masking than stimulus energy occurring after the signal. The double rounded-exponential fit, shown in Fig. 2, accounted for 97% of the variance in NoSo thresholds and 99% of the variance in NoS π thresholds. The value of Ts_b for NoSo exceeded the longest stimulus duration by more than one order of magnitude and should therefore be interpreted with caution. Simplifying the fitted function to eliminate the shallow skirt portion of the temporal window reduced the amount of variance accounted for to 90% in each of the two datasets. The results for the double rounded-exponential fits will be compared across conditions below, but the same pattern of results is obtained if values based on the single rounded-exponential fits are compared.

2. Temporal window duration and asymmetry

In both the NoSo and NoS π conditions, the best-fitting temporal window was asymmetric ($Tp_b > Tp_a$), reflecting greater forward than backward masking. To assess the significance of the differences in parameter fits in the mean data for NoSo and NoS π conditions, windows were fitted separately to each observer's data. While there were some individual differences in fits across datasets, all showed the same general trends evident in fits to the mean data. Asymmetry in the temporal window fits can be characterized in terms of the ratio of time constants before and after the temporal midpoint of the window. A paired *t*-test on the ratios indicated that asymmetry was not statistically different in fits to individual NoSo and NoS π data ($t_6 = 1.79$, $p = 0.124$). It should be noted that the non-significant trend in these results was for

more backward masking in the NoS π than the NoSo data, opposite to the difference that could be predicted based on previous data (e.g., [Berg and Yost, 1976](#)).

A similar analysis of the ERD fitted to the data of each observer was undertaken. The ERD was estimated by calculating the total energy passed by the double rounded-exponential window, assuming a continuous input, and then determining the duration of rectangular window with equivalent energy transmission. In both the NoSo and NoS π conditions the ERD was on the order of 10 ms. For NoSo conditions the ERD for individual observers' data ranged from 8.1 to 17.3 ms, with a mean of 11.8 ms. For NoS π conditions the associated range was from 8.1 to 24.6 ms, with a mean of 13.6 ms. A paired *t*-test indicated that the ERD did not differ significantly between NoSo and NoS π conditions ($t_6 = 0.80$, $p = 0.452$).

C. Discussion

The present study used a gapped-masker paradigm to characterize the temporal resolution associated with detecting a brief signal presented in a brief, 20-dB decrement in masking noise. Fits to both NoSo and NoS π data were consistent with comparable non-simultaneous masking and an ERD on the order of 10 ms. These results are similar to those obtained previously with monaural stimuli and masker bursts separated by silence ([Moore et al., 1988](#); [Plack and Moore, 1990](#)). Whereas there was a non-significant trend for greater backward masking in the NoS π than the NoSo data, this trend is opposite to the difference observed by [Berg and Yost \(1976\)](#), where backward masking was smaller in NoS π than NoSo conditions. The result of comparable non-simultaneous masking for NoSo and NoS π conditions is consistent with some previous results ([Small et al., 1972](#); [Zwicker and Zwicker, 1984](#)). In contrast to several previous studies of non-simultaneous masking, in which the signal was presented in quiet ([Berg and Yost, 1976](#); [Kohlrausch and Fassel, 1997](#)), the present data fail to provide evidence of differential magnitude or time course of non-simultaneous masking and support the use of a single temporal window to account for non-simultaneous masking in both NoSo and NoS π stimulus conditions.

One aspect of the present results that deserves further consideration is the way in which the effect of masker level on NoS π thresholds was treated in fitting the temporal window. The ability to benefit from binaural cues associated with an S π signal in No noise is positively correlated with stimulus level (e.g., [Yost, 1988](#)), resulting in a larger MLD at higher presentation levels. This is evident in the present data, where a 20-dB decrement in masker level is associated with a decrement of 18 dB in the NoS π steady masker conditions. In monaural processing models, stimulus power is integrated in the temporal window, and the SNR at output is used to estimate threshold. This approach assumes that threshold is associated with a fixed SNR, though the value of this SNR may differ across individual observers. As described above, the present approach accommodates the deviation from a constant SNR at threshold in the NoS π condition by integrating instantaneous masking, as characterized by the steady masker thresholds, rather than masker energy. This is equivalent to modeling the NoS π data as if the masker dropped by only

18 dB between masker bursts, with threshold estimated at a fixed SNR for this compressed range. Failure to make this type of adjustment can produce inaccurate temporal window fits.

