Masker-first advantage for cues in informational masking

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The detectability of a pure-tone signal may be reduced by adding a small number of randomly drawn masker tones remote from the signal frequency, an effect attributed to informational masking. A pretrial cue consisting of either the upcoming signal or masker releases informational masking, but a pretrial cue of the signal-plus-masker stimulus does not. In these experiments the relative potency of pre- and posttrial cues in releasing informational masking was examined. In separate conditions the masker-alone and signal-plus-masker stimuli were cues. The results indicated a masker-first advantage, i.e., sensitivity was superior when a masker cue preceded a yes/no trial interval compared to (a) when a signal-plus-masker preceded the trial, and (b) when either cue type followed the yes/no trial interval. A masker-first advantage was also obtained when the results from a two-interval forced-choice same/different task were examined. In contrast, a masker-first advantage was not obtained when the frequency of the signal to be detected was random. For detection tasks using random multi-tone maskers there may be differences in processing efficiency depending on the order in which stimuli are presented. The ''masker-first advantage'' may depend, in part, on observers maintaining their attention at the signal frequency. [DOI: 10.1121/1.1784433]

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I. INTRODUCTION

Observers' ability to detect a tone of fixed frequency added to a spectrally sparse multi-tone masker is degraded when the frequencies of the masker components are drawn at random on each presentation. Randomizing the frequencies of the masker components appears to introduce informational masking (e.g., Watson, 1987). Recent experiments reported by Richards and Neff (2004) showed that substantial release from informational masking was achieved when the detection trial was preceded by a pretrial cue. In those experiments, the pretrial cue was an exact preview of either the signal or the masker, depending on which type of cue was tested. For yes/no trials (a reminder task; e.g., Macmillan and Creelman, 1991), Richards and Neff found that a preview of the signal led to an average release in masking (relative to no cue) of 14.4 dB and the preview of the masker led to an average release in masking of 13.9 dB. Presumably, the cue reduced uncertainty in the task and thereby provided a release from informational masking.

In light of the results of Richards and Neff (2004), it is surprising that Richards and Huang (2003) reported no release from informational masking when a preview of the signal-plus-masker preceded a yes/no trial. For the six observers, the average threshold with a signal-plus-masker pretrial cue was approximately 3 dB *higher* than when there was no cue at all. In contrast, a masker cue led to an 8-dB reduction in threshold compared to no cue. This result casts doubt on the interpretation that pretrial cues reduce informational masking because the cues reduce stimulus uncertainty—were that so, it is difficult to imagine why a preview of the masker afforded a reduction in uncertainty while a preview of the signal-plus-masker did not. The purpose of this study was to attempt to better understand this cuing asymmetry and to learn more about the role of cuing in general in providing a release from informational masking.

The four experiments presented below report a variety of conditions in which the asymmetric cuing effect described above was explored. To some degree the exploration was sequential; the results of experiment I contributed to the development of experiment II, etc. (although the observers did not necessarily run the experiments sequentially). To perhaps a larger degree, though, the exploration was derived from basic questions as to what the underlying mechanism(s) might be.

Experiment I examined whether the cuing asymmetry remained when the cue followed, rather than preceded, the yes/no detection trial. The maskers were drawn at random prior to each two-interval sequence. Depending on whether the cue was presented in the first or second interval, the cue either preceded or followed the trial interval. Two types of cues, a copy of the masker and a copy of the signal-plus-masker, were tested. In the second experiment, we attempted to determine whether the cuing asymmetry reflected a heightened sensitivity to the addition of a signal tone compared to the removal of a signal tone (e.g., Bregman, 2003). Here the terms ''addition'' and ''removal'' refer to the sequential aspects of the two intervals of each trial. Observers

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indicated whether a sound was composed of N or $N+L$ tones, where N was six and L's of one and two were tested. In separate conditions, a preview of the N or $N+L$ stimulus was provided prior to each yes/no trial interval. If the cuing asymmetry depended on differential sensitivity to increments versus decrements in the number of components, our expectation was that sensitivity would be superior for the N-component compared to the $N+L$-component pretrial cue.

In the third experiment, the question was whether the cuing asymmetry remained when there was uncertainty with regard to cue type and to the temporal position of a cue within the trial sequence. The four conditions of experiment I were repeated, except that they were intermixed within a block of trials. Extrapolating from experiment I, on any one trial the cue might be in the first or second interval (pre- and posttrial cues of experiment I), and might be a copy of the masker or the signal-plus-masker. Under these circumstances, the detection task was equivalent to a two-interval, forced-choice (2IFC) same/different task. Comparing the results of this experiment to those of experiment I provided a rough estimate of the ''level of processing'' from which the cuing asymmetry was driven. To the degree that the cuing asymmetry remained in the face of randomization of the type of cue and the temporal position of the cue interval relative to the yes/no trial interval, that result would suggest the underlying mechanism is relatively low level, and possibly obligatory. On the other hand, if randomizing cue type and temporal position disrupted the cuing asymmetry, that result would suggest the asymmetry depended, at least in part, on observers' knowledge of the trial structures.

In the fourth experiment several conditions derived from experiment I were tested. These conditions examined whether the cuing asymmetry remained even when the signal frequency was randomly chosen, when the masker was fixed across all trials, and when the two stimulus intervals were presented to different ears.

II. EXPERIMENT I: EFFECT OF CUE TYPE AND TEMPORAL POSITION OF CUE

In experiment I the effect of the type of cue and the temporal position of the cue relative to the yes/no trial interval were jointly examined in an informational masking task. The signal to be detected was a 1000-Hz tone, and the masker was a six-component complex whose components had equal level but randomly drawn phases and frequencies. The task was to indicate whether the signal was present and d' was the dependent variable. Four conditions were tested depending on the type of cue and its position relative to the yes/no trial. The terms PreMCue, PreSMCue, PostMCue, and PostSMCue are used to distinguish the four conditions. ''Pre'' and ''Post'' specify the position of the cue relative to the detection trial. ''M'' and ''SM'' specify the type of cue, masker or signal-plus-masker.

Data collection was blocked. As a result, there was no uncertainty as to the cue type or the cue's temporal position relative to the detection trial.

A. Methods

1. Observers

Results from a total of 14 normal-hearing observers are reported. A fifteenth observer participated in this experiment and some of the experiments reported below, but her data were very erratic and therefore were not included. The observers range in age from 18 to 32. All had thresholds in quiet of 15 dB HL or better for octave frequencies from 250 to 8000 Hz as determined by audiometric testing. Except for Obs 5, the second author, all were paid for participation.

