Sequential effects on the detectability of a tone added to a multitone masker

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Abstract: The detectability of a tone added to a masker is superior when the detection trial is preceded by the masker than the signal-plus-masker. This auditory enhancement can withstand long temporal gaps between the precursor and the trial, suggesting that for yes/no trials sensitivity may depend on the stimulus presented in the prior trial. The results from an experiment examining the detectability of a 1000-Hz tone added to 6-tone maskers confirmed sequential effects on sensitivity. The values of d' were higher when the prior trial was a no-signal (masker alone) trial compared to a signal (signal-plus-masker) trial.

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1. Introduction

The detectability of a tone added to a masker can be substantially improved if the signal's onset is delayed relative to the masker's onset (e.g., Green, 1969). For relatively long-duration signal tones (hundreds of ms) delaying the signal onset relative to the masker onset can lead to threshold reductions of 10–20 dB if the masker and signal are not spectrally overlapping (e.g., Viemeister, 1980; McFadden and Wright, 1990; Wright *et al.*, 1993; Richards *et al.*, 2004; see also McFadden and Wright, 1992, for an example of reduced thresholds when there is masker energy at the signal frequency). Here, this phenomenon is described using a single term, enhancement, even though experiments in which this phenomenon has been demonstrated include experiments that appear to depend relatively more or relatively less on peripheral versus central limitations/processes (e.g., multiple narrowband noise maskers, McFadden and Wright, 1990; Wright *et al.*, 1993; noise maskers, Viemeister, 1980; multitone maskers, Viemeister, 1980; versus maskers composed of harmonics of a common fundamental frequency, Viemeister, 1980; multitone informational maskers, Richards and Neff, 2004; Richards *et al.*, 2004).

Enhancement occurs not only when the signal onset is delayed relative to the masker onset, but also when there is a temporal gap between the early masker and the onset of the simultaneously presented masker and signal (when presented) (e.g., Viemeister, 1980). Here, we refer to the early masker as the precursor. For a masker and signal that shared a common fundamental frequency, Viemeister (1980) found that enhancement withstood precursor-trial delays as long as 6 s. Indeed, owing to the persistence of the enhancement effect, Viemeister (1980) pointed out that the phenomenon does not lend itself to study using traditional psychophysical methods such as the two-interval, two-alternative forced-choice procedure. In a similar vein, in an informational masking task, Richards *et al.* (2004) decomposed same-different trials separated by several hundred ms and discovered that the resulting "virtual" single-interval trials preceded by a masker yielded higher values of d' than trials preceded by a signal-plus-masker. Also with regard to informational maskers, Lutfi and Alexander (2005) observed context effects such that the detectability of a tone in quiet could decrease when tone-in-quiet trials were intermixed with informational masking trials. This result may ultimately be found to reflect sequen-

tial trial-by-trial interactions similar to enhancement, although that hypothesis was not examined in their paper. With regard to experiments likely to reflect relatively more peripheral limitations, and again for relatively long signal durations (60 ms), McFadden and Wright (1990) obtained, for some subjects, enhancement that withstood at least a 350 ms delay between the precursor and the stimulus interval. In their experiment the signal to be detected was a narrowband of noise and the masker was composed of multiple narrow bands of noise.

These examples of relatively long-lived persistence of auditory enhancement suggest that auditory enhancement might give rise to sequential effects in yes/no experiments in a variety of psychophysical tasks. The hypothesis tested here is that sensitivity in a masked detection task changes depending on whether the prior trial was a no-signal or a signal trial. It should be noted that this report was based on a retrospective analysis of an existing data set, a data set for which the masking is presumed to be relatively peripheral (energetic) rather than relatively central. Due to the retrospective aspect of this report, the choice of the stimuli does not reflect an effort to maximize enhancement effects. Instead, the experiment and results reflect stimuli and stimulus presentations that are typically used in psychoacoustics experiments (e.g., the time between trials was self-paced, etc.).

