Auditory frequency focusing is very rapid

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The present experiments examine the effect of a weak 40-ms tone burst (cue) on the detection of a closely following 40-ms signal at the same frequency. Detection becomes more difficult as the temporal separation (onset to onset) between them shortens from around 300 ms to under 52 ms. The threshold increase or proximal interference is similar whether signal frequency is constant from trial to trial—frequency certainty—or changing—frequency uncertainty. The increase is also similar whether the cue goes to the same ear as the signal or to the opposite ear. This contralateral interference by such weak cues, only 4 dB SL against a continuous broadband noise, appears to exclude a role for forward masking by the cues. When the preceding tone burst differs in frequency from the signal, threshold increases little at any temporal separation. Combined with earlier results on frequency uncertainty (Scharf, B., \textit{et al.}, 2007, J. Acoust. Soc. Am. \textbf{121}, 2149–2157), the present results show that a listener can shift focusing to an unexpected signal frequency in less than 52 ms. However, the rapidity of focusing is usually obscured by proximal interference, which possibly occurs whenever cue and signal share the same period (~200 ms) of temporal integration.

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I. INTRODUCTION

Weak tonal signals of uncertain frequency are detected at lower levels when preceded by a cue that informs the listener about the frequency, than when not so cued. In fact, cueing makes detection when frequency is uncertain, i.e., the signal frequency changes randomly from trial to trial, as good as when frequency is certain, i.e., the same signal frequency occurs on every trial. For example, Gilliom and Mills (1976) showed that a signal, which was presented 700 ms after a contralateral cue (at the same frequency as the signal), was detected just well when frequency was uncertain as when certain. Precisely how a valid cue facilitates detection is unclear; one favored possibility is that the cue helps the listener to focus on the critical band containing the signal. Indeed, Slaquach and Hafer (1991) showed that in frequency uncertainty, a weak signal preceded 600 ms earlier by an ipsilateral cue was detected when at the same frequency as the cue, but missed when more than half a critical band away. Distinguishing among potential explanations requires some knowledge of the time course of the cuing effect. A complication is the possibility that weak cues sometimes hinder rather than help detection (Scharf \textit{et al.}, 2007). The present paper investigates both the positive and negative effects of ipsilateral and contralateral cues, in both frequency certainty and uncertainty, as a function of the delay of the signal onset relative to the cue onset.


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Scharf \textit{et al.} (2007) showed that an audible but weak ipsilateral cue presented 82 ms before a signal of uncertain frequency (but always at the same frequency as the cue) helped detection but less so than the same cue presented 352 ms before the signal. From 82 to 352 ms, detection improved monotonically with increasing signal delay. We ascribed, tentatively, poor detection at short signal delays primarily to the listener’s inability to focus attention rapidly, i.e., within 50 to 80 ms, on the signal frequency indicated by the cue. As an alternative we suggested that focusing was in fact very fast, but that when presented shortly before a signal, a cue interfered with signal processing, thereby raising threshold. To evaluate this second possibility, we have now repeated our earlier measurements in the presence of ipsilateral cues always at the same frequency as the signal but with frequency certain instead of uncertain. Given the same signal (and cue) on all trials, an increase in threshold with decreasing signal delay would be unlikely to reflect sluggish frequency focusing. Whatever the basis for the interference, its origin in the auditory pathway—whether cochlear or beyond—was elucidated by measuring detection with a contralateral cue in place of the ipsilateral cue, both in frequency certainty and uncertainty. Measurements with a contralateral cue are also relevant to the possible but unlikely role of forward masking in the interference found with an ipsilateral cue. Finally, we made the cue different in frequency from the signal. We could thus determine how the frequency relation between “cue” and signal affects the dependence of detection on signal delay, and also test the possibility that the cue raises threshold by interfering with attention to the signal frequency.