2. Stimuli and procedures

Observers were instructed to press one key if the two stimuli had the same sounds and another key if the two stimuli had different sounds. Feedback appropriate to those instructions was provided after every trial.[1]

Before each two-interval stimulus sequence, the phases of the masker components were drawn at random from a uniform distribution with a range of 2π rad. Additionally, the frequencies of the masker components were independently drawn from a uniform distribution on a logarithmic scale ranging from 200 to 5000 Hz with the exception that the component frequencies were not allowed to fall within a ''protected'' region of $\pm 12\%$ surrounding the 1000-Hz signal frequency. The purpose of the protected region was to reduce the amount of energetic masking that occurred (i.e., masking which is assumed to reflect interactions of the masker and signal at the auditory periphery).

The masker components were presented at a level of 50 dB SPL per component. The signal was played synchronously with the masker. The total stimulus duration was 100 ms including 5-ms cosine-squared onsets and offsets. The two observation intervals were separated by 350 ms. Richards and Neff (2004) reported little effect on thresholds of the time between a pretrial masker cue and the subsequent trial. The 350-ms ISI is in the middle of the range of values they studied.

The digitally generated stimuli were presented using two channels of a 16-bit DAC played at a sample rate of 20 kHz. The signal and maskers were then low-pass filtered at 7 kHz using matched filters (Stewart VBF 10M), separately attenuated, summed and presented diotically using Sennheiser HD410SL headphones. Observers were tested individually in a double-walled sound booth.

Observers 1–4 participated only in experiment I. The remaining observers participated in at least one of the other experiments reported below. Of those, Obs 5, 10, and 11 ran this experiment first. Before starting the experiment, observers practiced for 2–3 h. In addition, at least 300 practice trials preceded data collection when an observer began a new condition.

Each condition was tested using two signal levels (''high'' and ''low'') that were typically chosen during the initial 2–3 h of practice. When an observer had previously run another experiment (e.g., Obs 8, 9, 12, 13, and 14), the signal level used in that experiment was the high signal level in this experiment. The aim was to choose signal levels that, averaged across conditions, yielded percent correct scores

TABLE I. The low and high signal levels tested for experiment I are listed for the individual observers. Levels are in dB SPL.

	Low	High
Obs 1	36	45
Obs 2	33	51
Obs 3	36	45
Obs 4	30	51
Obs 5	30	42
Obs 6	36	45
Obs 7	39	48
Obs 8	36	51
Obs 9	36	51
Obs 10	36	48
Obs 11	33	45
Obs 12	28	39
Obs 13	38	44
Obs 14	40	48

near 70 and 90. Due to differences in sensitivity for different conditions, individual observers sometimes approached floor and ceiling levels of performance in one or another of the conditions. When choosing signal levels, the latter was more carefully controlled against than the former. The signal levels tested are listed in Table I for each observer.

Data collection in each condition and at each signal level was blocked. For Obs 1–5 the precue conditions were run before the postcue conditions. Within these subdivisions (pre-versus posttrial cues) the order in which the different signal levels and cue types were tested was random. For Obs 6–11 the four conditions (pre- and posttrial cues, masker and signal-plus-masker cues) and two signal levels were tested in random order. For Obs 12–14 the conditions were run in random order, but the high signal levels were run before the low signal levels. Trials were presented in either 50- (Obs 1–11) or 60- (Obs 12–14) trial sets, and participants were encouraged to take a break after finishing five sets. A minimum of 500 trials were used to estimate d'.

The estimate of d' was calculated using a standard equation for yes/no trials, $d' = z_{Hit} - z_{FA}$ (Macmillan and Creelman, 1991). That is, regardless of whether the cue preceded or followed the yes/no interval, d' depended only on the observer's responses relative to the presence or absence of the signal in the yes/no trial. For example, if the cue followed the trial, the hit rate is the rate at which the observer correctly detected that the first interval contained a signal-plus-masker stimulus.[1] For percent correct scores below 55,[2] d's were set to zero.

B. Results and discussion

Figure 1 shows the values of d' averaged across observers separately for the low and high signal levels (which yield lower and higher d's). Points plotted to the left indicate values of d' when the cue preceded the yes/no trial and points plotted to the right indicate values of d' when the cue followed the yes/no trial. Squares are for the masker-cue conditions and circles are for the signal-plus-masker-cue conditions. Error bars are the standard errors of the mean across 14 observers. Figure 2 shows the results averaged across signal levels and then across observers. In all other respects the figure is as Fig. 1, except that the ordinate has a smaller range of values. The appendix lists the individual results for each condition of experiment I, allowing a comparison between the summary and individual results.

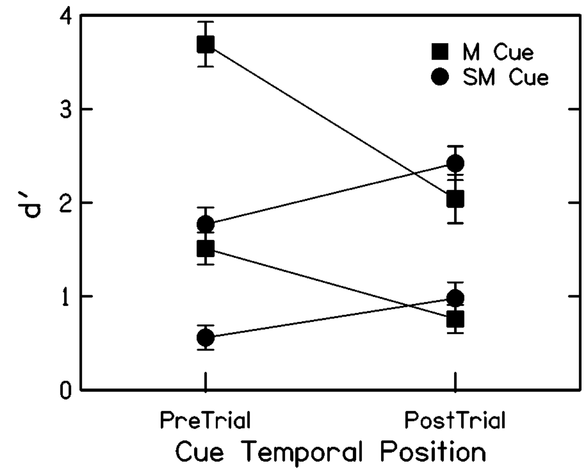

FIG. 1. Values of d' averaged across observers are plotted for low and high signal levels (yielding lower and higher d's) for pre- (left) and post- (right) trial cues. Squares are for the masker-cue conditions (MCue) and circles are for the signal-plus-masker-cue conditions (SMCue). Error bars are the standard errors of the mean across 14 observers.

The results plotted in Figs. 1 and 2, are consistent with the findings of Richards and Huang (2003). For pretrial cue conditions, d's were higher when the cue provided a preview of the subsequent masker stimulus (squares) than when it provided a preview of the subsequent signal-plus-masker stimulus (circles). This result held for both signal levels tested (Fig. 1). Averaged across signal levels, for all 14 observers the maximum d' was achieved in the PreMCue condition (Fig. 2, left, squares). For 10 of the 14 observers the minimum d' occurred in the PreSMCue condition (Fig. 2, left, circles).

Considering the postcue conditions, averaged d's tended not to depend strongly on the type of cue that followed the detection trial. On average the d's estimated in the PostSMCue condition were only 0.3 units higher than the d's estimated in the PostMCue condition. A coarse summary of the averaged results shown in Fig. 2 is that d's

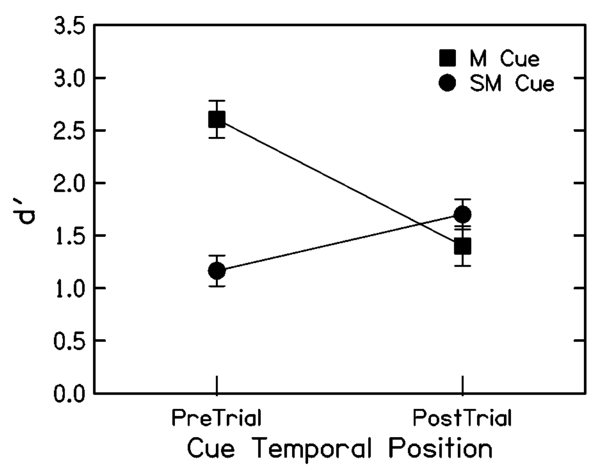

FIG. 2. The d' values averaged across levels and observers are plotted as in Fig. 1.

were higher for the PreMCue condition and relatively similar in the other three conditions. For that reason, the data shown in Figs. 1 and 2 will be referred to as demonstrating a "masker-first advantage."