In the experiment analyzed, 12 distinct maskers were tested in separate blocks. Each masker was composed of six tones with different frequencies for the different maskers. The signal to be detected was a 1000-Hz tone. A yes/no procedure was used. In order to test for sequential effects on sensitivity, detection trials were separated into groups based on whether the prior trial was a no-signal trial or a signal trial. In parallel with typical auditory enhancement experiments, for the former group of trials the prior trial would encourage enhancement because there was no energy at the signal frequency and for the latter group of trials the prior trial would not encourage enhancement because there was energy at the signal frequency. Thus, one would expect values of d' to depend on whether the current trial was preceded by a signal or a no-signal trial.

2. Methods

2.1 Subjects

Eight normal-hearing subjects (S1–S8) ranging in age from 20 to 32 years participated in the experiments. All subjects had thresholds in quiet of 15 dB HL or lower for octave frequencies from 250 to 8000 Hz. Four of the subjects (S1–S4) had previously participated in psychoacoustics experiments. Subjects were compensated for their participation, except S5, the second author. Subjects were tested individually in double-walled sound-attenuated booths.

2.2 Stimuli

The subjects' task was to detect a tonal signal added to a six-tone equal-amplitude "frozen" masker. Twelve maskers were tested and Table 1 shows the frequencies of the components that comprised each masker. The level of each component was 50 dB SPL and the phases of the masker components were originally chosen at random, but fixed across trials. The signal to be detected was a 1000-Hz sinusoid whose phase was chosen at random on each presentation. The signal, when present, was synchronous with the masker. The duration of the stimuli was 102 ms including 5-ms cosine-squared onset and offset ramps.

The digitally generated stimuli were presented using two channels of a 16-bit digital-to-analog converter at a sample rate of 20 kHz. The stimuli were low-pass filtered at 7 kHz using matched filters (Stewart VBF 10M), separately attenuated, summed and presented diotically through Sennheiser HD410 SL headphones.

2.3 Procedure

A single-interval yes/no procedure was used. Subjects indicated the presence/absence of the signal by pressing the appropriate response key. As a result, the time between trials was self-

Table 1. The frequencies for each masker component are indicated using dashes.

	Frequency (Hz)											
Masker	252	317	399	502	631	795	1259	1584	1993	2509	2157	3973
1	—	—	—							—	—	—
2				—	—	—	—	—	—			
3	—	—	—				—	—	—			
4				—	—	—				—	—	—
5	—		—		—			—		—		—
6		—		—		—	—		—		—	
7	—			—		—	—		—			—
8	—	—			—			—			—	—
9	—		—			—	—			—		—
10		—	—	—					—	—	—	
11		—			—	—	—	—			—	
12			—	—	—			—	—	—		

paced by the subjects. On average, the time that elapsed between trials was approximately 2.1 s, with a range of 1.5–2.8 s across subjects and maskers. Visual feedback as to the correctness of each response followed each trial.

Experienced subjects ran ten sets of 60 trials, with frequent breaks. Three signal levels were tested, those values having been chosen based on approximately 2 h of practice prior to data collection for each masker such that the values of d' were approximately 1, 1.6, and 2.2. Accordingly, different signal levels were tested for different subjects and different maskers. Within each 60-trial set, 30 trials were no-signal trials. Of the remaining 30 trials the signal levels were intermixed such that each signal level was presented ten times in random order. Data collection was blocked by masker, and the order in which the different maskers were tested was different for the different subjects.

2.4 Analysis

In order to examine the effect of the prior stimulus on signal detection performance, trials were separated into two groups: trials preceded by a signal trial and trials preceded by a no-signal trial. This grouping was done separately for each subject and each masker tested. Values of d' and the criterion, c [defined as z_{hit}-z_{FA} and $-0.5(z_{\text{hit}}+z_{\text{FA}})$, respectively; Macmillan and Creelman, 2005], were then estimated for both groups. However, various constraints were placed on the trial selection, as described below.