II. GENERAL METHOD

All tones, both signals and cues, lasted 40 ms, which did not include the cosine squared rise time of 7 ms and full time delays.
of 5.3 ms; the equivalent rectangular duration equaled 46 ms. Signals were always presented to the left ear via an earphone, and cues either went also to the left ear or to the right ear. A continuous background of broadband noise was presented binaurally in phase to the two earphones. Noise bandwidth (300–6000 Hz) and spectrum level (12.44 dB) were fixed in experiment 1 but varied in experiment 2 to accommodate different frequency ranges, as indicated below. Signal levels were set relative to the threshold measured, without cues, in the presence of the appropriate noise, at frequencies from 450 to 3400 Hz for each listener in preliminary measurements by a 2AFC procedure with feedback (79% asymptote). Standard deviations of the individual listeners’ thresholds averaged 1.87 dB across frequencies and were always less than 3.0 dB. The cue level was set either 4 or 12 dB higher than the 79% threshold.

The main measurements were made with a single-interval, yes-no procedure. We should have preferred a two-interval, forced-choice procedure. However, the original, published measurements with frequency uncertainty (Scharf et al., 2007) required a single-interval procedure so as to provide a unique and unequivocal measure of the time between the onset of a cue and the onset of the observation interval. The same procedure was used in the present measurements with frequency uncertainty in order to facilitate comparisons among the experiments. In general, frequencies and stimulus levels were chosen to match those in the earlier experiments. Each trial began always with a visual marker (LED) and with a simultaneously presented auditory cue; an observation interval then followed after a delay that was fixed appropriately for each block of trials. On half the trials, a signal was presented—always at the same level above the 2AFC threshold measured previously—during the observation interval, and on the other half, no signal was presented. The listener pressed one of two buttons to indicate whether or not a signal was heard, upon which the correct answer was indicated by an LED above the correct button. Listeners were encouraged to respond quickly, but no limit was placed on the response interval. Analyses of our previous experiments showed no interactions between response times and any of the relevant stimulus variables. Following the response, the next trial began after 850 ms.

Listeners sat in a sound-isolated booth. A Tucker-Davis System III signal processor (RP2.1) generated all sounds, sampled at a rate of 24.4 kHz. A microcomputer (Dell Opti-plex GX270) controlled the processor and collected data via a response box (TDT BBOX). Sounds were sent through a headphone driver (TDT HB7) to Sony MDR-V6 headphones. Waveforms, frequency content, and distortion were checked with a wave analyzer (GRC 1900) and an oscilloscope (Tektronix TAS220). Background noise was generated digitally as if passed through an analog bi-quad band-pass filter.

III. EXPERIMENT 1. THE EFFECT OF IPSILATERAL AND CONTRALATERAL CUES ON DETECTION AS A FUNCTION OF SIGNAL DELAY

Scharf et al. (2007) found that under frequency uncertainty an ipsilateral tonal cue reduced thresholds by as much as 3 to 5 dB compared to thresholds obtained with no cue, provided the cue preceded the signal by more than 200 to 300 ms. (The cue was always at the same frequency as the signal.) At longer signal delays (up to at least 500 ms), cued detection with frequency uncertainty was approximately as good as with certainty. However, at delays shorter than 200 to 300 ms, detection with uncertainty became poorer. As noted above, Scharf et al. (2007) suggested that detection became poorer either because the focusing of attention on the target frequency was relatively slow or because the cue somehow interfered with signal processing. (Of course, both effects are possible.) To assess the relative importance of interference (whatever the mechanism) and focusing, we have now measured detection as a function of signal delay with frequency certain, so the listener should have been focused on the correct frequency on every trial. In addition to ipsilateral cues, contralateral cues were used to shed light on the origin of any observed increase in threshold caused by ipsilateral cues. In all of experiment 1, cue and signal frequencies were the same.

A. Method

Signal frequencies were 500, 1500, and 4000 Hz. Measurements at each frequency were made on separate days. A daily session lasted about 1 h and comprised five blocks with an ipsilateral cue and six blocks with a contralateral cue. In each block of 64 trials, the signal delay, relative to cue onset, was fixed at 52, 82, 122, 212, or 352 ms. In addition, relative to a contralateral cue, the signal was also presented simultaneously (0-ms delay) in phase. Each block had the same signal delay throughout. Signal delays were tested in a different order for each listener. The ipsilateral cues were tested first in half the sessions, and the contralateral cues were first in the other half.