Whereas the present study estimated the effects of non-simultaneous masking on the ability to process binaural cues, there is also a sizeable literature describing the temporal resolution associated with processing of dynamic binaural cues. Estimates of the temporal resolution for tone-in-noise detection in binaurally dynamic conditions differ across paradigms and conditions, with most estimates of the ERD falling between 50 and 150 ms ([Grantham and Wightman, 1979](#); [Kollmeier and Gilkey, 1990](#); [Culling and Summerfield, 1998](#); [Holube et al., 1998](#); [Culling and Colburn, 2000](#)). In a study based on the gapped-masker paradigm, [Culling and Summerfield \(1998\)](#) constructed a masker with two 400-ms segments of interaurally uncorrelated noise and an intermediate segment of diotic noise. All three masker segments were presented at the same level. The signal was a brief 500-Hz tone, either So or S π , presented during this intermediate diotic masker segment. The results were modeled by fitting functions to integrate interaural correlation over time. The best-fitting windows were asymmetric, like those fitted to monaural data, and relatively long on the order of 100 ms (see also, [Kollmeier and Gilkey, 1990](#); [Holube et al., 1998](#); [Akeroyd and Summerfield, 1999](#)). Results like these are often interpreted as indicating that binaural processing is sluggish compared to monaural processing.

The results of the present study indicated that the time constants associated with NoSo and NoS π detection with binaurally static maskers did not differ significantly. A straightforward interpretation of this finding is that binaural sluggishness does not pertain in the present paradigm, where brief S π signals in a relatively low-level No noise were detected in the context of temporally proximal higher-level No noise. A reasonable generalization is that S π signals coincident with envelope minima of narrowband noise maskers are processed with a temporal selectivity that is consistent with the monaural temporal window rather than the longer temporal windows associated with binaural sluggishness. Whereas binaural sluggishness effects can be remarkable for maskers having dynamic interaural differences, binaural sluggishness may be weak or absent for maskers having interaural parameters that do not vary over time. The idea that binaural sluggishness may not pertain for signal detection in maskers having invariant binaural properties has been proposed previously ([Hall et al., 1998](#); [Goupell and Hartmann, 2007](#)) and has received some recent empirical support ([Goupell and Hartmann, 2007](#)). This conclusion is not universally accepted, however ([Krumbholz et al., 2009](#)).

IV. EXPERIMENT 2: ROLE OF TEMPORAL RESOLUTION IN INDIVIDUAL DIFFERENCES FOR NoS π DETECTION IN A NARROWBAND NOISE

The results of experiment 1 indicate that the detection of a brief signal in a bandpass masker is similarly affected by combined simultaneous and non-simultaneous masking for NoSo and NoS π conditions, with an ERD on the order of 10 ms for both types of stimuli. This result notwithstanding, it

is possible that temporal resolution could have a greater effect on NoS π than NoSo thresholds in a narrowband noise masker. Detection of a relatively long-duration signal in a narrowband NoS π condition has been argued to benefit from the improved SNR associated with masker envelope minima (Buss *et al.*, 2003), but this is not the case for diotic (Buss *et al.*, 2003) or for monaural presentation conditions (Buus *et al.*, 1996). In the absence of a binaural cue or an off-frequency monaural cue giving rise to comodulation masking release (Hall and Grose, 1991; Buus *et al.*, 1996), the auditory system does not derive benefit from dynamic reductions in masker level of a narrowband Gaussian noise masker. It is therefore possible that temporal resolution would have a greater effect on narrowband NoS π than NoSo thresholds.

Several studies have demonstrated large individual differences for NoS π detection in a narrowband noise masker (Bernstein *et al.*, 1998; Buss *et al.*, 2007). One possible source of individual variability is the temporal resolution with which binaural cues are processed. Buss *et al.* (2007) tested this hypothesis by comparing performance of individual listeners in a range of binaural detection tasks, including tasks providing transient cues, where temporal resolution would be important for good performance, and tasks providing relatively stable cues over time, where temporal resolution would be less critical to good performance. The expectation was that if NoS π detection in narrowband noise is limited by temporal resolution of cues coincident with envelope minima, then individuals' NoS π thresholds in narrowband noise should be more highly correlated with those in other transient cue conditions than in stable cue conditions. Buss *et al.* (2007) found comparably high correlations among all conditions, a finding that argues against the importance of temporal resolution in the large individual differences in narrowband NoS π conditions.