An ANOVA applied to the data of experiment I revealed that all potentially significant features, both main effects (signal level, cue type and temporal position of cue) and interactions, were statistically significant at a p value less than 0.02. Floor effects may play an important role in generating significant interactions. As an example, d' scores for 5 of the 14 observers were coded as zero in the PreSMCue condition for the low signal level. Therefore, changing from low to high signal levels would not be expected to produce parallel lines (see Fig. 1). This floor effect makes it likely that significant interactions would be obtained when signal level was a factor.

To summarize, the current experiment demonstrates a masker-first advantage. This term incorporates three features concerning stimulus cues in informational masking: (a) A pretrial masker cue provides a larger release from informational masking than does a pretrial signal-plus-masker cue, (b) the advantage depends on the temporal order of the cue and trial, and (c) much of the difference in values of d' for pre- and posttrial cues is due to the unusually high d's obtained when a masker cue preceded an informational masking trial.

III. EXPERIMENT II: EFFECT OF REMOVING LEVEL DIFFERENCES AND DETECTION OF CHANGES IN NUMBER OF COMPONENTS

The two experiments described in this section will be referred to as experiments IIa and IIb. In experiment IIa the conditions were identical to the conditions of experiment I, except that the addition of the signal did not lead to a consistent increment in level relative to masker-alone trials. This was achieved in two ways. First the overall levels of the masker and signal-plus-masker stimuli were equated. Second, the levels were randomly perturbed using draws from a uniform distribution with a 5-dB range. This experiment was designed to determine whether the increment in level associated with the change from a masker to a signal-plus-masker stimulus (cue followed by a signal trial) contributed to the masker-first advantage obtained in experiment I.

In experiment IIb a task similar to that described by Neff and Green (1987) was used. Observers indicated whether a complex sound was composed of N versus $N+L$ tonal components. The frequencies of the $N+L$ tones were drawn at random and the complex sounds had equal level regardless of the number of components. In addition, in separate conditions a pretrial cue of either N or $N+L$ tones was provided. Accordingly, each trial had two intervals, a cue interval followed by a yes/no trial interval. When the pretrial cue had N tones, the same N tones were presented on the subsequent trial interval—either with or without the additional L tones. When the pretrial cue had $N+L$ tones, the subsequent yes/no trial interval was composed of either those same $N+L$ tones, or only N of the tones.

If one considers the N-tone complex as the masker and the $N+L$-tone complex as the signal-plus-masker, then this experiment reproduces the pretrial-cue conditions of experiment I. That is, the pretrial cue can be thought of as a preview of either the masker-alone or signal-plus-masker stimulus. As a result, this experiment explores the question of whether observers are more sensitive to increments than decrements in the number of components. A fundamental difference between this experiment and experiment I is that here the added signal had a frequency (or frequencies if $L=2$) that was random. As a result, unlike experiment I, observers could not direct their attention to a signal frequency that was constant across trials.

A. Methods

The methods used for experiment IIa were nearly identical to those of experiment I. The signal levels tested were the same as those tested in experiment I. For one observer the mean overall stimulus level was equal to the masker stimulus, 58 dB SPL, while for the other two observers the mean stimulus levels had the slightly higher level that was equal to the signal-plus-masker stimulus. In addition, the overall level was chosen at random from a uniform distribution with a 5-dB range using a 0.1-dB gradation. Each estimated d' was based on responses to 600 trials.

Observers 12–14 participated in this experiment. For observers 13 and 14 data were collected at the same time as the data collected in experiment I. Observer 12 ran this experiment after completing experiment III. As in experiment I the feedback depended on whether the two intervals contained the same or different stimuli, but the d's were estimated assuming a yes/no trial structure.

For experiment IIb the stimuli, composed of N or $N+L$ tones, had median levels of 60 dB SPL. In addition, a 5-dB rove of the overall level was applied to the cue and yes/no trial intervals using a 0.1-dB gradation. Consistent with the methods adopted by Neff and Green (1987), the stimulus durations were 150 ms rather than the 100 ms tested in the other experiments reported here.

Prior to each two-interval stimulus sequence, the frequencies of the $N+L$ tones were chosen at random between 200 and 5000 Hz using a uniform distribution on a logarithmic scale. N of those tones were arbitrarily designated as the "masker" stimulus. L's of one and two were tested, with the value of L being chosen at random prior to each two-interval presentation sequence. Observers 6–11 participated in this experiment. Observers 6–9 ran this experiment before experiment I, while Obs 10 and 11 ran this experiment after experiment I. The feedback used was appropriate for a same/different task, but the d's were estimated assuming a yes/no trial structure. Responses to at least 360 trials were used to estimate d'.

B. Results and discussion

The results for experiment IIa are listed in top portion of Table II and the summary data are shown in Fig. 3 (filled symbols). Corresponding results from experiment I are also tabulated (lower portion of Table II) and plotted (unfilled symbols in Fig. 3). For Table II the low and high signal levels are indicated to the left and right, respectively, and the results are listed separately for the different cue positions

TABLE II. The d's for the individual observers are compared for experiment IIa (level difference removed) and experiment I. The masker (M) or signal-plus-masker (SM) cue either preceded (Pre) or followed (Post) the yes/no trial. Averages and standard errors of the mean are also shown for each experiment.

	Low signal level				High signal level			
	PreM	PostM	PreSM	PostSM	PreM	PostM	PreSM	PostSM
				Experiment IIa				
Obs12	1.3	0	0	0	2.1	0.6	0	1.4
Obs13	2.3	1.0	0	0.9	3.7	1.0	0.9	1.7
Obs14	1.3	1.5	1.1	0.9	2.1	2.3	1.4	2.1
AVG	1.6	0.8	0.4	0.6	2.7	1.3	0.8	1.7
SEM	0.3	0.5	0.4	0.3	0.5	0.5	0.4	0.2
				Experiment I				
Obs12	0.5	0	0	0.3	2.4	1.2	0.6	1.7
Obs13	1.7	0.9	0.7	2.0	3.2	2.0	1.6	2.3
Obs14	1.4	1.3	1.2	1.8	2.9	2.5	2.3	2.0
AVG	1.2	0.7	0.6	1.4	2.9	1.9	1.5	2.0
SEM	0.4	0.4	0.3	0.5	0.2	0.4	0.5	0.2

(pre-versus posttrial) and the different cue types [masker (M) or signal-plus-masker (SM)]. In Fig. 3 the abscissa indicates the position of the cue relative to the yes/no trial and the ordinate is d'. Squares are for the masker-cue conditions and circles for the signal-plus-masker-cue conditions. Comparing the results from experiments IIa and I, removing level differences had no effect on the values of d' for conditions in which the masker was the cue. When the signal-plus-masker was the cue, d''s fell an average of 0.5 d' units. This reflects lower d''s in the PostSMCue condition for the low signal level and in the PreSMCue conditions for the high signal level (see Table II). The consequence of removing useable level differences between the masker and signal-plus-masker stimuli was to *enhance* the efficacy of the masker cue relative to the signal-plus-masker cue.

