The role of off-frequency masking in binaural hearing

Emily Buss^{a)} and Joseph W. Hall III

Department of Otolaryngology/Head and Neck Surgery, University of North Carolina, School of Medicine, Chapel Hill, North Carolina 27599

(Received 17 April 2009; revised 22 February 2010; accepted 9 March 2010)

The present studies examined the binaural masking level difference (MLD) for off-frequency masking. It has been shown previously that the MLD decreases steeply with increasing spectral separation between a pure tone signal and a 10-Hz wide band of masking noise. Data collected here show that this reduction in the off-frequency MLD as a function of signal/masker separation is comparable at 250 and 2500 Hz, indicating that neither interaural phase cues nor frequency resolution are critical to this finding. The MLD decreases more gradually with spectral separation when the masker is a 250-Hz-wide band of noise, a result that implicates the rate of inherent amplitude modulation of the masker. Thresholds were also measured for a brief signal presented coincident with a local masker modulation minimum or maximum. Sensitivity was better in the minima for all NoS π and off-frequency NoSo conditions, with little or no effect of signal position for on-frequency NoSo conditions. Taken together, the present results indicate that the steep reduction in the off-frequency MLD for a narrowband noise masker is due at least in part to envelope cues in the NoSo conditions. There was no evidence of a reduction in binaural cue quality for off-frequency masking. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3377053]

PACS number(s): 43.66.Pn, 43.66.Dc, 43.66.Ba [RLF]

Pages: 3666–3677

I. INTRODUCTION

Interaural difference cues are important for sound source localization, particularly for localization on the horizontal plane. Interaural difference cues can also reduce masking (Hirsh, 1948). In one frequently studied stimulus configuration, a masker is presented diotically (No), and thresholds are measured for either a diotic signal (So) or a signal presented out of phase at the two ears (S π). Under most conditions thresholds are lower in the NoS π than the NoSo stimulus configuration, an effect described as the binaural masking level difference (MLD). With few exceptions, traditional MLD experiments have used maskers that spectrally overlap the signal frequency, and most of what we know about binaural masking release is based on studies of on-frequency masking. Under natural listening conditions, however, a background masker may not spectrally overlap the signal of interest. In these cases, spread of excitation and off-frequency masking of the signal could play a substantial role in sensitivity. The ability to use binaural cues to ameliorate the effects of off-frequency masking is the topic of the present report.

Zwicker and Henning (1984) examined the effects of spectral separation of a tonal signal and a narrowband noise masker on the MLD. In one set of conditions the masker was a 10-Hz-wide band of Gaussian noise centered on 250 Hz and fixed in frequency, and signal thresholds were measured for a 600-ms tone at a range of frequencies, including frequencies below and above the passband of the masker. In this paradigm the difference between NoSo and NoS π thresholds was largest when the signal frequency was within the pass-

band of the masker, with an MLD on the order of 25 dB under these conditions. Masking release fell off steeply with increasing spectral separation between the signal and masker. The MLD decreased to approximately 3 dB for a signal that was just 30 Hz outside the masker passband. It was argued that this effect could not be explained in terms of a reduction in baseline masking with increased spectral separation between the signal and masker, nor was it thought to be consistent with absolute frequency effects previously observed for on-frequency MLD conditions. Zwicker and Henning (1984) observed that the pattern of thresholds obtained in the NoSo condition was consistent with previous data and with an energy detector model, an observation which implicates NoS π thresholds in the steep decline in off-frequency MLD.

One hypothesis proposed by Zwicker and Henning (1984) to account for the steep decline in off-frequency MLD was related to the observation that increasing the spectral separation between the signal and the masker increases the rate at which interaural phase differences (IPDs) change over time. If the binaural system is insensitive to these rapid changes, then the MLD could be reduced as a consequence of poor thresholds in off-frequency NoS π conditions. McFadden *et al.* (1972) came to a similar conclusion based on off-frequency MLD data in which both the signal and masker were pure tones. In that study, NoS π thresholds initially fell with increased signal/masker separation up to 10–15 Hz, rose slightly for intermediate separations of 15–30 Hz, and then fell with further increases in the spectral separation. This non-monotonicity was interpreted as reflecting an ability to benefit from slow dynamic binaural cues, with a reduction in this benefit for increasingly rapid rates of change above 10–15 Hz. In a similar vein, Zurek and Durlach (1987) proposed that the reduction of the MLD with increasing masker bandwidth for on-frequency maskers may be due to reduced

^{a)}Author to whom correspondence should be addressed. Electronic mail: ebuss@med.unc.edu

sensitivity for rapidly changing binaural cues. Not all data are consistent with poor sensitivity to rapidly changing IPDs, however. Goupell and Hartmann (2006, 2007) argued that dynamic binaural cues are beneficial to the detection of interaural incoherence, with binaural temporal resolution on the order of milliseconds.

The basic off-frequency MLD results of Zwicker and Henning (1984) were recently replicated by Henning *et al.* (2007). That follow-up study used a relatively long-duration (600-ms) signal, like that used in the original study, as well as a brief (12-ms) signal. The purpose of using the brief signal was to control the effects of rapidly changing binaural cues. Henning *et al.* (2007) suggested that the ability to benefit from dynamic binaural cues with a long-duration signal could be limited by “binaural sluggishness” (Grantham and Wightman, 1978; Grantham, 1982, 1984; Kollmeier and Gilkey, 1990; Akeroyd and Summerfield, 1999). If increasingly rapid changes in the IPD limit masking release at increasingly wider signal/masker separations, then using a brief signal should limit these dynamic effects. The results obtained by Henning *et al.* (2007) were somewhat equivocal on this point. One listener showed the expected shallow reduction in MLD with increasing signal/masker separation for a brief signal, but the other did not.

Although the small magnitude of the off-frequency MLD may arise due to a decrease in binaural sensitivity as the signal and masker frequencies diverge, this effect might also be the result of monaural processes, as reflected in NoSo thresholds. For example, Carlyon (2007) suggested that cues related to comodulation masking release (CMR) could improve NoSo detection for off-frequency maskers. Buus (1985) showed that off-frequency monaural masking is reduced by up to 25 dB with the introduction of masker amplitude fluctuation. He suggested that this effect is related to CMR, wherein the coherent masker modulation in auditory channels remote from the signal frequency is used to differentiate masker from signal-plus-masker at the output of the auditory channel centered on the signal. There are other monaural cues that have been argued to improve sensitivity for detection of an off-frequency tonal signal with a narrowband masker, including dynamic spectral cues or cues related to changes in fine-structure (Moore and Glasberg, 1987), beats or combination tones (Nelson and Fortune, 1991; Moore *et al.*, 1998), changes in envelope statistics (Van Der Heijden and Kohlrausch, 1995), and possibly suppression (Fastl and Bechly, 1983; Wright, 1992; Moore and Vickers, 1997). If any of these monaural effects preferentially reduce NoSo as compared to NoS π thresholds, this could lead to a steep decline in the off-frequency MLD.

The present set of experiments assessed the possible role of binaural and monaural contributions to the steep decline in off-frequency MLD with narrowband maskers.

II. EXPERIMENT 1: THE EFFECT OF SIGNAL FREQUENCY ON THE OFF-FREQUENCY MLD

If the steep decline in the off-frequency MLD with an increasing signal/masker separation were due to an inability to benefit from rapidly changing IPDs, then one might expect these effects to differ substantially when measured in differ-

ent spectral regions, due to the availability of IPD cues below but not above about 1500 Hz. The MLD above 1500 Hz is attributed to the use of interaural envelope cues, and can be relatively robust for narrowband maskers (McFadden and Pasanen, 1978). In general the MLD is larger at low than high frequencies, however, even for narrowband maskers (van de Par and Kohlrausch, 1997). While the MLD at low and high frequencies share many common features (van de Par and Kohlrausch, 1997; Bernstein and Trahiotis, 2002), there is some evidence that binaural processing is less sluggish for interaural level differences (ILDs), dominant in higher spectral regions, than for IPDs, dominant in low spectral regions (Grantham, 1982, 1984). Additionally, Grantham (1984) argued that temporal resolution for dynamic binaural cues may be better at high than low frequencies even apart from the availability of IPD cues. Therefore, according to the sluggishness hypothesis, the decline in MLD with increasing signal/masker separation should be shallower at high than low frequencies.