One limitation of the Buss *et al.* (2007) study is that it did not fully differentiate effects of dynamic SNR and those of dynamic binaural cues, such as dynamic interaural time differences. It could be that NoS π thresholds in a narrowband noise masker are limited by the listener's ability to temporally resolve a brief epoch of improved SNR. This ability may be different from the ability to make use of a transient or dynamic change in binaural stimulus features. The present study therefore compared brief tone thresholds in an abbreviated set of gapped-masker conditions with long-tone thresholds in a narrowband noise masker. If temporal resolution contributed importantly to the large range of individual differences in NoS π thresholds in narrowband noise, then those thresholds should be more strongly correlated with thresholds for a signal in a brief masker gap than a signal presented in a steady masker. Whereas experiment 1 included only good listeners with prior experience in psychoacoustics, experiment 2 included both experienced and naïve observers. This protocol was intended to increase the range of individual differences obtained in both the gapped-masker paradigm and the narrowband noise conditions.

A. Methods

1. Observers

There were eleven observers, aged 18–54 (mean of 28 yr). Eight of these observers had little or no formal

psychoacoustic listening experience. The remaining three were very experienced in psychoacoustics, having previously participated in experiment 1 and other studies of binaural hearing.

2. Stimuli

The first set of conditions used stimuli identical to those described above for experiment 1. Briefly, the signal was a 500-Hz tone gated on and off with 10-ms raised-cosine ramps and no steady state. The masker was a diotic Gaussian noise that was bandpass filtered from 100 to 2000 Hz, with a new sample generated prior to each listening interval. When the gap was present, the masker was 40-dB spectrum level for the initial and final 200-ms bursts, and the level was reduced to 20-dB spectrum level for the inter-burst gap. In steady conditions, the masker was presented for 400 ms at a steady level of either 20- or 40-dB spectrum level. A subset of conditions from experiment 1 was included in the present experiment: The two steady maskers and the gapped masker with the symmetric, 10-ms signal/masker interval ($t_1 = t_2$, 20-ms total gap duration). Thresholds were measured for both So and S π signals.

In the second set of conditions the signal was a 500-Hz tone, with a 15-ms raised-cosine ramps and a 185-ms steady portion. The masker was a narrow band of Gaussian noise, 50 Hz wide and centered on 500 Hz. This masker was played continuously at 60 dB sound pressure level (SPL) and repeated every 10.7 s. A new sample was generated prior to each threshold estimation track. The signal, when present, was temporally centered in a 400-ms listening interval. Thresholds with the narrowband masker were measured for both So and S π signal conditions.

3. Procedures

As in the previous experiment, stimuli were presented in a three-alternative forced-choice design, and signal detection thresholds were estimated using a three-down one-up adaptive procedure which converges on 79% correct. All observers began with the gapped-masker paradigm. For the three experienced observers these data were collected in the course of experiment 1, interleaved with conditions not completed by the eight other observers in the present experiment. All threshold estimates for a particular condition were obtained in sequence, but the order of conditions was randomized independently for each observer. Following completion of the gapped and steady masker conditions, the two narrowband noise conditions (NoSo and NoS π) were likewise completed in random order. Refer to the General Methods section for more details.

B. Results

Mean thresholds are shown in Table II, with thresholds in comparable conditions of experiment 1 included for reference. The pattern of thresholds in the gapped-masker paradigm was consistent with data from corresponding conditions of experiment 1, with a trend for higher thresholds in the present dataset. Averaging across the three conditions associated with each signal phase, thresholds were on average 0.4

TABLE II. Mean thresholds in a subset of conditions of the gapped-masker paradigm are shown in the first three columns for experiment 1 ($n = 7$) and experiment 2 ($n = 11$). Thresholds in the narrowband noise condition of experiment 2 are shown in the last column. Standard deviations appear in parentheses below each mean. Recall that three of the listeners participated in both experiments 1 and 2.

		Steady, 40 dB	20-ms gap, $t_1 = t_2$	Steady, 20 dB	Narrowband noise
NoSo	Exp. 1	74.32	67.38	53.76	
		(1.68)	(4.05)	(1.21)	
	Exp. 2	75.32	67.63	53.83	62.45
		(1.89)	(3.24)	(1.61)	(1.00)
NoS π	Exp. 1	56.88	49.67	38.91	
		(1.71)	(4.11)	(2.47)	
	Exp. 2	59.18	52.67	42.24	46.09
		(3.91)	(4.45)	(4.99)	(3.52)

dB higher in NoSo conditions and 2.9 dB higher in the NoS π conditions of the present experiment. The difference is likely due to the more restrictive observer selection criteria for experiment 1. Individual differences aside, thresholds in the 20-ms gap condition were intermediate between the corresponding 20- and 40-dB steady masker thresholds for all observers in both NoSo and NoS π conditions. As in experiment 1, approximately 35%–40% of the threshold reduction associated with a 20-dB reduction in masker level was evident in the 20-ms gap thresholds.