Figure 4 displays the averaged results for experiment IIb. The ordinate shows d' and the abscissa indicates the number of added tones that constitute the signal, $L=1$ (left) or 2 (right). Squares show the averaged d''s for the condition in which the pretrial cue was the N-component stimulus and circles show the averaged d's when the pretrial cue was the $N+L$-component stimulus. Although d' increased as L increased from one to two, there was no effect of the number of components in the pretrial cue stimulus. Thus, changes in the number of components *per se* did not drive the masker-first advantage obtained in experiment I.

To summarize, the results of experiment IIa indicated that level equalization did not adversely affect the masker-first advantage, and may have enhanced the effect because the signal-plus-masker cue became less beneficial. The results of experiment IIb failed to reveal a "fewer tones first" advantage parallel to the masker-first advantage obtained in experiment I. Given the findings in experiment IIa, the difference in the results of experiments I and IIb are unlikely to depend on the fact that useable level differences were removed in experiment IIb. Rather, the fact that a masker-first advantage was obtained in experiments I and IIa but not IIb may be driven by other differences in stimuli, including

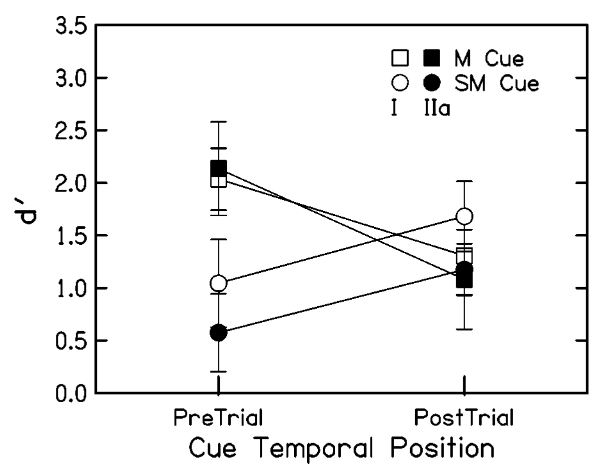

FIG. 3. The d' values averaged across level and observers are plotted as a function of whether the cue preceded (left) or followed (right) the trial. Squares are for the masker-cue conditions and circles are for the signal-plus-masker-cue conditions. The filled symbols are for experiment IIa (no level differences) and the unfilled are for experiment I. Error bars are the standard errors of the mean across three observers.

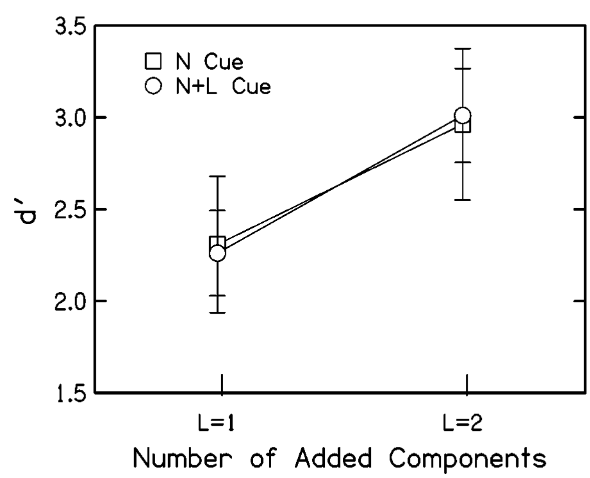

FIG. 4. The d' values averaged across observers are plotted for experiment IIb. $N=6$ and L's of one and two were tested (abscisa). The pretrial cue either previewed the N-tone or the $N+L$-tone complex (squares and circles, respectively). Error bars indicate the standard error of the mean across three observers.

whether or not the signal frequency was randomized. The masker-first advantage may have depended in part on observers having directed their attention toward a known signal frequency (experiments I and IIa) and accordingly disappeared when signal frequency was uncertain (experiment IIb).

IV. EXPERIMENT III: DETECTION OF AN ADDED TONE IN A SAME/DIFFERENT TASK

The aim of experiment III was to explore whether the masker-first advantage reflected observers' reliance on a different detection strategy when the masker was reliably present in the first interval than when it was not. This issue was examined by intermixing trials drawn from all four conditions tested in experiment I: PreMCue, PreSMCue, PostMCue, and PostSMCue. Intermixing conditions encourages the observer to adopt a single strategy for all trial types encountered. As a result, if the masker-first advantage reflected different strategies in the PreMCue condition than in the other conditions, intermixing conditions could reduce or eliminate the advantage. It is important to appreciate, however, that generalized uncertainty effects may lead to the same prediction. An increase in uncertainty, if treated as an added source of variance,[3] would have a larger detrimental effect in the PreMCue condition where d's are highest and a smaller detrimental effect in the PreSMCue condition where the d's are lowest. Referring to Fig. 2, increasing uncertainty would be expected to both reduce d's and reduce the magnitude of the interaction. If increased uncertainty does not diminish the masker-first advantage, it is unlikely that the advantage reflects a difference in strategy for the PreMCue conditions compared to the other conditions studied in experiment 1.

Note that intermixing trials from the four conditions of experiment I leads to a same/different procedure. The logic is as follows. Denoting the masker stimulus using an M, and the signal-plus-masker stimulus using an SM, the trials of experiment I may be identified as follows. For the PreMCue condition, the two possible trial sequences are ⟨M M⟩ and ⟨M SM⟩. As another example, trials from the PostSMCue condition are ⟨M SM⟩ and ⟨SM SM⟩. Together, the four conditions of experiment I include four trial types: ⟨M M⟩, ⟨M SM⟩, ⟨SM M⟩, and ⟨SM SM⟩. When these different trial structures are intermixed and chosen at random a same/different procedure results.