The first experiment assessed the effect of stimulus frequency on the steep decline in off-frequency MLD observed for a tonal signal and a low-frequency narrowband noise masker. This was accomplished by measuring S_0 and S_π thresholds at a range of spectral positions relative to a narrowband No masker centered on 250 or 2500 Hz. If the use of binaural cues in off-frequency NoS π conditions is limited by dynamic changes in IPDs, as opposed to interaural envelope or ILD cues, then no such effect should be observed at 2500 Hz, where IPD cues are not useable. If the steep decline in MLD with increasing signal/masker frequency separation is due to binaural sluggishness, then the slope of this function could be shallower at high frequencies, where binaural sluggishness may be less pronounced. Alternatively, if monaural cues introduced in off-frequency conditions are primarily responsible for the pattern of MLD, then there should be no effect of frequency. For example, if signal/masker separation introduces monaural cues related to envelope beats (Moore *et al.*, 1998), then this cue would be equally viable in both the 250-Hz and 2500-Hz frequency regions and would result in parallel reductions in the MLD as a function of signal/masker separation (in Hz).

A. Methods

1. Observers

Observers were five adults, ages 21.0–53.9 yrs. old, with a mean age of 32.3 yrs. All had pure tone thresholds of 20 dB HL or better at octave frequencies 250–8000 Hz bilaterally (ANSI, 2004), and all had previously participated in psychophysical studies. None reported a significant history of ear disease.

2. Stimuli

The masker was a continuous band of Gaussian noise, 10 Hz wide and arithmetically centered on either 250 or 2500 Hz. This band was played diotically (No) and presented at a 60-dB spectrum level.

The signal was a pure tone, either S_0 or S_π , presented for 500 ms including 50-ms raised-cosine ramps. The signal

frequency was near the masker center frequency (cf) of 250 or 2500 Hz. For the 250-Hz masker, the signal was frequency 210, 230, 240, 250, 260, 270, or 290 Hz. The signal frequencies associated with the 2500-Hz masker were chosen based on similarity with the ± 20 -Hz signal/masker separation at the 250-Hz cf. Signal frequencies of 2480 and 2520 Hz had equal linear spacing with respect to the masker cf (± 20 Hz). The distance between masker cf and signals at 2383 and 2617 Hz was approximately equal in ERB units to the ± 20 Hz, low cf stimuli (~ 0.4 ERBs; Glasberg and Moore, 1990). The most widely spaced signals at 2300 and 2700 Hz were proportional to those at 230 and 270 Hz, both defined as $\pm 8\%$ of the masker cf. Data were also collected at 2490 and 2510 Hz (± 10 Hz) to assess the effect of very small signal/masker separations.

The continuous masker was generated in MATLAB prior to each threshold estimation track. Maskers were generated in the frequency domain using random Gaussian draws to define the real and imaginary values of components in the passband. Each array produced a 10.7-s sample that repeated seamlessly, with 2^{17} points played at 12,207 samples/s. The signal was generated in an RPDs (TDT) circuit, including ramps. The stimuli were played out of a real-time processor (RP2, TDT), routed through a headphone buffer (HB7, TDT) and presented over deeply inserted earphones (ER-2, Ety-motic).

3. Procedures

Thresholds were collected in a three-interval, three-alternative forced-choice, 3-down/1-up track to estimate threshold for 79% correct detection (Levitt, 1971). The track continued for eight reversals. The signal level was adjusted in steps of 4 dB until completion of the second reversal and steps of 2 dB thereafter. The final threshold estimate was the average level at the last six track reversals. Signal frequency and interaural signal phase (So and $S\pi$) were held constant across trials within a track. Three tracks were obtained in sequence in each condition, and a fourth estimate was collected in cases of 3 dB or more variability across prior estimates. All (three or four) threshold estimates were averaged to obtain the final threshold. Lights on a hand-held response box marked each 500-ms listening interval, and intervals were separated by 350 ms. Correct-answer feedback was also provided visually after every trial. Thresholds were collected in blocks by condition, and conditions were completed in a different random order for each observer.

B. Results and discussion

The pattern of thresholds for the five observers was consistent, so mean data are shown in Fig. 1. Detection thresholds are plotted as a function signal frequency, with the abscissa in each panel scaled to equal proportional steps. The top panel shows results for the 2500-Hz masker, and the bottom shows results for the 250-Hz masker. Thresholds for the diotic signal (NoSo) are plotted with filled circles and those for the dichotic signal (NoS π) are plotted with open circles. Error bars indicate 1 standard error of the mean.

FIG. 1. Mean thresholds are plotted as a function of signal frequency, indicated on the abscissa in Hz. The top panel (a) shows thresholds with a 10-Hz-wide masker centered on 2500 Hz, and the bottom panel (b) shows thresholds with a 10-Hz-wide masker centered on 250 Hz. Signal phase is indicated with symbol type: NoSo results are plotted with filled circles and NoS π with open circles. Error bars show 1 standard error of the mean ($n = 5$). Those bars extend above the mean for NoSo data and below the mean for NoS π data in order to prevent ambiguity where points overlap.

Results at the 250-Hz masker frequency closely resembled those shown by Zwicker and Henning (1984; Fig. 4a) under comparable stimulus conditions. Thresholds were roughly symmetrical around the masker cf, with improving sensitivity as a function of signal/masker separation in both NoSo and NoS π conditions. Data collected in the region of 2500 Hz followed a similar pattern, though improvement as a function of signal frequency was much more sharply tuned than that at the lower frequency when compared in equal ERB or proportional steps. The very sharp tuning at 2500 Hz in both the NoSo and NoS π conditions is inconsistent with a power spectrum model of masking, wherein sensitivity in off-frequency conditions is determined solely by spread of excitation. This observation is revisited below.

Thresholds for the NoSo condition will be considered in detail first. For the 250 Hz masker, moving the signal 10 Hz off the masker cf improved thresholds by 11.4 dB (240 Hz) and 9.8 dB (260 Hz). Introducing a 20-Hz separation improved thresholds by 23.3 dB (230 Hz) and 21.3 dB (270 Hz). The improvements in threshold for small signal/masker separations were similar at 2500 Hz, where a 10-Hz separation improved thresholds by 8.1 dB (2490 Hz) and 8.7 dB (2510 Hz), and a 20-Hz separation improved thresholds by 17.6 dB (2480 Hz) and 16.6 dB (2520 Hz). Improvements in the 2500-Hz thresholds were greater than those in the ± 20 Hz, low-cf masker conditions when the “equal ERB” signal frequencies were used for comparison. In these conditions thresholds improved by 27.7 dB (2383 Hz) and 28.3 dB (2617 Hz). Improvements in NoSo thresholds were even greater for signal frequencies at equal proportional spacing, with threshold improvements of 36.0 dB (2300 Hz) and 34.7 dB (2700 Hz) relative to the on-frequency threshold. If NoSo thresholds had been determined solely by excitation arising

FIG. 2. Mean values of MLD are plotted as a function of signal frequency relative to the masker center frequency. Symbols indicate the masker cf: 250-Hz values are plotted with down-pointing triangles and 2500-Hz values with up-pointing triangles. Error bars indicate 1 standard error of the mean across values for individual observers ($n=5$). The dashed horizontal line indicates no benefit in the NoS π as compared to NoSo condition.

from the masker, then off-frequency thresholds at the two masker frequencies would have improved as a function of signal/masker separation in a parallel fashion when compared in equal ERB spacing and approximately so in proportional spacing. The pattern of NoSo results is consistent with the conclusion that thresholds in these conditions were affected by factors other than masker-related excitation, such as temporal cues based on beats between the signal and masker.