Thresholds in the NoSo conditions of the narrowband noise paradigm were relatively consistent across observers, with a standard deviation of 1.0 dB. In contrast, there was more variability across observers in the NoS π condition, with a standard deviation of 3.5 dB. The relationship between NoS π thresholds in the narrowband and gapped-masker paradigms is illustrated in Fig. 3, with letters indicating thresholds of the individual observers. Observers who previously participated in experiment 1 are indicated as *a*, *b*, and *c* in this figure. Panels A (left) and C (right) show NoS π thresholds in the steady masker conditions of the gapped-masker paradigm, plotted as a function of NoS π thresholds in the narrowband noise paradigm. Panel B (middle) shows corresponding results for the gapped masker, with the signal temporally centered in the 20-ms reduction in masker level. There is a modest but significant correlation ($p < 0.05$ one-tailed) between

all three pairs of thresholds, with r -values of 0.58 (steady, 40 dB), 0.58 (20-ms gap), and 0.55 (steady, 20 dB), respectively. These associations are indicated by the dotted lines in each panel of Fig. 3. There were comparable correlations between analogous NoSo thresholds (not shown; $0.42 \leq r \leq 0.72$).

If binaural temporal resolution were the dominant factor in determining S π threshold in a narrowband noise masker, there should be a stronger association between NoS π thresholds in narrowband and 20-ms gapped maskers (panel B) than between narrowband thresholds and those in the steady masker conditions (panels A and C). However, that does not appear to be the case. Instead, these results are consistent with the conclusion that the individual differences evident in the narrowband NoS π thresholds were uniformly associated with NoS π thresholds in the steady and gapped-masker conditions. That is, individual differences were correlated across conditions, but this relationship was no stronger for conditions associated with pronounced masker envelope fluctuation than steady NoS π conditions.

C. Discussion

Thresholds in the narrowband noise masker were consistent with those reported previously for similar stimuli (Buss *et al.*, 2007), with larger individual differences in the

FIG. 3. Mean NoS π thresholds in the selected conditions of the gapped-masker paradigm are plotted as a function of NoS π thresholds in narrowband noise masker. Panel A shows results of the steady masker presented at 40 dB spectrum level. Panel B shows results for a gapped masker, with the signal temporally centered in a 20-ms, 20-dB reduction in masker level. Panel C shows results for the steady masker presented at 20 dB spectrum level. Letters indicate individual observers' thresholds, assigned according to the rank order of narrowband noise thresholds. The three observers with the lowest narrowband noise thresholds (observers *a*, *b*, and *c*) had previously participated in the full set of gapped-masker conditions of experiment 1.

NoS π than NoSo conditions. It has been argued that detection of a long S π signal in a narrowband No noise is based on signal cues coincident with masker envelope minima (Grose and Hall, 1998; Buss *et al.*, 2003, 2007). If the temporal resolution with which these cues are processed is the limiting factor in performance, then there should be a particularly strong correlation between S π thresholds for narrowband noise conditions and those for the gapped masker. This hypothesis was not supported. Thresholds were correlated to a comparable extent for both steady and gapped stimuli, consistent with previous results using binaurally dynamic stimuli (Buss *et al.*, 2007).

V. EXPERIMENT 3: NoSo AND NoS π FOR SIMULTANEOUS AND NON-SIMULTANEOUS MASKING AS A FUNCTION OF MASKER BANDWIDTH

The NoSo thresholds reported for the gapped-masker paradigm in experiments 1 and 2 indicate an ability to benefit from transient improvements in SNR. In contrast, published data on detection of an So signal in an No narrowband noise indicate an *inability* to benefit from dynamic changes in masker level associated with inherent masker modulation (e.g., Buss *et al.*, 2007). In the data of Buss *et al.* (2007), the average detection benefit of presenting a 500-Hz signal in a narrowband masker envelope minimum (as compared to maximum) was 7.0 dB for the NoS π condition and not significantly different from zero for the NoSo condition. In contrast, for the bandpass masker conditions of the gapped-masker paradigm, presenting the signal in the temporal center of a 20-ms gap improved thresholds by approximately 7 dB for both the NoSo and NoS π conditions (Exps. 1 and 2). That is, the narrowband masker MLD is associated with a “dip advantage,” but the MLD for the gapped-masker paradigm is not.