The analysis of the data obtained in this experiment was devised in an effort to estimate the detrimental effect of trial-type randomization. Towards that end, responses to different trial types were extracted from the data set and used to estimate values of d' for comparison with those obtained in experiment I. For example, extracting responses to the ⟨M, M⟩ and ⟨M, SM⟩ trials in the current intermixed-trials condition provides data that may be compared to those obtained from the blocked-trials design used in the PreMCue condition of experiment I. These extracted trials form a "virtual" PreMCue condition. "Virtual" PreSMCue, PostMCue, and PostSMCue conditions were formed in a similar manner. After extracting the trials appropriate to each of these virtual conditions, values of d' were determined in the same manner as in experiment I. Difference in d's estimated from the

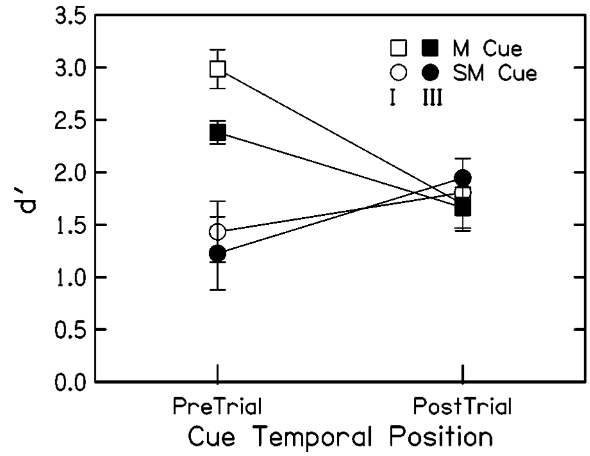

FIG. 5. The d' values averaged across observers are compared for the same/different task (filled) and experiment I (unfilled). Squares are for the masker-cue-conditions and circles are for the signal-plus-masker-cue conditions. In other respects the figure is as Fig. 2.

blocked (experiment I) and virtual (current experiment) conditions indicated the detrimental effect of intermixing trial types.

A. Methods

The methods used for this experiment were similar to those of experiment I. The fundamental difference, as indicated above, was that the trials from the different conditions were intermixed rather than blocked. The signal level tested in this experiment was the "high" signal level of experiment I. The maskers were drawn at random prior to each trial and the same masker was used in the two observation intervals. Observers were instructed to indicate whether the two intervals contained the same versus different sounds, and feedback appropriate to those instructions was provided after each trial. Observers 5 and 11–14 participated in this experiment. All of the observers, except Obs 12, had completed at least one other experiment before beginning this experiment.

One aspect of the "virtual" analysis was that responses to the same trials were used to form two virtual conditions. Consider, for example, the trials in which there was a signal-plus-masker in the first interval and a masker alone in the second interval. Using the notation introduced above, this would be a ⟨SM M⟩ trial. Responses to these trials contributed to two virtual conditions; the virtual PreSMCue condition (a no-signal trial because there was no signal in the second, yes/no trial interval) and the virtual PostMCue condition (a signal trial because there was a signal in the first, yes/no trial interval). The d's extracted for different virtual conditions, therefore, are not all statistically independent from one another. Each virtual d' was based on 600 trials which were derived from a total of 1200 trials.

B. Results and discussion

The filled symbols in Fig. 5 show the results of the same/different experiment averaged across observers. The leftmost points are for the virtual precue conditions and the rightmost points are for the virtual postcue conditions. The squares are for the virtual masker-cue conditions and the circles are for the virtual signal-plus-masker-cue conditions. Bear in mind that these "virtual" d''s were derived from trials extracted from the larger data set. The unfilled symbols in Fig. 5 show the results from experiment I for the five observers who were tested in this experiment. The pattern of results for four of the five observers corresponds closely to the averaged patterns shown in Fig. 5. For Obs 14 there was, for all intents and purposes, no difference between the four virtual conditions in the current same/different experiment.

The averaged data indicate that intermixing trial types reduced the values of d' more in the PreMCue condition than the other conditions. It might be that this reduction reflects a floor effect in the other conditions, where d's were already lower. This seems unlikely given that the obtained d's were above chance levels of performance, plus the fact that a modest reduction in d' was obtained for two of the three remaining conditions. Even noting that the largest detrimental effect of intermixing conditions occurred when the masker stimulus was in the first interval, d's in the virtual PreMCue condition remained higher than in the other conditions. Thus, intermixing trial types reduced, but did not abolish, the masker-first advantage. An ANOVA applied to the virtual conditions of this experiment did not reveal statistically significant main effects at the 0.05 level ($p>0.05$ for cue type, $p>0.2$ for temporal position of the cue). The interaction term, however, was significant [$F(1,4)=10.1, p<0.05$]. The pattern of results shown in Fig. 5 reflects the following pattern in the raw data: performance, as percent correct, was generally good when the masker was in the first interval (regardless of what followed) and generally poor when the signal-plus-masker was followed by a masker stimulus.

These results suggest that observers might take special advantage of the masker being played in the first interval when the masker was a cue, i.e., when the first interval was reliably the masker stimulus. Under those conditions, a unique perceptual cue might be incorporated into the observers' detection decision. An alternative account is that uncertainty more strongly affected the PreMCue condition than the other conditions.[3] Whatever the explanation, the masker-first advantage remained robust for four of the five observers even when the trial types were intermixed. It would appear that only Obs 14 was likely to have substantively altered his detection strategy among the different conditions of experiment I.

V. EXPERIMENT IV: EFFECT OF RANDOM SIGNAL FREQUENCY, FIXED MASKERS, AND DICHOTIC PRESENTATION

Experiment IV is composed of three experiments, which will be referred to as experiment IVa, IVb, and IVc. All of the experiments used the same/different task described in experiment III. And, as in experiment III, the responses to different trial types were extracted to form virtual conditions. These experiments further explored conditions in which the masker-first advantage might be maintained/abolished.

In experiment IVa the effect of randomly assigning the signal frequency prior to each trial on the masker-first advantage was revisited. We were interested in examining signal frequency randomization in more detail because it was the only manipulation in any of the experiments described above that abolished the masker-first advantage.

In experiment IVb stimulus uncertainty was minimized. In this experiment, the signal and masker frequencies were fixed for all trials. This experiment was designed to help us better understand the somewhat ambiguous role of varying uncertainty in the earlier experiments. In experiment IVc the stimuli were presented dichotically. The first interval of the same-different task was presented to the left ear and the second interval was presented to the right ear. This experiment was included in order to test whether the masker-first advantage might be due to a peripheral effect, such as neural adaptation.

A. Methods

The methods are similar to those of experiment III. Deviations from those methods are detailed separately for each experiment below. Observers 5 and 12–14 participated in these experiments. All observers had completed experiments I, IIa and III before beginning this experiment.

In experiment IVa the signal frequency was randomly chosen from a range of 200–5000 Hz on each trial. The random masker was constrained such that no component fell within $\pm 12\%$ of the randomly drawn signal frequency. This process was followed even on masker-alone trials; that is, a signal frequency was chosen and masker components were excluded from falling near that frequency but the signal was not presented. The signal level tested in this condition was the high signal level of experiment I. As a result, unlike experiment IIb for $L=1$, the level of the signal was not equal to the levels of the masker components which we hypothesized might have been a factor in abolishing the masker-first advantage.