The first constraint reflects the fact that in past informational masking experiments (e.g., Richards *et al.*, 2004) when trials were preceded by a "signal-plus-masker" cue, the signal level was the same for both the cue and the signal. In the current experiment, when a trial was preceded by a signal trial, the signal might have one of three levels. In an effort to reduce the potential confound of differences in signal levels presented in the current and previous trial, only trials for which the signal levels were the same for both were considered. Additional work will be required to determine whether this constraint is necessary, or whether the current sorting procedure could be applied to data from experiments in which signal levels are adjusted adaptively. Second, for the lowest signal level the resulting values of d' were sometimes near zero and so the results from the lowest signal level were not considered. Third, for the highest signal levels, the resulting values of d' sometimes approached infinity (a hit rate of 1), and so those trials were also removed from the analysis. Thus, in the final evaluation, only midlevel signal trials were evaluated.

Table 2 shows the summary information for the trials ultimately studied. The intensities of the midlevel signals and the corresponding global values of d' are shown for each masker

Table 2. The signal level (dB SPL) and d' are listed for each masker and each subject.

	Subject															
	S1		S2		S3		S4		S5		S6		S7		S8	
Masker	*L*	*d'*	*L*	*d'*	*L*	*d'*	*L*	*d'*	*L*	*d'*	*L*	*d'*	*L*	*d'*	*L*	*d'*
1	18	*1.7*	22	*1.7*	16	*1.1*	27	*0.9*	26	*1.8*	33	*1.4*	36	*2.2*	35	*1.7*
2	40	*1.5*	39	*2.0*	35	*1.6*	40	*1.4*	37	*2.6*	49	*1.9*	43	*2.1*	48	*1.7*
3	31	*1.1*	30	*1.1*	33	*2.1*	41	*1.1*	36	*2.6*	46	*1.7*	44	*1.5*	36	*0.9*
4	32	*1.7*	35	*1.1*	26	*1.2*	38	*1.7*	31	*2.2*	41	*1.6*	40	*2.5*	41	*2.0*
5	27	*1.7*	41	*2.8*	24	*1.2*	39	*0.9*	27	*1.8*	44	*1.4*	48	*2.3*	39	*1.6*
6	37	*1.4*	38	*1.6*	35	*1.0*	42	*1.4*	34	*0.9*	49	*1.4*	51	*2.0*	45	*1.4*
7	41	*1.6*	47	*2.1*	37	*1.1*	42	*1.7*	39	*1.5*	53	*2.0*	46	*1.1*	48	*1.5*
8	32	*1.2*	35	*1.5*	29	*0.7*	45	*0.8*	37	*1.7*	44	*0.9*	44	*2.0*	36	*1.6*
9	39	*2.2*	36	*1.6*	38	*1.9*	48	*1.3*	37	*1.4*	47	*1.3*	48	*2.2*	48	*1.3*
10	26	*0.9*	33	*1.0*	29	*1.5*	39	*1.6*	31	*1.1*	41	*1.5*	45	*2.0*	43	*1.9*
11	34	*2.1*	32	*0.8*	25	*1.0*	36	*0.1*	35	*1.5*	44	*2.3*	46	*2.7*	45	*1.4*
12	25	*1.4*	32	*1.6*	24	*1.6*	33	*0.9*	28	*0.3*	40	*1.2*	39	*1.7*	46	*2.1*

and each subject. The values of d', while somewhat variable, are near the target value of 1.6. The variation in signal level across maskers makes clear that not all maskers were equally effective. For example, due to the absence of masker energy in the region of the 1000-Hz signal (see Table 1), masker No. 1 provided less masking than the others.

For the primary analysis, the values of d' and c were separately estimated depending on whether the prior trial was a signal or no-signal trial, and this analysis was applied separately for each subject and for each of the 12 maskers tested. As a result, relatively few trials contributed to some of the estimates. Given the total of 600 trials for each masker, half of which were signal trials, and the fact that three signal levels were tested, a midlevel signal trial was preceded, on average, by a midlevel signal trial only 17 times and by a no-signal trial 50 times. For no-signal trials the expected numbers are somewhat improved: a no-signal trial was preceded by a midlevel signal trial 50 times and preceded by a no-signal trial 150 times. The expectation was that even though the number of trials contributing to each value of d' and c may be modest, the large number of maskers (12) and subjects (8) would provide sufficient statistical power to test the hypothesis that there is a change in sensitivity conditional upon whether the prior trial was a signal or a no-signal trial.