Thresholds in the NoS π condition improved less steeply as a function of signal/masker separation than those in the NoSo condition. For the 250-Hz masker, a 10 Hz separation improved thresholds by 5.5 dB (240 Hz) and 3.6 dB (260 Hz), and a 20-Hz separation improved thresholds by 6.4 dB (230 Hz) and 5.7 dB (270 Hz). At 2500-Hz, a 10-Hz separation improved thresholds by 4.7 dB (2490 Hz) and 4.1 dB (2510 Hz), and 20-Hz separation improved thresholds by 4.7 dB (2480 Hz) and 5.4 dB (2520 Hz). As in the NoSo conditions, NoS π thresholds in the two frequency regions were more comparable for equal signal/masker separation in Hz than for comparable ERB or proportional spacing.

Figure 2 shows the MLD plotted as a function of signal/masker frequency separation in absolute frequency units (Hz). Symbols indicate the masker cf, and error bars show 1 standard error of the mean across the five observers' values of the MLD. The on-frequency MLD, where signal frequency is equal to masker cf, was larger for the 250-Hz than the 2500-Hz masker by about a factor of two, with mean values of 25.7 and 13.6 dB, respectively. This is comparable to the within-observer frequency effects in narrowband, on-frequency MLD that have been previously reported (Buss *et al.*, 2007). As observed by Zwicker and Henning (1984), the MLD for a masker centered on 250 Hz declined steeply as signal/masker separation increased. The MLD obtained in the region of 2500 Hz also declined steeply with increasing signal/masker spectral separation. The slopes of these functions were similar when compared in dB-per-Hz, suggesting that factors related to absolute frequency separation rather than spectral resolution could underlie the decline in the off-frequency MLD. These observations were confirmed with a repeated-measures analysis of variance (ANOVA) performed on the MLDs, with two levels of cf (250 and 2500 Hz) and five levels of separation (-20 , -10 , 0 , $+10$, and $+20$ Hz), the separations for which data are available at both masker frequencies. This analysis resulted in significant main effects of

cf ($F_{1,4}=21.29, p<0.01$) and separation ($F_{4,16}=30.47, p<0.0001$), but no interaction ($F_{4,16}=0.82, p=0.53$).¹

The results of this experiment indicate that the steep reduction in the MLD was not due specifically to difficulties in processing dynamic IPDs, as the MLD declined abruptly in a frequency region where the auditory system is insensitive to IPDs. Furthermore, the results failed to support the hypothesis that the reduction in off-frequency MLD with increasing signal/masker separation is strongly related to binaural sluggishness. If binaural sluggishness were limiting the off-frequency MLD, the prediction was for sharper tuning in the 250-Hz than the 2500-Hz frequency regions, due to the possibility of greater sluggishness for low-frequency stimuli (Graham, 1984).

To summarize the results of experiment 1, the basic findings of Zwicker and Henning (1984) were replicated in the 250-Hz masker conditions, for which the MLD fell steeply with increasing signal/masker separation. This result was also seen at the 2500 Hz masker frequency, with similar patterns across frequency regions when compared for small signal/masker frequency separations of ± 10 and ± 20 Hz. Parallel reduction in the MLD at low and high frequencies, when plotted as a function of frequency separation in Hz, indicates that this result is not specific to performance relying primarily on IPDs and fails to support the hypothesis that the off-frequency MLD is limited by binaural sluggishness. A noteworthy aspect of these results is the steep improvement in NoSo thresholds for signals just 10–20 Hz above or below the 2500-Hz masker cf. A 20-Hz signal/masker separation is associated with a spectral gap between the edge of the masker band and the signal of approximately 0.05 ERBs, so threshold improvements on the order of 20 dB strongly implicate effects other than overall masker-related excitation in the pattern of NoSo thresholds. This result is consistent with the hypothesis that changes in cues available monaurally play an important role in the steep decline in the off-frequency MLD. The convergence of NoSo and NoS π thresholds with increasing signal/masker separations is consistent with progressive improvement in monaural relative to binaural cue quality. By this view, the reduction and eventual elimination of the MLD (e.g., at the widest separations in 2500-Hz data) is due to the reduced ability of binaural cues to outperform monaural cues.

III. EXPERIMENT 2: THE ROLE OF INHERENT MASKER AMPLITUDE MODULATION

The second experiment assessed the role of inherent amplitude modulation (AM) of the masker in the off-frequency MLD. Previous studies have shown that monaural masking can be affected to some extent by the inherent AM of narrowband noise maskers. Bos and de Boer (1966), for example, reported that detection thresholds for a pure tone centered in a band of noise can be 3–4 dB greater than expected based on energetic masking if the noise bandwidth is narrow. One explanation for this finding is that the inherent AM of a narrowband masker makes it difficult to detect a signal based on the associated increase in stimulus level. This interpretation is bolstered by the finding of lower detection thresholds

for a pure tone presented in narrowband low-fluctuation noise as compared to narrowband Gaussian noise (Hartmann and Pumplin, 1988) and by intensity discrimination results showing better performance for stimuli with relatively flat temporal envelopes than for stimuli that fluctuate markedly in amplitude (Bos and de Boer, 1966; Eddins, 2001). Whereas masker AM can reduce sensitivity for an on-frequency signal, cues related to envelope fluctuation may aid monaural detection in off-frequency masking (Buus, 1985).

The effects of inherent AM were tested in the present experiment by assessing on- and off-frequency MLDs with different masker bandwidths (10 and 250 Hz) and, therefore, different equivalent rates of AM. It was reasoned that faster rates of AM associated with the wider, 250-Hz bandwidth would be associated with a reduction in both the detrimental on-frequency monaural masking effects associated with the fluctuations of a narrowband noise (Bos and de Boer, 1966) and the beneficial off-frequency monaural masking effects associated with a narrowband noise (Buus, 1985). The experiment tested the hypothesis that the off-frequency MLD would decline less steeply with increasing signal/masker separation for the 250-Hz-wide masker. This masker bandwidth is associated with relatively fast rates of inherent AM which should result in (a) better on-frequency NoSo thresholds and (b) poorer off-frequency NoSo thresholds. Such a result would be consistent with the interpretation that AM-related effects on the NoSo baseline contribute strongly to reductions in off-frequency MLD observed with narrowband maskers. Preliminary supporting evidence for this prediction can be found in the data of Zwicker and Henning (1984). In that study NoSo and NoS π thresholds were measured as a function of signal frequency for three masker bandwidths: 10, 31.6, and 100 Hz. The resulting MLDs were more sharply tuned for the narrower masker bandwidths. Because narrower bandwidths of Gaussian noise are associated with slower rates of inherent AM (Rice, 1954), this bandwidth effect for off-frequency MLD could be due in part to rate-specific effects of masker modulation on NoSo thresholds.² In the present study, a cf of 500 Hz rather than 250 Hz was used to ensure comparable audibility across-frequency for the narrow and wide bandwidth maskers.

A secondary goal of Experiment 2 was to further examine the role of frequency region on the off-frequency MLD. In Experiment 1 the MLD at 2500 Hz was very sharply tuned, with little or no MLD for signal/masker separations of 20 Hz or more. One interpretation of this result is that monaural cues are introduced as a function of absolute signal/masker separation, with ± 20 Hz providing a cue capable of improving thresholds by about 16.9 dB, a large improvement relative to the 13.6-dB MLD observed for on-frequency masking. By this account, the off-frequency MLD is small or absent at 2500 Hz because the high-frequency MLD is relatively modest even in the on-frequency masker condition, such that monaural cues support comparable performance for signal/masker separations of 20 Hz or more. An alternative interpretation is that off-frequency masking is fundamentally different in regions supporting phase locking (e.g., 250 Hz) and regions where phase locking does not contribute to bin-

aural hearing (e.g., 2500 Hz). For the 500-Hz cf used in experiment 2, it was predicted that the MLD would be comparable in size to that found at 250 Hz and that tuning would also be comparable when plotted in absolute signal/masker separation. Such a result would corroborate an interpretation of the results of experiment 1 in terms of a dominant role for monaural cues in the steep decline of the MLD with signal/masker separation for a narrowband noise masker.