In experiment IVb the six tones that comprised the masker were fixed in frequency across all trials. The component frequencies were 252, 380, 795, 1259, 2200, and 3973 Hz. The phases of the individual components were randomly drawn prior to each trial. This particular masker was chosen based on results obtained in a separate experiment that indicated this masker provided substantial masking for most subjects. The signal, when present, had fixed level and frequency (1000 Hz), but a randomly drawn phase. Compared to conditions in which masker frequencies were randomly drawn, somewhat lower signal levels were required for most observers in order to maintain average percent correct values of approximately 75. For Obs 5, 12, 13, and 14 signal levels of 33, 39 (equal to the high signal level tested in experiment I), 40, and 42 dB SPL, respectively, were tested. Due to the change in signal level, the results from this experiment cannot be directly compared to the results of the other experiments. Instead, the goal was to determine whether the pattern of d's estimated for the virtual conditions was similar to those obtained from experiments I and IIa.

In experiment IVc the stimulus in the first interval was played to the left ear and the stimulus in the second interval was played to the right ear. Note that because a same/different task was used, the dichotic separation is not based on stimulus type, i.e., each ear was as likely to receive a

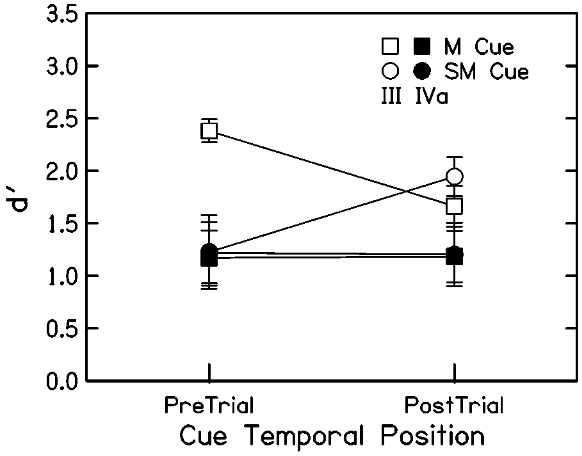

FIG. 6. The d' values averaged across observers for experiment IVa in which the signal frequency was drawn at random (filled) are compared to the results of experiment III (unfilled) for the same observers. In other regards the plot is as Fig. 5.

masker as a signal-plus-masker stimulus. To the degree that a masker-first advantage was obtained in this condition, it would seem unlikely that the effect was associated only with monaural processing.

B. Results and discussion

Figure 6 shows the averaged virtual d's from experiment IVa (filled symbols) in which the signal frequency was chosen at random prior to each trial. The averaged results of experiment III for the same observers are displayed using unfilled symbols. Conditions for virtual pre- and posttrial cue conditions are plotted left and right, respectively. Squares are for the trials in which the masker was the virtual cue and circles are for the trials in which the signal-plus-masker was the virtual cue. Error bars are the standard errors of the mean across four observers.

In experiment IVa, shown with filled symbols, there was no effect of cue type (masker versus signal-plus-masker) and additionally no effect of the temporal position of the virtual cue relative to the virtual yes/no trial. The individual data similarly did not indicate a strong effect of cue type or the ordering of the virtual cue and the virtual trial. Also, not surprisingly given the fact that the signal frequency was random, the virtual d's were lower in this experiment than in experiment III, which used the same signal levels.

These results are consistent with the findings of experiment IIb and demonstrate that even when level cues were available, and when the spectral components were not of equal level (the signal was not the same level as the masker components), signal frequency randomization abolished the masker-first advantage.

Figure 7 shows the results of experiment IVb in which the masker was composed of fixed-frequency tones across all trials. Because the pattern of d's in the virtual conditions was different for different observers, the results for individual observers are plotted in separate panels. The bottom panel plots the group mean results and error bars show the

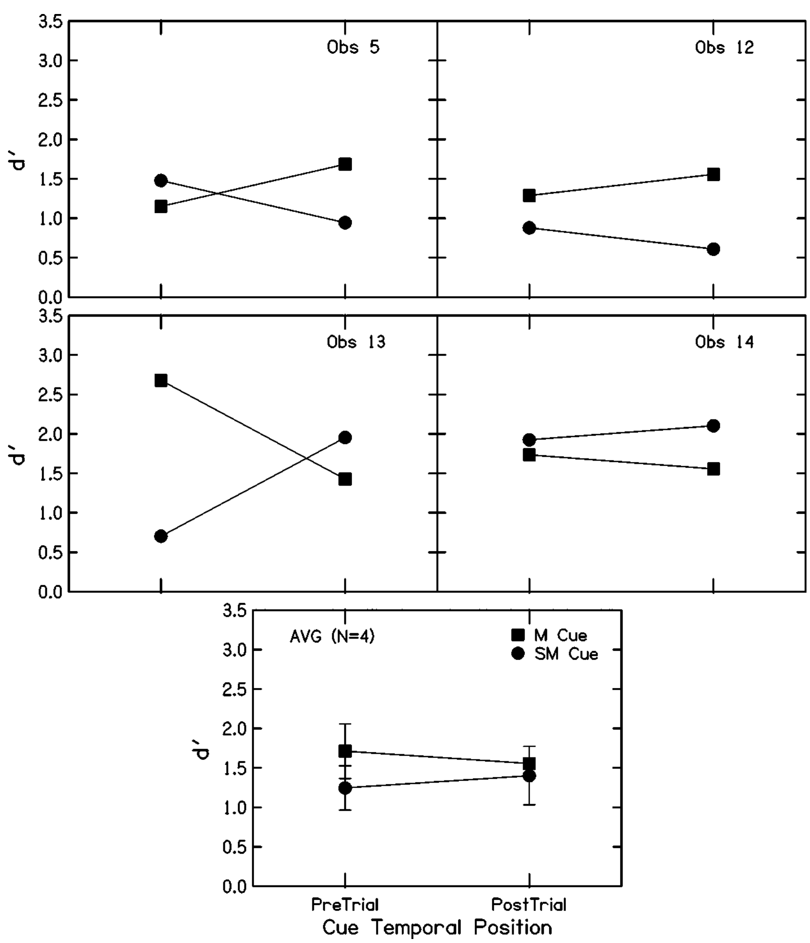

FIG. 7. For each observer, and for the average across observers (bottom panel), virtual d's are plotted for experiment IVb in which both the signal and the masker frequencies were fixed across all trails. In other regards the plot is as Fig. 5.