3. Results and discussion

Table 3 tabulates the estimates of d' for trials preceded by no-signal (d'_N) and signal (d'_S) trials for each masker and each listener. Figure 1 plots these results as a scatterplot. Results for different subjects are plotted using different symbols and for each subject the results for 12 maskers are plotted separately using only one symbol. The diagonal indicates points of equal d', i.e., no effect of the type of the prior trial. The data tend to fall below the diagonal, suggesting superior sensitivity when a trial was preceded by a no-signal than a signal trial. On average the values of d' were 0.3 larger when the trial was preceded by a no-signal trial than when it was preceded by a signal trial (see Table 3).

These results were analyzed using two repeated-measures ANOVAs. For the first ANOVA the random variable was subject identity and the fixed variables coded the preceding trial type and masker identity. For the second ANOVA, the random variable was masker identity and the fixed variables coded the preceding trial type and subject identity. Note that main effects of either subject or masker identity are not meaningful because the signal levels were chosen for different subjects and different maskers—a main effect would simply point to a failure to achieve equal values of d' across subjects and maskers. The interaction terms are, however, of

Table 3. Values of d' for trials preceded by no-signal trials (d'_N) and signal trials (d'_S) are listed for each masker and each subject.

	Subject																	
	S1		S2		S3		S4		S5		S6		S7		S8		AVG	
Masker	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S	d'_N	d'_S
1	1.6	2.3	2.4	1.1	1.5	1.0	1.1	0.6	1.8	2.4	1.6	0.9	2.2	2.2	1.8	1.8	1.7	1.5
2	1.6	1.2	2.7	1.5	2.0	1.5	1.7	1.2	2.4	2.7	2.3	2.0	2.3	2.5	2.2	2.1	2.2	1.8
3	1.0	0.9	0.9	1.3	1.9	2.1	1.5	0.7	2.6	2.8	2.1	1.6	1.4	2.0	1.2	0.6	1.6	1.5
4	1.7	1.6	1.6	0.7	1.7	1.0	2.2	2.2	2.2	2.4	1.8	1.0	2.9	2.3	2.9	3.4	2.1	1.8
5	1.9	1.4	3.5	2.7	1.4	1.3	1.0	1.4	2.1	1.5	1.4	1.4	2.5	2.6	2.1	1.8	2.0	1.7
6	1.6	1.4	2.1	1.5	1.0	1.5	1.8	0.9	0.7	1.2	1.7	1.2	1.9	2.4	2.0	1.8	1.6	1.5
7	1.9	1.6	2.5	1.8	1.4	1.0	1.8	2.1	1.4	1.7	2.1	2.5	1.0	1.0	2.0	1.2	1.8	1.6
8	1.4	1.0	1.6	1.4	0.8	0.8	1.0	0.6	2.1	1.9	0.5	1.7	2.4	1.9	1.8	1.0	1.5	1.3
9	2.3	1.6	1.6	1.5	1.9	2.4	1.7	1.1	1.1	1.9	1.0	1.7	2.5	1.3	1.8	0.9	1.8	1.5
10	1.2	1.0	1.3	1.2	1.6	2.1	1.9	1.7	1.2	0.8	1.6	1.2	2.2	2.8	1.9	2.4	1.6	1.6
11	2.6	1.8	1.3	0.5	1.5	0.3	0.2	0.0	1.8	1.6	2.7	1.7	2.9	2.4	1.7	1.1	1.8	1.2
12	1.7	1.3	1.9	2.0	2.0	1.6	0.8	1.2	0.6	0.0	1.5	0.6	2.1	0.6	2.7	1.4	1.7	1.1
																Grand Average	1.8	1.5

interest in order to evaluate whether the change in sensitivity associated with the type of prior trial (if a change exists) depends on individual differences or masker spectra, respectively.