A. Methods

1. Observers

Observers were six adults, ages 18.5–29.4 yrs. old, with a mean age of 27.6 yrs. All met the inclusion criteria of experiment 1, though none had participated in that study.

2. Stimuli

The masker was a band of noise presented continuously and diotically (No). In one set of conditions the masker was 10 Hz wide, spanning 495–505 Hz and presented at a 60-dB spectrum level. In a second set of conditions the masker was 250-Hz wide, spanning 255–505 Hz, and presented at a 55-dB spectrum level. The level of the 250-Hz-wide masker was chosen to approximately match thresholds for a 500-Hz signal in the on-frequency NoSo conditions for the 10- and 250-Hz masker bandwidths.

The signal was a pure tone, either So or S π , presented for 500 ms including 50-ms raised-cosine ramps. For the 10-Hz narrowband noise conditions the signal frequency was 440, 460, 480, 500, 520, 540, or 560 Hz. For the 250-Hz bandwidth, only signal frequencies at 500 Hz and above were tested. These frequencies were 500, 520, 540, 560, 620, or 740 Hz.

3. Procedures

Procedures were identical to those of experiment 1. Signal detection thresholds for 79% correct were estimated using a three-alternative forced-choice procedure. Signal frequency, signal phase, and masker bandwidth were held constant across trials within a track. Three tracks were obtained in sequence in each condition, and a fourth estimate was collected in cases of 3 dB or more variability across prior estimates. The NoSo conditions were completed before the NoS π conditions, with signal frequencies run in pseudo-random order.

B. Results and discussion

The general pattern of results was consistent across the six observers, so only mean data are reported. The reader is reminded that the levels of the maskers were different both in terms of spectrum level (60 dB for the 10-Hz bandwidth and 55 dB for the 250-Hz bandwidth) and total sound pressure level (SPL; 70 dB for the 10-Hz bandwidth and 79 dB for the 250-Hz bandwidth). Thresholds are plotted in Fig. 3(a) as a function of signal frequency. Symbols reflect the signal phase condition and the masker bandwidth, as indicated in the legend, and error bars show 1 standard error of the mean. The pattern of results for the 10-Hz masker bandwidth re-

FIG. 3. The top panel (a) shows mean thresholds, plotted as a function of signal frequency indicated on the abscissa in Hz. Lines indicate associated estimates of energetic masking predicted on the basis of partial loudness for NoSo stimulation. The bottom panel (b) shows the corresponding MLD. In both panels circles indicate thresholds with the 10-Hz masker bandwidth (60 dB/Hz spectrum level), and triangles indicate data for the 250-Hz masker bandwidth (55 dB/Hz spectrum level). Thresholds for NoSo are shown with open symbols, thresholds for NoS π are shown with gray symbols, and MLDs are shown with solid black. Error bars indicate 1 standard error of the mean ($n=6$).

sembls that reported in experiment 1 for the low 250-Hz frequency region (compare circles in Figs. 1(b) and 3(a)). In both cases thresholds improved steeply as the signal frequency moved off of masker cf in both NoSo and NoS π conditions. For the 500-Hz NoSo conditions, moving the signal 20-Hz away from masker cf improved thresholds by 20.5 dB (480 Hz) and 19.3 dB (520 Hz). This can be compared with the mean effect of 22.3 dB observed in analogous NoSo conditions of experiment 1. For the 500-Hz NoS π conditions, moving the signal 20-Hz off masker cf improved thresholds by 6.3 dB (480 Hz) and 5.5 dB (520 Hz), compared to the 6.1-dB effect observed in comparable conditions of experiment 1. These results lend further support to the conclusion that factors related to absolute frequency, rather than proportional frequency or frequency selectivity, are responsible for the decline in both NoSo and NoS π thresholds. Thresholds for the 250-Hz masker bandwidth also improved with increasing signal/masker separation, but that effect was more gradual than for the 10-Hz bandwidth. For both masker bandwidths, the NoSo thresholds improved more steeply than those in the NoS π condition, resulting in a reduction of the MLD with increasing signal/masker frequency separation.

Figure 3(b) shows the MLD plotted as a function of signal frequency. There was a very close correspondence between MLDs with a 10-Hz bandwidth masker in the present experiment (cf=500 Hz) and experiment 1 (cf=250 Hz). The 250-Hz-cf MLDs were within 1 standard deviation of the 500-Hz-cf MLDs at all five signal/masker separations common to both experiments (0, ± 20 , and ± 40 Hz). The steep decline in MLD between the 0- and 20-Hz signal/masker separations is consistent with the possibility that beneficial monaural envelope cues were weak or absent for on-

frequency conditions, but came into play for increasingly wider separations. As with a 10-Hz masker bandwidth, the MLD for a 250-Hz wide masker decreased as the signal was moved off-frequency. The slope of this decline appeared more gradual than that for the 10-Hz masker bandwidth, however, particularly for small signal/masker separations. The MLD for the 250-Hz bandwidth decreased from 15.3 dB at 500 Hz to 12.2 dB at 520 Hz. This 3.1-dB decrease can be compared to the decrease of 13.8 dB over the same range of signal frequencies in 10-Hz bandwidth data. This result is consistent with the interpretation that the rate of inherent masker envelope modulation plays a role in the pattern of off-frequency MLD.

It was hypothesized at the outset that the decline in off-frequency MLD with increasing signal/masker separation would be shallower for the wider masker bandwidth, due to reduced utility of off-frequency monaural envelope cues for stimuli characterized by higher rates of inherent modulation. It was further hypothesized that the on-frequency MLD would be reduced for the wider bandwidth due at least in part to a reduction of the detrimental effects of masker AM for on-frequency NoSo thresholds. In other words, an interaction between masker bandwidth and signal/masker separation was expected. This hypothesis was tested with an ANOVA performed on the MLDs of individual observers. There were two levels of masker bandwidth (10- and 250-Hz) and four levels of signal frequency (500, 520, 540, and 560 Hz). There was a main effect of frequency ($F_{3,15}=33.79, p<0.0001$), no effect of bandwidth ($F_{1,5}=1.87, p=0.23$), and a significant interaction ($F_{3,15}=15.35, p<0.0001$). A contrast was performed to further evaluate the frequency $\times$ bandwidth interaction, and specifically to test the prediction of different bandwidth effects for the on-frequency and off-frequency signals. This contrast was significant ($F_{1,5}=37.08, p<0.005$). This result is evident in Fig. 3(b) as a larger MLD for the 10-Hz-wide masker than the 250-Hz-wide masker in the on-frequency condition and a reversal of this ordering in the off-frequency conditions.

A significant interaction in the MLD data between masker bandwidth and signal frequency (and therefore signal/masker separation) is consistent with the idea that effects of masker modulation on NoSo thresholds contribute importantly to the steep reduction in the off-frequency MLD with a narrowband noise masker. An alternative, though not mutually exclusive interpretation of these data is that rate-dependent masker AM effects also influenced NoS π thresholds, and that these effects were different for on- and off-frequency masking. The possible effect of masker AM on NoS π thresholds is addressed in more detail in experiment 3. The contribution of masker AM to NoSo thresholds of the present data set was assessed by computing estimates of energetic masking using the excitation-based loudness model of Moore *et al.* (1997).³ This model has recently been used to predict thresholds across a range of paradigms thought to rely on energetic cues (Jesteadt *et al.*, 2007; Leibold and Jesteadt, 2007; Buss, 2008). Used in this way, the model calculates the partial loudness associated with the addition of a signal to a masker. Model estimates of partial loudness were computed for each stimulus condition in the present

experiment at a range of signal levels, spanning 30–70 dB SPL in 1-dB steps. A spline fit was then used to estimate the signal level associated with an 8-phon change in partial loudness, and this was taken as an estimate of threshold. The choice of an 8-phon criterion is somewhat arbitrary. Previous work has used criteria ranging from 4 to 8 phons (Jesteadt *et al.*, 2007; Leibold and Jesteadt, 2007; Buss, 2008). The inferences drawn from the partial loudness modeling performed here would not be materially different with the choice of a 4-phon criterion.