One reason for the differences in results between the gapped-masker and narrowband noise paradigms could be related to informational masking, defined as threshold elevation that cannot be attributed to energetic masking and may be related to confusion effects.¹ Simultaneous masking of a pure tone by a band of noise is typically assumed to be dominated by energetic rather than informational masking, particularly for relatively spectrally wide maskers (e.g., Gallun *et al.*, 2008), but this might not be the case for narrowband noise maskers. In the NoSo narrowband noise condition, an added signal may perceptually resemble a feature of inherent masker modulation, such that thresholds exceed those associated with energetic masking (Neff, 1986). In contrast, in the NoSo gapped-masker conditions the wider masker bandwidth could introduce off-frequency cues that disambiguate masker fluctuation from fluctuation associated with a signal (e.g., Moore and Glasberg, 1982), or the wider masker bandwidth could increase inherent masker modulation rate so that the masker envelope no longer contains modulations that resemble an added signal. By this view, the dip advantage for the MLD observed for a narrowband noise masker might be better described in terms of increased masking in the dips of the So condition rather than particularly good performance in S π condition. The binaural cues associated with an S π signal could provide release from such informational masking.

If binaural difference cues support a release from informational masking for a signal presented simultaneous with a narrowband noise masker, then a similar effect could be observed for a brief signal presented under non-simultaneous masking conditions. Previous data have demonstrated that detection thresholds for a brief signal presented immediately before or after a narrowband noise masker can be improved by inclusion of an off-frequency cue indicating masker onset and offset (Puleo and Pastore, 1980; Moore and Glasberg, 1982). This finding has been interpreted as showing that informational masking, as contrasted with energetic masking, can play an important role in non-simultaneous masking. The purpose of experiment 3 was to determine whether the binaural cues available for an S π signal in the context of a narrowband No masker might also serve to reduce non-simultaneous informational masking. Thresholds were measured for a brief tone presented before, during, or after a gated masker presentation, and that masker was a narrow or a relatively wide bandpass noise. The hypothesis was that the MLD would be particularly large in the forward and backward masking conditions with the narrowband noise masker due to large informational masking in NoSo but not NoS π conditions. In contrast, the MLD for the wideband masker was expected to be more modest in forward and backward masking conditions.

A. Methods

1. Observers

There were six observers, aged 21–54 (mean of 35 yr). This group included two observers who had previously participated in both experiments 1 and 2. These two observers had the lowest NoS π narrowband noise thresholds in experiment 2 (observers *a* and *b*, Fig. 3). The remaining four observers were experienced in psychoacoustics, having completed at least one prior experiment unrelated to the present research.

2. Stimuli

The masker was a band of noise, played at a 40-dB spectrum level. In the narrowband masker conditions, that band was 50 Hz wide (475–525 Hz), and in the wideband masker conditions it was 1900 Hz wide (100–2000 Hz). In both cases the masker was presented diotically for 500 ms, gated on and off with 15-ms raised-cosine ramps, and a new sample was generated prior to each 500-ms listening interval. The signal was a 500-Hz pure tone, gated on and off with 15-ms raised-cosine ramps and no steady state. That signal was presented either immediately prior to masker onset, in the temporal center of the masker, or immediately after masker offset. These conditions will be described as reflecting backward, simultaneous, and forward masking, respectively. In the non-simultaneous masking conditions the signal and masker ramps abutted at the zero-voltage points, with no delay. Thresholds were measured for a signal that was in phase in the two ears (NoSo) and for a signal that was out of phase (NoS π).

FIG. 4. Mean thresholds are plotted as a function of the temporal position of the brief signal relative to the masker, with results for the wideband masker in the left panel and those for the narrowband masker in the right panel. Symbol and line style indicate signal phase, as defined in the legend. Error bars show 1 standard error of the mean ($n = 6$).

3. Procedures

As in the previous experiment, stimuli were presented in a three-alternative forced-choice design, and signal detection thresholds were estimated using a three-down one-up adaptive procedure which converges on 79% correct. Conditions were run blocked by the signal timing condition (backward, simultaneous, or forward masking), with the order of signal timing conditions randomized independently for each observer. Within a block, the order of masker bandwidth (narrowband and wideband) and signal phase (So and $S\pi$) was randomized. All thresholds for a particular set of conditions were collected in sequence before proceeding to the next condition. In three cases replicate thresholds for a particular condition and observer spanned a range of 8 dB or more. In these cases the original threshold estimates were discarded, and the condition was repeated at the end of the experiment. Refer to the General Methods section for more details.