The former ANOVA indicated a significant effect of the preceding trial type ($F(1,7)=18.7, p<0.005$), but the effect of masker identity and the interaction term were not significant ($p>0.25$). The latter ANOVA indicated a significant effect of the preceding trial type ($F(1,11)=19.1,\ p<0.005$). Additionally there was a significant effect of subject identity ($F(7,77)=2.6,\ p<0.05$) but the interaction term was not significant ($p>0.3$). Thus, the 0.3 shift in d' associated with the properties of the prior trial is statistically significant, and is consistent with expectations associated with auditory enhancement. As a counter point to this finding, Purks *et al.* (1980) failed to reveal a significant effect of prior trials on sensitivity in an identification task.

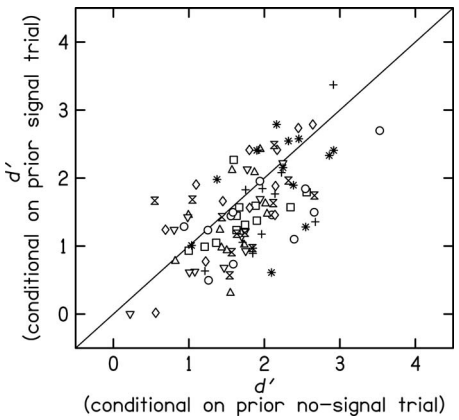

Fig. 1. Values of d' for trials preceded by signal trials (ordinate) and trials preceded by no-signal trials (abscissa) are plotted in a scatter plot. The different symbols are for different subjects. For each subject, the results for 12 maskers are plotted separately.

Next, consider the criteria. Past research has demonstrated both positive and negative sequential effects in detection experiments (e.g., Carterette *et al.*, 1966; Sandusky and Ahumada, 1971). Such phenomena would typically be revealed as a reduction, or increase, in the criterion value relative to neutral, respectively. In the current experiment, however, the value of d' depended on the prior trial. Thus, shifts in "signal" and "no signal" response rates cannot be simply described as changes in criteria because it is unknown how the assumed underlying distributions changed (e.g., do both the signal and no-signal distribution shift depending on the prior trial type?). Nonetheless, we were interested in evaluating whether subjects' criteria placement changed depending on the preceding trial type. A repeated-measures ANOVA was run for the estimated criterion c using subject identity as the random variable and the preceding trial type and masker identity as the fixed variables. Neither the main effects, nor the interaction term, were significant ($p > 0.2$). Thus, listeners' predilection to vote signal did not depend on the prior trial type, although listeners' sensitivity did depend on the prior signal type.

To summarize, the data indicate that for the detection of a tone added to a sparse multitone masker, sensitivity in yes/no trials depends on the prior trial. The effect size was small, a change of 0.3 in d'. Keeping in mind that the maskers tested here were not chosen to maximize the magnitude of the enhancement, the current finding is of particular interest because many types of stimuli tested in psychophysical experiments might, when examined, be found to contain sequential effects.

4. Summary and conclusions

Past work (e.g., Viemeister, 1980) has indicated an enhancement effect in which the detection of a tone added to a masker is improved when a masker is continuous compared to when the masker is pulsed with the signal. Viemeister's results (see also Richards and Neff, 2004) indicate enhancement effects can be quite long-lived, on the order of seconds. This suggests that sensitivity in a yes/no masked detection task might depend on the characteristics of the stimulus in the prior trial. An evaluation of an existing data set thought to reflect energetic, or peripheral, masking confirmed sequential effects of prior trials on sensitivity in a simple yes/no masked detection task. Regardless of whether the masking effects are thought to reflect relatively central or relatively peripheral limitations/processing, there may be value in testing for sequential effects in masked detection experiments when yes/no trials are used.

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