Thresholds predicted on the basis of excitation arising from the masker are shown in Fig. 3(a). Values for the 10-Hz bandwidth are indicated with a dotted line, and values for the 250-Hz bandwidth are indicated with a dashed line. Thresholds for the NoSo conditions with a 10-Hz masker bandwidth were higher than predicted for the on-frequency signal and lower than predicted for off-frequency conditions. The difference between threshold and prediction ranged from –19.7 to 6.6 dB. In contrast, NoSo thresholds for the 250-Hz bandwidth were much closer to predictions based on partial loudness, with differences of –3.4 to 2.8 dB. Whereas an 8-phon criterion provided a relatively good fit to the data for the 250-Hz bandwidth, the general pattern of predicted thresholds is relatively insensitive to changes in criterion loudness. Decreasing the criterion to 4 phons decreased threshold predictions by a maximum of 2.3 dB, with only slightly larger effects for signals at than above masker cf. As such, the effect of changing the criterion is small relative to the nearly 20-dB over-prediction of NoSo off-frequency thresholds for the 10-Hz bandwidth masker.

Overall, these modeling results support the hypothesis that NoSo thresholds obtained with the 250-Hz bandwidth are much more consistent with masker-related excitation than those obtained with the 10-Hz bandwidth data. This result implicates temporal fluctuation cues in the 10-Hz data, as these cues are not captured in excitation-based models [for discussion, see Van Der Heijden and Kohlrausch (1994)]. Estimates of masking based upon masker excitation, in combination with the broader tuning of the MLD for 250-Hz bandwidth masker, lend support to the interpretation that monaural cues related to inherent masker AM rate play an important role in the very sharp MLD tuning observed with 10-Hz masker bandwidths in experiments 1 and 2.

These results do not, however, rule out a contribution of envelope effects in NoS π conditions. In fact, there is some indication that masker AM may have affected both NoSo and NoS π off-frequency thresholds with the narrowband masker in the results of experiment 2. For the 10-Hz masker, thresholds for both NoSo and NoS π improved more steeply with signal/masker separation than expected based on the partial loudness model for NoSo stimulation. In contrast, thresholds improved more gradually for the 250-Hz bandwidth, with slopes for both the NoSo and NoS π signal conditions nearly parallel to the NoSo thresholds predicted by the partial loudness model. This result is consistent with the introduction of beneficial cues in off-frequency conditions for both monaural and binaural processing, with the size of this effect related to bandwidth of the masker. Such a result is contradictory to the hypothesis that binaural sluggishness is responsible for the

steep decline in MLD of off-frequency signal conditions. Instead of a reduction in the quality of binaural cues, this modeling is consistent with an improvement in binaural cues in off-frequency masking, albeit a relatively small improvement compared to the improvement in monaural cues.

IV. EXPERIMENT 3: FURTHER EFFECTS RELATED TO MASKER FLUCTUATION

Previous work has shown that threshold for a brief, low-frequency S π tone centered in a narrowband No masker is lower when that tone is presented simultaneously with an envelope minimum than an envelope maximum (Buss *et al.*, 2003). This result is analogous to the “dip advantage” observed in comodulated maskers (Hall and Grose, 1991; Buus *et al.*, 1996). These NoS π and comodulated noise results can be thought of in terms of across-frequency and across-ear cues that facilitate the auditory system in taking advantage of local improvements in the signal-to-noise ratio that occurs in masker envelope minima. Transient improvements in signal-to-noise ratio do not improve thresholds for a tonal signal centered in a narrowband noise for either monaural (NmSm) or diotic (NoSo) conditions (Buus *et al.*, 1996; Buss *et al.*, 2003). Whereas the ability to benefit from cues coincident with envelope minima of a narrowband masker is quite different for on-frequency NoSo and NoS π conditions, it is unknown whether these differences persist for off-frequency signals.

Experiment 3 was designed to assess the possible contribution of masker AM effects on performance in on-frequency and off-frequency masking conditions. It was hypothesized that sensitivity to a brief S π signal would be greater if that signal coincided with an No masker envelope minimum than a masker envelope maximum for both on- and off-frequency conditions. Buus (1985) hypothesized that detecting a tone in an off-frequency narrowband noise masker in monaural conditions could rely on across-frequency comparisons related to CMR. Thus, a dip advantage for NoSo conditions, if present, was expected to be restricted to off-frequency masking conditions. An effect of signal/masker separation on the dip advantage for NoSo but not NoS π conditions would be consistent with the conclusion that the effects of masker AM on NoSo thresholds play a dominant role in the pattern of MLD as a function of signal/masker separation for a narrowband noise masker.

A. Methods

1. Observers

Observers were five adults, ages 20.7 to 53.9 yrs., with a mean age of 32.7 yrs. All met the inclusion criteria of the two previous experiments. A sixth observer was recruited and later excused due to poor reliability of thresholds. Of the observers who were retained, one had previously participated in experiment 1 and another had participated in experiment 2.

2. Stimuli

The masker was a 10-Hz-wide band of noise spanning 495–505 Hz and presented diotically (No) at 60-dB spectrum

level. Continuous maskers were constructed from concatenated noise segments in such a way that the temporal center of each listening interval was aligned with either an envelope minimum or maximum. Maskers were generated in the frequency domain as described above. A masker sample composed of 2^{17} points was generated at the start of each threshold estimation track. This masker, referred to here as the “surround” masker, was 10.7 s in duration and played continuously between trials and between listening intervals. An independent “interval” masker sample was computed prior to every listening interval based on 2^{13} points. The Hilbert envelope of the interval masker was computed, allowing identification of the envelope minimum or maximum. The masker array was then rotated so that envelope feature (either the minimum or maximum) was temporally centered in the interval masker array. At the beginning of a listening interval the surround masker was gated off just as the interval masker was gated on, with the transition shaped by temporally overlapping 75-ms raised-cosine ramps. This process was reversed at the end of the listening interval, with the surround masker gating on just as the interval masker was gated off. Transitions between the interval and surround maskers were not associated with any perceptual discontinuity, and the resulting auditory stream was indistinguishable from a continuous narrowband noise. This stimulus generation method allows fine control over the masker envelope features coincident with the signal presentation, while maintaining the subjective impression of a random noise band.

The signal was a brief pure tone, ramped on and off using 75-ms raised-cosine ramps and no steady state, and presented in either So or $S\pi$ interaural phase. The signal frequency was 380, 440, 460, 480, 500, 520, 540, 560, or 620 Hz. Presentation of the signal was temporally centered in the 600-ms listening interval, such that the peak of the signal was coincident with the temporal center of a masker envelope minimum or an envelope maximum.

3. Procedures

Procedures were identical to those of the previous experiments. Signal detection thresholds for 79% correct were estimated using a three-alternative forced-choice procedure. Signal frequency, phase, and timing with respect to the masker envelope were held constant across trials within a track. Conditions were organized in four blocks characterized by a fixed interaural signal phase (So or $S\pi$) and masker envelope condition (*max* or *min*). The order of these four blocks was randomly assigned for each observer. Signal frequencies were visited in random order within a block, with three tracks obtained in sequence for each signal frequency and a fourth in cases of 3 dB or more variability across prior estimates. After completing all conditions, the data were examined for evidence of variability or practice effects. Thresholds were replaced in cases of 6 dB or more variability across estimates.