B. Results

Mean thresholds are shown in Fig. 4, plotted as a function of the temporal position of the signal. Symbol shape and line style reflect signal phase, and error bars show 1 standard error of the mean. Thresholds for the So signal in simultaneous masking conditions were 5.3 dB lower in the narrowband than the wideband masker. The equivalent rectangular bandwidth at 500 Hz is 78.7 Hz (Glasberg and Moore, 1990), so approximately 2 dB of this bandwidth effect can be attributed to the greater masking noise in the auditory filter centered on 500 Hz for the wideband than the narrowband masker. In contrast, So thresholds in the non-simultaneous masking conditions were higher in narrowband than wideband masker conditions, with a mean difference of 31.3 dB in backward masking and 17.1 dB in forward masking. Compared to simultaneous masking, non-simultaneous So signal presentation had a much more beneficial effect in wideband than narrowband masker conditions, with a bandwidth effect of more than 20 dB. Relative to simultaneous masking, wideband masker thresholds in non-simultaneous conditions improved by 38.8 dB (backward) and 26.7 dB (forward). Narrowband masker thresholds improved by 2.2 dB (backward) and 4.3 dB (forward).

In contrast to the pattern of NoSo data, the pattern of NoS π thresholds was roughly similar for the associated narrowband and wideband maskers. Thresholds for an $S\pi$ signal in simultaneous masking conditions were 3.4 dB lower in the narrowband than the wideband masker. Mean thresholds in the non-simultaneous masking conditions were only slightly higher in narrowband than wideband masker conditions, with a mean difference of 1.8 dB in backward masking and 1.2 dB in forward masking. Compared to simultaneous masking, non-simultaneous $S\pi$ signal presentation had a slightly greater effect for wideband than narrowband masker conditions, a bandwidth effect of approximately 5 dB. Relative to simultaneous masking, non-simultaneous presentation improved wideband thresholds by 24.9 dB (backward) and 11.5 dB (forward). Narrowband masker thresholds improved by 19.7 dB (backward) and 6.9 dB (forward).

One consequence of the relatively high thresholds in the narrowband NoSo non-simultaneous masking conditions is that the MLD was much larger for narrowband than wideband maskers in the non-simultaneous making conditions. The MLD for wideband masker conditions was 4.3 dB (backward) and 2.9 dB (forward), whereas the MLD for narrowband masker conditions was 33.8 dB (backward) and 18.8 dB (forward). The MLD was comparable across bandwidths for simultaneous masking conditions, with values of 18.1 dB for wideband and 16.3 dB for narrowband maskers.

The simultaneous masking MLD was not significantly different for the narrow and wide masker bandwidths ($t_5 = 1.57$, $p = 0.178$). In contrast to the present brief tone results, previous data for relatively long-duration signals have shown a larger MLD for narrowband than wideband maskers (e.g., Bernstein *et al.*, 1998). This difference may be reduced under the present conditions due to the increased MLD for short-duration tones in wideband maskers (Blodgett *et al.*, 1958; Green, 1966). Additional data, not reported here, were collected to rule out spectral splatter effects in the narrowband masker condition. In these supplemental conditions a Gaussian function was used to gate the signal in the time domain (half-rise duration of 15 ms) and to filter the masker in the frequency domain (6-dB bandwidth of 58 Hz). This procedure resulted in closely matched long-term spectra for the brief signal and the narrowband masker. Simultaneous

masked thresholds for nine observers were consistent with the narrowband data of the present report, indicating that cues related to spectral splatter in the narrowband masker conditions are unlikely to play an important role in the present data. It is unclear whether failure to obtain a larger simultaneous masking MLD for the narrowband than the wideband masker in the primary dataset is due to the signal duration or to substantial individual differences, as NoS π thresholds for the six listeners spanned 6.7 and 0.8 dB for the narrowband and wideband conditions, respectively.

C. Discussion

This experiment was designed to assess the hypothesis that the large MLD observed for narrowband noise maskers is due in part to a release from non-energetic, informational masking. As observed in previous studies, there was relatively more non-simultaneous masking in NoSo conditions for the narrowband than the wideband noise masker (Puleo and Pastore, 1980; Moore and Glasberg, 1982; Neff, 1986). This result has been explained in terms of the off-frequency cues to masker onset and offset available in wideband maskers, cues which disambiguate the effects of adding a signal and reduce informational masking (Puleo and Pastore, 1980; Moore and Glasberg, 1982). Compared to NoSo results, there was less evidence of greater non-simultaneous masking in narrowband than wideband NoS π conditions. This result is consistent with the conclusion that low-rate inherent masker fluctuation of the narrowband noise masker introduces substantial non-energetic masking in NoSo conditions and that the binaural cue in NoS π conditions provides a release from informational masking. A low-level So signal perceptually resembles envelope features of a narrowband masker, whereas an S π signal is qualitatively different. One observer described the NoS π signal as “spread out in space,” in contrast to the centralized auditory image of the No masker alone. The informational masking effect observed here for forward and backward masking may also be responsible for preventing observers from “listening in the dips” of a narrowband noise under NoSo, simultaneous masking conditions.