To be sure that signals in the main experiments would be presented at levels at which detection is neither too difficult nor too easy, we sought to set the signal level so that d’ would be somewhat above 1.0. At the beginning of a session, masked thresholds at the frequency to be subsequently tested with contralateral cues and 1.88 ± 0.39 obtained for each listener; their average was used to set the levels of the signals and cues in the main experiment with the yes/no procedure. (We refer to these as 2AFC thresholds to distinguish them from thresholds calculated to yield a d’ of 1.0.) The signal was set to 1 dB above 2AFC threshold at the longer signal delays and to higher levels at the shorter delays in an attempt to keep d’ roughly constant. The cue was set 4 or 12 dB above masked 2AFC threshold, depending on the session. Thus, each listener was run in six sessions (three frequencies by two cue levels). At a given frequency, the 2AFC thresholds changed little over sessions (standard deviation or sd=0.24 dB).

Performance was assessed by calculating the mean d’. The value of d’ was taken as equal to z(H)−z(F) where H is the hit rate and F the false-alarm rate averaged across listeners. Over all frequencies and signal delays, the mean d’ was 1.63 (sd=0.39) with contralateral cues and 1.88 (sd=0.61)
with ipsilateral cues. Aside from two ipsilateral conditions with 4-dB cues, d’ ranged from 0.8 to 2.6. Despite our attempts to maintain d’ constant across signal delay by manipulating signal level, in some conditions d’ increased at longer delays. Therefore, to facilitate comparisons among conditions, from each d’ and associated mean signal level we calculated the level required for d’ to equal 1.0. For these calculations, we assumed that d’ changes with signal level at the rate of 1.0 unit d’ per 3 dB (as in Scharf et al., 2007). Our calculation of the SPL level to reach d’=1 is within 0.3 dB of the calculation based on the assumption that performance changes at the rate of 5% per dB (Green and Swets, 1988, p. 193) and is within 0.5 dB of the calculation based on the assumption that d’ is proportional to energy (Buus et al., 1986). Moreover, for signals preceded by a pulsed noise cue 100 ms earlier, Buus et al. (1986) measured a slope of 5% to 6% per dB, the same as for uncued signals (Green, 1958). Accordingly, we assumed that the same rate of change (1.0 unit d’ per 3 dB) applied across all cue delays. The mean thresholds obtained are shown in the following figures and tables. Repeated-measures ANOVAs required d’’s calculated separately for each listener; on average, these thresholds were 0.4 dB lower than those presented in the figures and tables.

Five listeners served in these experiments. All had normal audiometric thresholds as determined at the Northeastern University hearing clinic and, except for one of two laboratory members, were paid for their services. One of the laboratory members was 34 years old; the other four listeners were under 25 years. All but one had served previously in similar psychoacoustical experiments.

B. Results

The mean signal SPL calculated to yield a d’ of 1.0 is plotted as a function of signal delay in Fig. 1 for each of the three signal frequencies. The means are from the five listeners. Thresholds at 500 Hz are plotted 3 dB higher than measured to compensate for binaural unmasking at low frequencies with an in-phase broadband noise (e.g., Durlach and Colburn, 1978). Data are averaged over the two cue levels of 4 and 12 dB SL, which did not differ significantly (p =0.25). Data are also averaged over ipsilateral and contralateral cues, although their difference was marginally significant (F1,4=4.97, p=0.09) and other results (see below) suggest that contralateral cues are more detrimental than ipsilateral cues. Collapsing data across cue level and lateralization gives prominence to the effects of signal frequency and delay. The main effect of delay was highly significant (F4,16=22.6, p<0.001), showing that the cue interfered with detection at the shorter delays even with frequency certainty. Neither cue level nor lateralization interacted significantly with frequency (p>0.35). For clarity, standard errors, which hovered around 1 dB, are not shown in Fig. 1. Also not shown are the results at a signal delay of 0 ms because no ipsilateral cues were tested at 0 ms. The 0-ms data, which are in line with those at a signal delay of 52 ms, are considered later.