B. Results and discussion

Results were consistent across the five observers, so only mean data are reported. Figure 4(a) shows thresholds

FIG. 4. The top panel (a) shows mean thresholds plotted as a function of signal frequency indicated on the abscissa in Hz. The middle panel (b) shows corresponding values of MLD, and the bottom panel (c) shows the difference between thresholds in the max and min masker conditions. Symbols correspond to stimulus condition, as shown in the legend. Error bars in the bottom two panels indicate 1 standard error of the mean ($n=5$).

plotted as a function of signal frequency, with symbol shading reflecting signal phase and shape indicating envelope position, as defined in the legend. As in the data previously reported for a long-duration signal, thresholds for the brief signal improved as signal frequency diverged from the masker cf of 500 Hz. Also consistent with previous data, the threshold improvement with increasing signal/masker separation was more pronounced for NoSo conditions than NoSπ conditions. This aspect of the results is illustrated more clearly in Fig. 4(b), where the MLD is plotted as a function of signal frequency. For both max and min conditions the MLD was largest at masker cf, with mean values of 17.7 and 26.7 dB, respectively. The MLD fell by approximately 45% of the peak value when the signal was as little as 20 Hz away from masker cf, with a decrease of 7.6 dB for the max and 12.2 dB for the min masker envelope conditions. Referring back to Fig. 4(a), it is evident that this reduction in the MLD is attributable primarily to changes in NoSo thresholds, which were on the order of 15 dB, and less to changes in NoSπ thresholds, which were on the order of 5 dB. These results with brief signals are consistent with those reported in the previous two experiments using longer signals. As in previous data, the steep decline in MLD between the 0 and ± 20 -Hz signal/masker separations is consistent with the possibility that beneficial monaural envelope cues were weak or absent for on-frequency conditions, but come into play for the 20-Hz and wider separations.

The most novel result of experiment 3 is apparent in Fig. 4(c), where the difference between thresholds in the max and min masker conditions is plotted as a function of signal frequency. As in previous figures, filled symbols indicate NoSo conditions and open symbols indicate NoS π conditions. In the NoSo conditions, on-frequency thresholds were effectively identical for max and min conditions, with a detection advantage for the min condition emerging only for signal/masker separations of greater than 20–40 Hz. In contrast to the NoSo data, NoS π thresholds were lower for min than max conditions both on- and off-frequency, as evident in the consistently positive max/min difference in Fig. 4(c). The significance of this result was assessed with a repeated-measures ANOVA on the difference between thresholds in max and min conditions. There were nine levels of frequency (380, 440, 460, 480, 500, 520, 540, 560, and 620 Hz) and two levels of signal phase (NoSo and NoS π). This analysis resulted in a main effect of phase ($F_{1,4}=154.15, p < 0.0001$), but no main effect of frequency ($F_{8,32}=1.99, p = 0.08$). The phase $\times$ frequency interaction was significant ($F_{8,32}=4.73, p < 0.005$). A quadratic contrast on this interaction was significant ($F_{1,4}=35.34, p < 0.005$), consistent with the visual impression that the functions associated with NoSo and NoS π conditions were similar at low signal frequencies, diverged for frequencies near masker cf, and then converged again at high signal frequencies.

For NoSo conditions, the finding of a max/min difference for off-frequency but not on-frequency masking is broadly consistent with the results of previous CMR studies indicating that weights applied in a signal detection task are higher during masker envelope minima in the presence of comodulated flanking bands but not when the on-frequency masker band is presented alone (Hall and Grose, 1991; Buus *et al.*, 1996). For NoS π conditions, the finding of a consistently positive max/min difference is consistent with previous demonstrations of a dip advantage in on-frequency MLD conditions (Grose and Hall, 1998; Buss *et al.*, 2003). The present data indicate that this on-frequency NoS π result generalizes to off-frequency NoS π masking. A parsimonious interpretation of this result is that low-rate masker AM benefits performance in both the on-frequency and off-frequency NoS π conditions due to the introduction of prominent masker modulation minima. To the extent that this effect is uniform across signal/masker separations it would not contribute to the steep reduction in off-frequency MLD observed with narrowband maskers.

Overall, the results of experiment 3 support the conclusion that the steep reduction in the off-frequency MLD is due to the effects of masker AM on monaural cues rather than an inability to benefit from rapidly changing IPDs. However, estimation of the effects of binaural cues alone is complicated by the presence of both monaural and binaural cues in the NoS π condition. That is, performance in the off-frequency NoS π condition could be due to a combination of binaural and monaural cues, both of which are associated with a dip advantage. Such a possibility is not inconsistent

with the conclusion that binaural processing is preserved in off-frequency masking, however, as the combination of cues would lead to an overall reduction in off-frequency, NoS π thresholds.

V. GENERAL DISCUSSION AND CONCLUSIONS

The results of experiment 1 show a rapid decline in MLD with increasing signal/masker separation. Data from the 250-Hz frequency region largely replicate the findings of Zwicker and Henning (1984), where thresholds fell more steeply with increasing signal/masker separation for the NoSo than for the NoS π conditions. Thresholds for NoSo and NoS π conditions also converged with increasing signal/masker separation for the narrowband masker centered on 2500 Hz. Moving the signal 20 Hz off masker cf reduced the MLD by an average of 16.3 dB at 250 Hz and 12.0 dB at 2500 Hz. Thresholds obtained in the NoSo condition cannot be understood simply in terms of masker excitation. Rather, temporal envelope cues introduced by signal/masker interactions could have a large effect on performance in these conditions. Previous results have been interpreted as suggesting that binaural sluggishness effects may be smaller for ILDs and high-frequency stimuli than for IPDs and low-frequency stimuli (Grantham, 1982, 1984). By such an interpretation, binaural sluggishness would have led to different NoS π data patterns in the present study at frequencies of 250 and 2500 Hz rather than to the similar patterns actually observed.⁴ Because IPDs are thought to be unavailable at 2500 Hz, the steep reduction in off-frequency MLD cannot be attributed to inability to make use of rapidly changing IPD cues.

Experiment 2 measured the MLD in the region of 500 Hz for both a 10-Hz and a 250-Hz masker bandwidth. As in experiment 1, the MLD with the 10-Hz bandwidth was sharply tuned as a function of signal/masker separation. There was a close correspondence between the MLD at 500 Hz with a 10-Hz masker bandwidth and the data from experiment 1 when the MLD was compared as a function of absolute signal/masker separation in Hz. This result suggests that temporal cues arising from interaction between the signal and masker could play a large role in the relatively good NoSo, off-frequency thresholds obtained with narrowband noise maskers. This interpretation received support from estimates of energetic masking based on an excitation pattern model of partial loudness. This model predicted a more modest effect of moving the signal off masker cf than was observed for the 10-Hz bandwidth. In contrast, the MLD associated with the 250-Hz bandwidth was less sharply tuned than that for the 10-Hz bandwidth, and the pattern of NoSo thresholds as a function of signal/masker separation more closely matched the pattern predicted by an excitation-based model. This finding supports the interpretation that inherent fluctuation rate is an important variable in the pattern of NoSo off-frequency thresholds.

Experiment 3 measured thresholds in on- and off-frequency masking conditions for a brief 500-Hz signal coincident with a masker envelope minimum or maximum. Thresholds were lower for min than max conditions for all NoS π conditions and for off-frequency NoSo conditions

with greater than 20–40 Hz signal/masker separation. This result provides support for the idea that off-frequency thresholds are based on some of the same cues underlying MLD and CMR, where stimulus weights tend to be larger in masker AM minima than maxima. The finding of a max/min difference in NoSo thresholds only for separations greater than 20–40 Hz is consistent with a shift from within-channel cues to greater contribution of across-channel cues, but could also reflect the introduction of a cue based on envelope beats with increased signal/masker separation. While these results are consistent with introduction of a cue to off-frequency NoSo detection that is not present in on-frequency conditions, it does not rule out a combination of monaural and binaural cues in analogous NoS π conditions.