VI. GENERAL DISCUSSION

Results of the gapped-masker paradigm utilized in the first experiment indicate that non-simultaneous masking of a 500-Hz signal presented in a brief, 20-dB decrement in level of a 1900-Hz-wide band of masking noise follows a comparable time-course in NoSo and NoS π conditions. Temporal windows fitted to NoS π data were comparable to those fitted to NoSo data, in both asymmetry and duration. In other words, temporal resolution was indistinguishable for NoSo and NoS π conditions. This is inconsistent with the idea that sensitivity for a brief S π signal in No noise is limited by binaural sluggishness under these conditions. The present results are consistent with an interpretation that effects of binaural sluggishness may be restricted to maskers having dynamic interaural properties.

Experiment 2 compared individual differences in sensitivity for an S π signal in No noise for gapped and steady maskers of the gapped-masker paradigm and for a narrow-

band masker. Thresholds in a narrowband noise were no more highly correlated with thresholds in a gapped-masker than those in the steady maskers. This result fails to support to the hypothesis that variability in narrowband noise thresholds is due to differences in the ability to temporally resolve brief improvements in SNR. Instead, the correlation observed for narrowband and all three wideband masker conditions reflect individual differences in the ability to process binaural cues irrespective of masker envelope fluctuation.

The final experiment measured simultaneous and non-simultaneous masking thresholds for a wideband and a narrowband noise masker. Thresholds for an So signal were consistent with previous data showing relatively pronounced forward and backward masking for the narrowband masker. This result has been interpreted as reflecting confusion between inherent masker modulation and an added signal. Thresholds were more similar across masker bandwidths for an S π signal, consistent with the hypothesis that non-energetic masking effects observed in narrowband maskers can be reduced with the introduction of a binaural cue disambiguating features of the masker and features of the added signal. These results are consistent with the view that the greater MLD in simultaneous masking for narrowband than wideband noise maskers is due in part to a release from informational masking.

One aspect of the results of the third experiment that deserves mention is the relatively small MLD obtained in non-simultaneous, wideband masker conditions. Whereas the MLD for simultaneous masking was 18.1 dB, the MLD was only 2.9 dB for forward masking. One factor that could account for a reduction in the MLD is the reduced amount of baseline masking: Thresholds for an So signal dropped from 72.4 dB in simultaneous masking to 45.7 dB in forward masking. Assuming that NoSo thresholds directly reflect excitation, this threshold reduction would correspond to simultaneous conditions in which the masker was reduced from 40 to 13.3 dB spectrum level. A number of studies have documented a reduction in the MLD with reduced masker level, particularly for masker levels near threshold (McFadden, 1968; Hall and Harvey, 1984; Yost, 1988). This reduction in the MLD is thought to reflect the effects of internal noise on sensitivity in NoS π conditions (Yost, 1988; Breebaart *et al.*, 2001a; Bernstein and Trahiotis, 2008). While published studies have typically used longer duration stimuli than the brief signals used here, most predict more than 2.9 dB of MLD for a masker at 13.3 dB spectrum level. This observation raises the possibility that the relationship between NoSo and NoS π non-simultaneous masking is different for signals presented in epochs of silence (Exp. 3) than for signals presented in brief, 20-dB reductions in masker level (Exps. 1 and 2). This possibility would be consistent with the findings of Kohlrausch and Fassel (1997) who reported much steeper recovery from forward masking in NoSo than NoS π conditions when the signal was presented after masker offset. If that is the case, then the presence of simultaneous masking in all of the gapped-masker conditions of experiments 1 and 2 could be critical to the finding of comparable temporal resolution in NoSo and NoS π conditions.

This consideration prompted collection of two sets of supplemental data, both based closely on conditions in

FIG. 5. Mean thresholds ($n = 2$) are plotted as a function of masker spectrum level. Symbol shading and line style indicate signal phase, as defined in the legend.