Threshold decreases as the delay between cue and signal lengthens from 52 ms to 352 ms at all three frequencies, but less so as signal frequency increases from 500 to 1500 to 4000 Hz. This interaction between frequency and delay is nearly significant (F8,32=2.19, p=0.055). Although thresholds at none of the three frequencies appear to have reached asymptote at 352 ms, they were no more than 0.8 dB higher than the thresholds measured with no cue by the 2AFC procedure. Moreover, measurements on a different group of listeners with the signal delayed 552 ms yielded thresholds as low as the 2AFC thresholds. Accordingly, it appears that threshold reaches asymptote when signal delay is between 352 and 552 ms.

Figure 2 combines the three signal frequencies and two cue levels to show how threshold depends on signal delay.
with ipsilateral cues as compared with contralateral cues. Except at 52 ms, contralateral cues lead to higher thresholds than do ipsilateral cues. Although this difference is not statistically significant (p=0.09), greater detrimental effects with a contralateral cue were also found in two similar experiments with five other listeners. Given that even a contralateral cue has a negative impact on threshold, the cue-induced threshold increase or proximal interference is likely to be central to the auditory periphery.

C. Discussion

As these measurements were made under full frequency certainty, we cannot ascribe the poorer detection at short delays to the listener’s need for more time to focus on the signal frequency. Except possibly for random perturbations, focusing would have been maintained throughout a block of trials in the present experiments. It follows that the weak cue, which served no cueing function, must have interfered with the processing of the signal when in close temporal proximity. At longer delays, the cue did not hinder (or help) detection since the threshold for a signal delayed 352 ms was nearly the same as in a separate series of measurements for a signal delayed 552 ms or for one presented with no cue (data not shown). We can now determine how much if any of the increase in threshold measured by Scharf et al. (2007) in uncertainty at brief delays can be attributed to slow focusing.

Figure 3 compares threshold changes measured under frequency certainty (filled symbols), based on the present data, to changes measured under uncertainty (unfilled symbols, from Scharf et al., 2007). The differences plotted in Fig. 3 are based on thresholds calculated for $d' = 1$ in the same manner as described above. The uncertainty data come from two experiments, in both of which the cue and signal frequency were always the same but changed randomly from trial to trial. Thresholds with ipsilateral cues are from Scharf et al. (2007) for the signals at low, middle, and high frequencies that were closest in value to those used in the present experiment (500, 1500, and 4000 Hz). Thresholds with contralateral cues are from a replication of the measurements of Scharf et al. with binaural noise in place of monaural noise and contralateral cues in place of ipsilateral cues. Because in the experiments with certainty and with uncertainty, the listeners were different and the signal frequencies were not quite the same, threshold differences are plotted instead of thresholds. (Thresholds are given in Table I below.) The differences plotted are the threshold at each respective signal delay minus the threshold at the longest delay of 352 ms. As the cue in the earlier uncertainty measurements was 8 dB above threshold whereas it was 4 dB or 12 dB in the present certainty measurements, we have averaged the differences plotted.

![Figure 2](image-url)  
**FIG. 2.** Threshold as a function of signal delay, plotted separately for contralateral and ipsilateral cues, but averaged over 4-dB and 12-dB cue levels, from experiment 1 in which signal frequency was certain and equal to cue frequency.