Previous work on the combination of monaural and binaural cues indicates wide variability across paradigms and across observers, with evidence of cue additivity in some but not all cases [for a review, see Hall *et al.* (2006)]. This variability makes it infeasible to accurately estimate the efficacy of binaural cues alone based on the present data. In the most extreme case of monaural and binaural cue interaction, a recent study by Hall *et al.* (2006) argued that the combination of binaural cues and monaural, envelope-based detection cues may act synergistically to produce better performance than expected from the combination of independent cues, particularly when performance is limited by external rather than internal noise. This supra-additivity of cues could occur if monaural envelope cues support improved efficiency in temporal weighting of binaural cues, a process that would likely emphasize signal energy coincident with masker modulation minima.

One possible interpretation of the results reported here is in terms of confusion effects. For on-frequency conditions, the addition of a brief So signal in an No masker is difficult to differentiate from ongoing inherent masker fluctuation, such that the observer is unable to make use of the improved signal-to-noise ratio associated with masker envelope minima. The binaural cue present in the NoS π stimuli could ameliorate that segregation problem, supporting selective use of cues coincident with epochs of improved signal-to-noise ratio. Analogous factors relating to sound segregation could also play a role in some of the off-frequency, NoSo conditions. One cue that could improve NoSo thresholds in off-frequency conditions is the introduction of envelope beats due to interactions between the signal and masker. The inherent fluctuation of a narrow band of noise is limited by its bandwidth. For a 10-Hz wide band of noise, the presence of fluctuation rates greater than 10 Hz would indicate the presence of an off-frequency signal. In contrast, the envelope spectrum of a 250-Hz wide masker would include much higher rates, even after passing through an auditory filter, such that changes in envelope spectra would not be as sensitive an indicator of addition of a neighboring signal.

Another account of the effect of masker fluctuation rate posits that across-frequency coherence in the spread of masker energy introduces cues akin to those responsible for CMR. In off-frequency masking with a single narrowband masker, the outputs of auditory filters passing that masker are coherently modulated, introducing possible across-channel

detection cues. This observation prompted Buus (1985) to hypothesize that the better than expected off-frequency thresholds obtained for narrowband maskers could be based on the same cues as those responsible for comodulation masking release. Because monaural masking release tends to be larger for low rates of fluctuation (Carlyon *et al.*, 1989; Schooneveldt and Moore, 1989), this effect might also diminish with increases in masker fluctuation rate.

While across-channel cues could play a role in the results obtained here, such an interpretation is not consistent with all aspects of the data. In all three experiments there is evidence that NoSo thresholds associated with a narrowband masker fall sharply with a relatively small signal/masker separation of 10 to 20 Hz. For example, introducing a ± 20 -Hz separation from a 10-Hz diotic masker improved threshold for a long-duration signal by 22.3 dB at a cf of 250 Hz (Expt. 1), 19.9 dB at 500 Hz (Expt. 2), and 17.1 dB at 2500 Hz (Expt. 1). This consistency across cf is incompatible with an across-channel effect, wherein tuning would be expected to broaden with increasing cf, reducing the availability of across-channel cues. Instead, these observations implicate within-channel processes, such as reliance on beats between the signal and masker for small signal/masker separations. While this aspect of the data is inconsistent with use of an across-channel cue, other aspects of the results are consistent with introduction of an across-channel cue for wider signal/masker separations. The difference in threshold for max and min conditions grows with increasing separation greater than 20–40 Hz in the 500-Hz data of experiment 3, consistent with the conclusion that preferential weighting of masker envelope minima may play a role in detection for wide but not narrow signal/masker separations. The idea that both within and across-channel cues could contribute to NoSo sensitivity in off-frequency masking conditions is consistent with the conclusions of Moore and Glasberg (1987).

Regardless of the specific cues underlying NoSo detection, the present results indicate that the steep decline in off-frequency MLD with increasing separation of a tonal signal and narrowband noise masker is dominated by monaural cues that are introduced in off-frequency signal conditions. Further, off-frequency MLDs can be large under some stimulus conditions, particularly conditions for which diotic, off-frequency signal presentation does not introduce additional cues that are favorable for detection. The present results provide little indication that binaural cues are less effective for off- than on-frequency masking.

ACKNOWLEDGMENTS

This work was supported by NIH NIDCD under Grant No. R01 00397 (J.W.H.). We would like to thank John Grose, Associate Editor Richard Freyman, and three anonymous reviewers for contributions to this work.

¹One limitation of this analysis is that the MLD for ± 20 Hz at the 2500-Hz cf is very small, introducing the possibility that these values may be biased by floor effects. An additional ANOVA was therefore performed, omitting the ± 20 Hz data. In this analysis there were two levels of cf (250 and 2500 Hz) and three levels of separation (-10 , 0 , and $+10$ Hz). The pattern of significance was the same as that reported for the analysis including ± 20 Hz data: there were significant main effects of CF ($F_{1,4}$

=44.78, $p < 0.01$) and separation ($F_{2,8}=5.46, p < 0.05$), but no interaction ($F_{2,8}=0.83, p=0.47$). These results lend further support to the conclusion that the off-frequency MLD for close signal/masker separation declines with parallel slopes at 250 and 2500 Hz.

²We opted to gather additional data rather than analyzing these published results for two reasons. First, the data of Zwicker and Henning (1984) were collected using a Békésy tracking procedure, so the results obtained might not be directly comparable to those collected using adaptive staircase methods employed in the present experiments. Second, the previous data were collected using a fixed masker cf and variable bandwidth. As a result, off-frequency signals differed in absolute frequency for different masker bandwidths. It was anticipated that the comparison of thresholds as a function of masker modulation rate would be more straightforward for conditions in which the signal frequencies were consistent across masker bandwidth conditions.

³This model includes filters representing outer and middle ear transfer functions, excitation pattern calculation, and a transform of excitation pattern to a specific loudness pattern. These computations were performed using partloud.exe, which is available for download from: <http://hearing.psychol.cam.ac.uk/Demos/demos.html>.

⁴Failure to find evidence of binaural sluggishness in off-frequency masking of a pure tone signal and a narrowband noise does not rule out such an effect under other conditions, such as those described by McFadden *et al.* (1972). In that study the masker was a continuous 400-Hz tone, and the signal was a 100-ms tone, parametrically varied in frequency. The MLD initially rose with the introduction of a signal/masker separation of approximately 10 Hz and then fell with further increases in spectral separation. This result is due to non-monotonicity in both the NoSo and NoS π conditions: small signal/masker separations tended to hurt NoSo performance and improve NoS π performance. One interpretation of this result is that the monaural envelope cues associated with beating between the signal and masker hurts performance for very low rates, to the extent that it introduces level uncertainty, and does not begin to help performance until the beat period exceeds the signal duration (~ 10 Hz). This introduces the possibility that good performance in NoS π conditions for small signal/masker separations is due to dynamic binaural cues that are slow enough to be resolved, with elimination of this binaural benefit for faster dynamic rates that occur with larger signal/masker separations. An alternative interpretation unrelated to binaural sluggishness is that at very slow beat rates the detection cue in NoS π conditions is an interaural level difference, with level differences being caused by the envelope beats being out of phase at the two ears, and that this cue becomes degraded as the beat rate increases. Experiments are presently under way to discriminate between these two possible accounts of off-frequency tonal MLD data. In either case, these effects related to small signal/masker separations were not evident in the present data with a narrowband noise masker, perhaps due to masker fluctuation and modulation masking.

Akeroyd, M. A., and Summerfield, A. Q. (1999). "A binaural analog of gap detection," *J. Acoust. Soc. Am.* **105**, 2807–2820.

ANSI (2004). *ANSI S3.6–2004, American National Standard Specification for Audiometers* (American National Standards Institute, New York).

Bernstein, L. R., and Trahiotis, C. (2002). "Enhancing sensitivity to interaural delays at high frequencies by using "transposed stimuli,"" *J. Acoust. Soc. Am.* **112**, 1026–1036.