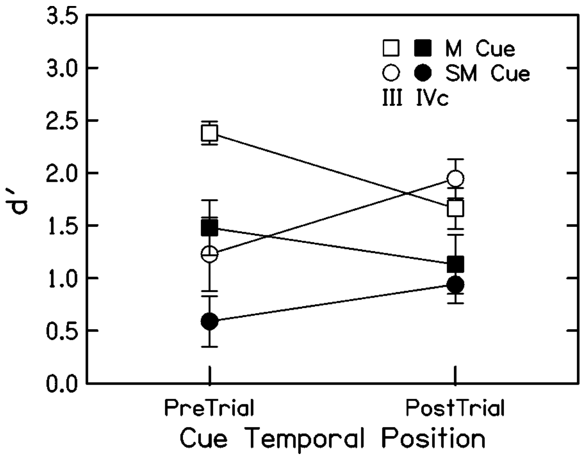

FIG. 8. The d' values averaged across observers for experiment IVc in which the first interval was presented to left ear and the second interval was presented to the right ear (filled symbols). The unfilled symbols are from experiment III for the same observers. In other respects the figure is as Fig. 5.

standard errors of the mean. Recall that in order to maintain comparable d's the signal levels tested in this experiment were generally lower than those tested in the previous experiments. As a result, a comparison of the magnitude of virtual d's across experiments is not meaningful. For the averaged data there was a small advantage for virtual masker pretrial cue compared to the signal-plus-masker pretrial cue. As would be expected based on the results shown in Fig. 7, an ANOVA failed to reveal significant main effects of virtual cue type (masker versus signal-plus-masker) and virtual cue order (pre versus post relative to the virtual yes/no trial). Nor was the interaction term significant. Thus, the masker-first advantage was not reliably present under conditions of minimal uncertainty.

Figure 8 shows the results for experiment IVc in which the stimulus in the first interval was played to the left ear and the stimulus in the second interval was played to the right ear (filled symbols). For the sake of comparison, the averaged results for the same observers in experiment III are shown using unfilled symbols. Error bars are the standard errors of the mean across four observers. For the dichotic experiment (filled symbols) the results for one observer (Obs 14) differed from the pattern apparent in the averaged data; as for the averaged data his d's were generally higher for the masker cue conditions, but were higher in the virtual PostMCue than the virtual PreMCue condition (i.e., an interaction in the opposite direction, with larger differences in d''s when the virtual cue followed the trial). The averaged data reasonably reflect the results of the other three observers.

The averaged data plotted in Fig. 8 clearly show a loss in sensitivity associated with presenting the sequential stimuli dichotically (filled symbols) compared to diotically (unfilled symbols). An ANOVA applied to the dichotic data set indicated a main effect of cue type (masker versus signal-plus-masker), but did not reveal significant effect of temporal position of the cue ($p>0.99$) nor interaction ($p>0.2$). It is unlikely that the absence of an interaction term reflected a floor effect—the d's were measurable for all of the virtual conditions. Rather, it seems that the interaction was not strong enough to overcome individual differences. It is difficult to envision a consistent explanation for a significant difference in cue type without an interaction; thus we suggest the masker-first advantage remained, but was weakened. To the degree that this speculation is accurate, we would suggest that the masker-first advantage does not depend only on peripheral/monotic processing.

To summarize the results of this final sequence of measurements: randomizing the signal frequency abolished the masker-first advantage; a weakened masker-first advantage appeared to remain when sequential stimuli were presented to different ears; and little can be made of the reduction in uncertainty associated with the use of a single masker across many trials—individual differences defy a clear interpretation.

VI. SUMMARY AND GENERAL DISCUSSION

These experiments addressed an asymmetry in the potency of different types of cues in providing a release from informational masking. Informational masking was introduced by randomly choosing a spectrally sparse masker prior to each trial. The results of experiment I corroborated those of Richards and Huang (2003) by demonstrating that a pretrial masker cue provided a greater release from informational masking than did a pretrial signal-plus-masker cue. Averaging across two signal levels and 14 observers, the difference in d' was 1.45. Moreover, the results of experiment I indicated that when a yes/no trial was reliably followed by a posttrial cue, the d's depended only slightly on whether the posttrial cue was the masker or the signal-plus-masker. Again using averaged results, the d' was 0.3 units smaller for the masker than for the signal-plus-masker posttrial cue. These findings suggested that the relative effectiveness of cues in informational masking tasks does not depend just on reductions in uncertainty.

The "masker-first advantage" demonstrated in experiment I was largest when the cue was consistent across trials, e.g., when data were collected using a blocked design. Nonetheless the effect was obtained, at least for four of the five observers tested, when there was no consistent "cue," i.e., for a same/different task. This result suggested that the masker-first advantage did not depend only on differences in strategies adopted when different cue types were tested using blocked designs. On the other hand, no masker-first advantage was obtained when the signal frequency was randomly drawn prior to each trial. This result implied that the phenomenon is at least partly due to processing that occurs beyond the auditory periphery, i.e., it is sensitive to the incorporation of *a priori* knowledge about a fixed signal frequency or at least about the perceptual ramifications of such a signal's presence. That a modest masker-first advantage appeared to be present when dichotic presentations were tested is also consistent with the suggestion that peripheral processing was not critical to the masker-first advantage.

The masker-first advantage is an indication of enhanced sensitivity when a yes/no detection trial is preceded by a preview of the masker. This might reflect sensory adaptation—the frequency channels excited by the masker components might be adapted, thereby enhancing the relative strength of a signal tone of another frequency. A related explanation is one in which psychophysical enhancement (Viemeister, 1980; Viemeister and Bacon, 1982) plays a role—the initial masker stimulus reduced the suppression acting on neighboring frequencies, and in particular the signal frequency. However, at least three factors suggest that adaptation effects were not the sole mechanism behind the masker-first advantage. First, the masker-first advantage was absent when the frequency of the signal tone was chosen at random. Second, because the masker was spectrally sparse with components having frequencies that were chosen at random across trials, the signal frequency was the most likely of all frequencies to be present in the stimulus. This suggests that, if anything, adaptation would be strongest at the signal frequency than at masker frequencies. Indeed, it seems more likely that adaptation at the signal frequency might contribute to the relatively small impact of the signal-plus-masker pretrial cue. Third, Viemeister (1980; see also Summerfield *et al.*, 1984) found that psychophysical enhancement did not withstand dichotic presentations. The current findings suggested that the masker-first advantage remained, albeit attenuated, when the stimuli were presented dichotically. Importantly, in this study, the signal was not always in the ear opposite the masker, making comparisons with Viemeister's experiment, which ensured a separation of masker and signal, tenuous.