experiment 1. Two highly practiced observers (observers *a* and *b*, Fig. 3) participated. In the first set of conditions NoSo and NoS π thresholds were measured for a 500-Hz signal, with 10-ms ramps and no steady state. The masker was a steady 400-ms bandpass noise (100–2000 Hz) played at 0, 10, 20, 30, or 40 dB spectrum level. The resulting thresholds were highly consistent across the two observers, and the means are plotted in Fig. 5. The difference between NoSo and NoS π thresholds increased with masker level, as reported previously (McFadden, 1968). These data predict an MLD of 10.5 dB for masker presented at a 13.3-dB spectrum level. This is 7.6 dB greater than the 2.9 dB MLD obtained in the wideband noise, forward masking conditions of experiment 3. The second set of supplemental conditions replicated those of experiment 1 but with the masker turned completely off during the inter-burst gaps. The temporal windows fitted to these data were sharper than those associated with the 20-dB reduction in masker level. Fitting data from just the two observers who participated in supplemental conditions, the mean ERD was 10.6 ms for the 20-dB gap conditions (Exp. 1) and 6.6 ms for the fully gapped conditions (supplemental data). This effect of masker level in the inter-burst interval was quite consistent for the NoSo and NoS π conditions, however: Turning the masker off in the gaps reduced the ERD by 4 ms in both cases. These two sets of supplemental data confirm that the wideband, forward-masking results of experiment 3 reflect a smaller MLD than expected based on reductions in baseline (NoSo) masking, but this discrepancy cannot be attributed to differences in temporal resolution between NoSo and NoS π .

Several models of the MLD currently incorporate mechanisms to simulate non-simultaneous masking, particularly forward masking. Breebaart *et al.* (2001b), for example, achieved this using adaptation loops and noted that this process matches some but not all psychophysical temporal resolution data. The present results indicate that incorporating a temporal window having an ERD on the order of 10 ms might also be appropriate to capture energetic masking effects. However, it is likely that additional, non-energetic masking effects elevate thresholds under some conditions, such as the NoSo detection of a brief tone in a narrowband noise. Informational masking could play an important role in

stimuli for which the signal resembles some features of the inherent masker modulation. Based on the present data these effects could be large, on the order of 30 dB in some conditions. Modeling informational masking effects could be complicated by the fact that it is unclear whether similar binaural processes underlie the MLD for energetic and informational masking (Gallun *et al.*, 2008). The present results provide no support for the idea that an additional temporal window reflecting binaural sluggishness is necessary to capture effects related to masker level fluctuation.

VII. CONCLUSIONS

The MLD obtained for a long-duration tonal signal spectrally centered in a narrowband noise is dominated by signal cues coincident with masker envelope minima (Grose and Hall, 1998; Buss *et al.*, 2003, 2007). Large individual differences in these conditions motivated the hypothesis that the temporal resolution with which these minima are processed could play an important role in detection. Experiments of the present report evaluated the role of temporal resolution in the MLD obtained with a narrowband noise masker.

- (1) Experiment 1 quantified temporal resolution by fitting temporal window functions to brief tone thresholds for a wideband masker that was either steady in level or had an abrupt 20-dB reduction in level. Temporal windows fitted to NoSo and NoS π data were similar, with ERDs near 10 ms in both cases. This outcome is consistent with an interpretation that binaural sluggishness for masked signal detection may be restricted to conditions in which interaural parameters of the masker change dynamically.
- (2) Experiment 2 evaluated the role of temporal resolution in the narrowband MLD by comparing individual differences in narrowband and wideband conditions, including steady and gapped maskers. The correlation of S π thresholds in narrowband and wideband conditions was no larger for gapped maskers than for steady maskers. Although we cannot rule out the possibility that temporal resolution plays some role in NoS π detection in narrowband noise, other factors would appear to be responsible for individual differences. One possibility is that observers differ in their ability to use binaural difference cues to reduce masking.
- (3) Experiment 3 measured detection thresholds in simultaneous and non-simultaneous masking conditions with either a narrowband or a wideband masker. As observed in previous studies with monaural stimuli, NoSo thresholds in non-simultaneous masking conditions were elevated in narrowband as compared to wideband maskers. In contrast, NoS π thresholds were more comparable for the two masker bandwidths. This result is consistent with the idea that non-simultaneous masking in the narrowband masker conditions is dominated by informational masking and that masking release can be obtained by widening the masker bandwidth or by introducing binaural difference cues.

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¹In general, informational masking tends to be found under conditions of stimulus uncertainty or when the target and masker are perceptually similar (Durlach *et al.*, 2003). These effects have been observed under a wide range of stimulus conditions, including pure tone detection in a multi-tonal masker (e.g., Kidd *et al.*, 1994) and processing of speech presented in a speech masker (e.g., Freyman *et al.*, 2007). Under both of these conditions, the introduction of binaural cues improves performance, an effect attributed to the reduced informational masking. Confusion effects have also been demonstrated for tonal signals that are forward masked by a narrowband noise masker (Neff, 1986), though it is unclear how binaural cues might affect thresholds for these stimuli.

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