Bos, C. E., and de Boer, E. (1966). "Masking and discrimination," *J. Acoust. Soc. Am.* **39**, 708–715.

Buss, E. (2008). "The effect of masker level uncertainty on intensity discrimination," *J. Acoust. Soc. Am.* **123**, 254–264.

Buss, E., Hall, J. W., and Grose, J. H. (2003). "The masking level difference for signals placed in masker envelope minima and maxima," *J. Acoust. Soc. Am.* **114**, 1557–1564.

Buss, E., Hall, J. W., and Grose, J. H. (2007). "Individual differences in the masking level difference with a narrowband masker at 500 or 2000 Hz," *J. Acoust. Soc. Am.* **121**, 411–419.

Buus, S. (1985). "Release from masking caused by envelope fluctuations," *J. Acoust. Soc. Am.* **78**, 1958–1965.

Buus, S., Zhang, L., and Florentine, M. (1996). "Stimulus-driven, time-varying weights for comodulation masking release," *J. Acoust. Soc. Am.* **99**, 2288–2297.

Carlyon, R. P. (2007). "Comment on: Remote masking and the binaural masking-level difference," in *Hearing, From Sensory Processing to Perception*, edited by B. Kollmeier, G. Klump, V. Hohmann, U. Langemann,

M. Mauermann, S. Uppenkamp, and J. Verhey (Springer-Verlag, Berlin), p. 465.

Carlyon, R. P., Buus, S., and Florentine, M. (1989). "Comodulation masking release for three types of modulator as a function of modulation rate," *Hear. Res.* **42**, 37–45.

Eddins, D. A. (2001). "Monaural masking release in random-phase and low-noise noise," *J. Acoust. Soc. Am.* **109**, 1538–1549.

Fastl, H., and Bechly, M. (1983). "Suppression in simultaneous masking," *J. Acoust. Soc. Am.* **74**, 754–757.

Glasberg, B. R., and Moore, B. C. J. (1990). "Derivation of auditory filter shapes from notched-noise data," *Hear. Res.* **47**, 103–138.

Goupell, M. J., and Hartmann, W. M. (2006). "Interaural fluctuations and the detection of interaural incoherence: Bandwidth effects," *J. Acoust. Soc. Am.* **119**, 3971–3986.

Goupell, M. J., and Hartmann, W. M. (2007). "Interaural fluctuations and the detection of interaural incoherence. III. Narrowband experiments and binaural models," *J. Acoust. Soc. Am.* **122**, 1029–1045.

Grantham, D. W. (1982). "Detectability of time-varying interaural correlation in narrow-band noise stimuli," *J. Acoust. Soc. Am.* **72**, 1178–1184.

Grantham, D. W. (1984). "Discrimination of dynamic interaural intensity differences," *J. Acoust. Soc. Am.* **76**, 71–76.

Grantham, D. W., and Wightman, F. L. (1978). "Detectability of varying interaural temporal differences," *J. Acoust. Soc. Am.* **63**, 511–523.

Grose, J. H., and Hall, J. W. (1998). "Masker fluctuation and the masking-level difference," *J. Acoust. Soc. Am.* **103**, 2590–2594.

Hall, J. W., Buss, E., and Grose, J. H. (2006). "Binaural comodulation masking release: Effects of masker interaural correlation," *J. Acoust. Soc. Am.* **120**, 3878–3888.

Hall, J. W., and Grose, J. H. (1991). "Relative contributions of envelope maxima and minima to comodulation masking release," *Q. J. Exp. Psychol. A* **43**, 349–372.

Hartmann, W. M., and Pumplin, J. (1988). "Noise power fluctuations and the masking of sine signals," *J. Acoust. Soc. Am.* **83**, 2277–2289.

Henning, G. B., Yasin, I., and Witton, C. (2007). "Remote masking and the binaural masking-level difference," in *Hearing, From Sensory Processing to Perception*, edited by B. Kollmeier, G. Klump, V. Hohmann, U. Lange-mann, M. Mauermann, S. Uppenkamp, and J. Verhey (Springer-Verlag, Berlin), pp. 457–466.

Hirsh, I. J. (1948). "The influence of interaural phase on interaural summation and inhibition," *J. Acoust. Soc. Am.* **20**, 536–544.

Jesteadt, W., Tan, H., Khaddam, S., and Leibold, L. J. (2007). "Prediction of behavioral thresholds using a model of partial loudness," in *Proceedings of the 30th Midwinter Research Meeting of the Association for Research in Otolaryngology*, Denver, CO.

Kollmeier, B., and Gilkey, R. H. (1990). "Binaural forward and backward masking: Evidence for sluggishness in binaural detection," *J. Acoust. Soc. Am.* **87**, 1709–1719.

Leibold, L. J., and Jesteadt, W. (2007). "Use of perceptual weights to test a model of loudness summation," *J. Acoust. Soc. Am.* **122**, EL69–EL73.

Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoust. Soc. Am.* **49**, 467–477.

McFadden, D., and Pasanen, E. G. (1978). "Binaural detection at high frequencies with time-delayed waveforms," *J. Acoust. Soc. Am.* **63**, 1120–1131.

McFadden, D., Russel, W. E., and Pullman, K. A. (1972). "Monaural and binaural masking patterns for a low-frequency tone," *J. Acoust. Soc. Am.* **51**, 534–543.

Moore, B. C. J., Alcantara, J. I., and Dau, T. (1998). "Masking patterns for sinusoidal and narrow-band noise maskers," *J. Acoust. Soc. Am.* **104**, 1023–1038.

Moore, B. C. J., and Glasberg, B. R. (1987). "Factors affecting thresholds for sinusoidal signals in narrow-band maskers with fluctuating envelopes," *J. Acoust. Soc. Am.* **82**, 69–79.

Moore, B. C. J., Glasberg, B. R., and Baer, T. (1997). "A model for the prediction of thresholds, loudness and partial loudness," *J. Audio Eng. Soc.* **45**, 224–240.

Moore, B. C. J., and Vickers, D. A. (1997). "The role of spread excitation and suppression in simultaneous masking," *J. Acoust. Soc. Am.* **102**, 2284–2290.

Nelson, D. A., and Fortune, T. W. (1991). "High-level psychophysical tuning curves: Simultaneous masking with different noise bandwidths," *J. Speech Hear. Res.* **34**, 374–378.

Rice, S. O. (1954). "Mathematical analysis of random noise," in *Selected Papers on Noise and Stochastic Processes*, edited by N. Wax (Dover, New

- York), pp. 133–294.
- Schooneveldt, G. P., and Moore, B. C. J. (1989). “Comodulation masking release (CMR) as a function of masker bandwidth, modulator bandwidth, and signal duration,” *J. Acoust. Soc. Am.* **85**, 273–281.
- van de Par, S., and Kohlrausch, A. (1997). “A new approach to comparing binaural masking level differences at low and high frequencies,” *J. Acoust. Soc. Am.* **101**, 1671–1680.
- Van Der Heijden, M., and Kohlrausch, A. (1994). “Using an excitation-pattern model to predict auditory masking,” *Hear. Res.* **80**, 38–52.
- Van Der Heijden, M., and Kohlrausch, A. (1995). “The role of envelope fluctuations in spectral masking,” *J. Acoust. Soc. Am.* **97**, 1800–1807.
- Wright, B. A. (1992). “The role of envelope fluctuations in an apparent demonstration of suppression in simultaneous masking,” *J. Acoust. Soc. Am.* **91**, 3436–3442.
- Zurek, P. M., and Durlach, N. I. (1987). “Masker-bandwidth dependence in homophasic and antiphasic tone detection,” *J. Acoust. Soc. Am.* **81**, 459–464.
- Zwicker, E., and Henning, G. B. (1984). “Binaural masking-level differences with tones masked by noises of various bandwidths and levels,” *Hear. Res.* **14**, 179–183.