Next consider two strategies that have been proposed by Durlach and colleagues to account for informational masking, at least as it occurs in some conditions similar to those tested here (Durlach *et al.*, 2003). For one strategy, the ''Listener Max'' strategy, it was hypothesized that observers used the first stimulus of a trial to form an acceptance filter, allowing the energy at the signal frequency to pass, or be maximized, on a subsequent interval. For a second strategy, the ''Listener Min'' strategy, it was hypothesized that observers used the first stimulus of a trial to form a rejection filter so that masker energy was minimized in subsequent intervals. Because a signal cue was not tested in the present experiments, only the Listener Min model is considered here. Imagine that, upon hearing a pretrial cue, the listener formed a rejection filter based on information available from the cue. If the cue is a preview of the masker, a rejection filter matching the cue could aid the observer in detecting the signal. For a signal-plus-masker cue, however, there is little basis for forming a useful rejection filter. As a result, the subsequent signal would be more readily detected when the masker preceded the trial than when the signal-plus-masker preceded the trial. However, this model also predicts that randomizing the signal frequency should have no effect on d' when the masker cue preceded the trial. We know from the data presented above that this prediction is incorrect. Thus, it seems unlikely that a rejection filter model can succeed in accounting for the masker-first advantage without additional stages, such as a mechanism by which observers attend to a known signal frequency, etc.

Finally, consider the effect a masker-first advantage might have on informational masking studies in general. At a minimum the results of the current experiments suggest caution in interpreting data obtained when a pretrial cue is used. Because a ''virtual'' masker-first advantage was observed when a same/different procedure was tested, it seemed possible that biases may also occur in informational masking studies that use 2IFC detection procedure. The parallel stimulus configuration is one in which the same masker is presented across intervals but random maskers are used on different trials. This assumes, as is usually the case, that the signal is as likely to be in the first as in the second interval. The logic is as follows. When the masker is in the first interval, and the signal-plus-masker is in the second interval observers ought to be very accurate in choosing the second interval, thereby leading to a large number of ''interval 2'' responses. When the signal-plus-masker is in the first interval and the masker-alone is in the second interval, observers ought to be less accurate, and thus respond ''interval 1'' at a relatively lower rate (assuming, of course, that they pay attention to the response feedback and incorporate that into their decision strategy). The end result would be that more ''signal in interval 2'' responses would be generated. We examined data on hand from two such 2IFC experiments.[4] One data set, taken from Tang and Richards (2003), included results from 12 observers. Of the twelve, the data for four of the observers indicated no response bias, i.e., the observers responded ''interval 1'' and ''interval 2'' at statistically indistinguishable rates. Of the remaining eight observers, one reliably overresponded ''signal in interval 2'' and seven reliably over-responded ''signal in interval 1'' (based on at least 490 trials per observer, $p<0.05$). In a second unpublished data set, four of the observers from the current study (Obs 5, 12–14) subsequently completed a 2IFC experiment in which the maskers were drawn randomly on every trial but were the same across intervals of a trial. All four exhibited statistically significant response biases; they overresponded ''signal in interval 1'' (at least 360 trials per observer, $p<0.05$). These retrospective analyses indicated that many observers were biased in their responses and the biases tended to be in the same direction across observers. The probability that an observer exhibited a response bias may have depended on past experience (in this case, whether they had participated in the current experiments). More importantly, in light of the current discussion, the *direction* of the response bias was not in the expected direction; observers were *not* more likely to respond ''interval 2'' than ''interval 1.'' Even so, the presence of consistent response biases suggests that analyses of experiments similar to those tested here should be scrutinized for potential sequential effects and/or consistent response biases.

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APPENDIX: INDIVIDUAL RESULTS FOR EXPERIMENT I.

TABLE III. The results for experiment I are listed for different signal levels and conditions. The entries are d's. The final two rows show the averages and standard errors of the mean across observers.

	Low signal level				High signal level			
	PreM	PostM	PreSM	PostSM	PreM	PostM	PreSM	PostSM
Obs1	1.35	0.63	1.21	1.59	4.21	1.30	1.33	2.94
Obs2	1.32	0.00	0.00	0.71	4.91	2.44	1.36	3.54
Obs3	1.24	0.78	0.36	0.79	2.92	1.88	1.51	1.54
Obs4	1.44	0.00	0.00	0.00	5.28	0.70	1.50	2.72
Obs5	1.36	0.39	0.00	0.67	2.86	1.72	1.68	1.47
Obs6	1.94	1.59	1.18	1.52	3.65	3.71	2.47	3.30
Obs7	1.29	1.08	0.83	0.43	3.01	2.66	2.21	2.97
Obs8	1.33	1.56	1.19	0.84	4.52	4.09	3.28	2.30
Obs9	1.74	0.80	0.55	1.37	3.45	1.99	1.71	2.57
Obs10	3.38	1.24	0.71	1.63	4.85	1.36	2.27	2.95
Obs11	1.14	0.38	0.00	0.00	3.53	1.08	1.05	1.57
Obs12	0.54	0.00	0.00	0.34	2.42	1.23	0.57	1.72
Obs13	1.74	0.87	0.66	1.97	3.22	1.96	1.58	2.29
Obs14	1.38	1.29	1.17	1.78	2.91	2.49	2.28	1.99
AVG	1.51	0.76	0.56	0.98	3.69	2.04	1.77	2.42
SEM	0.17	0.15	0.13	0.17	0.24	0.26	0.18	0.18

[1]From the observer's perspective, the two intervals might be treated as (1) a cue interval and a yes/no trial, and (2) two intervals containing sounds that are the same or different. If observers adopted the latter interpretation, but feedback was appropriate to the former interpretation, response incompatibilities would be introduced when the conditions change. In our initial work with the PreMCue and PreSMCue conditions, signal-present feedback was used. When faced with higher thresholds in the PreSMCue condition compared to the PreMCue condition, observers were instructed as to the response contingencies, etc. Ultimately, we repeated the experiment using a same/different response structure. The resulting thresholds indicated no effect of feedback contingency. Given the large number of conditions tested in the current experiments, a same/different response/feedback contingency was used. The trials were treated as cued yes/no trials, and the estimate of d' was based on formulas appropriate for yes/no trials.

[2]The minimal number of trials contributing to a single d' is 500. Based on a binomial distribution, this leads to 95% confidence limits about $p=0.5$ of approximately $\pm 5\%$. We chose 55% as an upper limit on guessing, and set d's to zero if the percent correct scores were less than 55. This affected a total of 14 d' scores, nine of which were in experiment I (low signal level). Only one of the scores fell below 45% correct—Obs 2 in the PreSMCue condition of experiment I.

[3]Here typical signal-detection theory assumptions are made, including that uncertainty adds the same independent variance to the internal signal and no-signal distributions regardless of condition and that due to the fixed signal level the differences between the means of the internal signal and no-signal distributions do not depend on condition. Under these assumptions, because the total variance in the task is smallest in the PreMCue condition (largest d'), the effect of uncertainty is expected to be largest in that condition. Likewise, because the d' is smallest in the PreSMCue condition, d''s are expected to shift the least in that condition.

[4]The trials came from experiments in which the signal was altered using an adaptive algorithm. After removing trials within two steps of the lowest and highest signal levels encountered, the proportions of "1" and "2" responses were determined for the trials in which the signal level was in the lower $\frac{1}{3}$ of the remaining signal levels. The percent correct scores for those trials were approximately 70% correct. High signal levels were not included because high percent correct scores are incompatible with response biases.

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