![Figure 3](image-url)  
**FIG. 3.** Changes in threshold at low, middle, and high frequencies as a function of delay. Measurements were made under frequency certainty (filled symbols) with the cue and signal the same and fixed throughout a block of trials and under frequency uncertainty (open symbols) with the cue and signal always the same but changing unpredictably from trial to trial. Data have been averaged over ipsilateral and contralateral cues. For clarity, differences have been increased 3 dB at the high frequencies and decreased 3 dB at the low frequencies.
TABLE I. Signal SPL for $d' = 1.0$ with frequency certainty (present measurements with cue and signal frequency the same and constant throughout a session) and with uncertainty (from Scharf et al., 2007, with cue and signal frequency the same but randomly changing throughout a session). With uncertainty, the low frequencies were those from Scharf et al.’s lowest of their eleven frequency groups whose means were 632 and 767 Hz; the middle frequencies were from their three middle frequency groups with means at 1266, 1481, and 1720 Hz; the high frequencies came from the two highest groups with means at 2693 and 3140 Hz. Signal delays in the 100-ms range were, with certainty, 102 and 122 ms, and with uncertainty, 152 and 212 ms. At a delay of 52 ms with uncertainty, a different group of listeners (results in italics) was tested than at the other delays. At a delay of 0 ms, measurements were made only with contralateral cues.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Contralateral</th>
<th>Ipsilateral and contralateral cues, averaged</th>
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<tbody>
<tr>
<td></td>
<td>Certainty</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>500</td>
<td>38.3</td>
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</tr>
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</tr>
<tr>
<td>High</td>
<td>41.0</td>
<td>38.3</td>
</tr>
</tbody>
</table>

A direct comparison of the thresholds measured in the different experiments is provided in Table I. These thresholds were the basis for the differences plotted in Fig. 3. The threshold values in the table were averaged across ipsilateral and contralateral cues for signal delays from 352 to 52 ms. The values for certainty in the table are the same as those plotted in Fig. 1 and were averaged across the cue levels of 4 and 12 dB. New are the thresholds at 0 ms, which are not given in the figures because they were measured with only contralateral cues. Moreover, the italicized thresholds at 52 ms with uncertainty were measured on new listeners who were not the same as for the rest of the table.

Table I shows that at the longer delays, threshold increases as much as 5 dB when signal frequency goes from 500 to 4000 Hz. This increase is considerably more under frequency certainty than under uncertainty and more than previously found for brief signals like ours (see Dai and Wright, 1996, for a summary). However, it is also more than we found in very similar measurements in certainty with a signal delay of 450 ms (Scharf et al., 2007). Accordingly, we do not believe that the difference between certainty and uncertainty with respect to the dependence of threshold on signal frequency is meaningful.

As to the results at 0 ms, the thresholds are about the same with certainty and uncertainty and in both cases are highest there. The fact that at 0 ms, threshold increased with frequency certainty about as much as with uncertainty suggests that frequency focusing is accomplished in less than 40 ms, the duration of the simultaneous cue and signal. However, interpretation of the data at 0 ms is complicated by interactions between simultaneous tone bursts presented binaurally (represented in our experiments by the contralateral cue and signal). Thresholds are normally some 3 dB lower for such equally-intense binaural signals than for monaural signals (e.g., Chocholle, 1954), a finding that our results, like the 4- and 12-dB data (which did not differ statistically). For the same reason, we averaged data with ipsilateral and contralateral cues from all experiments, both with frequency certain and with it uncertain. In each experiment a given group of listeners was run at all delays. The one exception was the uncertainty measurements with an ipsilateral cue at a delay of 52 ms, which were obtained with five new listeners long after the original measurements by Scharf et al. (2007).

Figure 3 suggests that threshold increases as the signal delay shortens whether frequency is certain or not. The increase did not differ consistently between certainty and uncertainty except at the shortest common signal delay of 52 ms where the threshold increase was greater with frequency certainty than with uncertainty. Accordingly, the threshold increase observed by Scharf et al. (2007)—with uncertainty at signal delays shorter than about 200 ms—most likely reflects some kind of difference from the cue rather than sluggish focusing. To determine if the interaction between delay and certainty was significant, we carried out a 3-way ANOVA with signal delay (52, 82, 122 or 102, and 352 ms) as a within-subject variable, and with certainty versus uncertainty and ipsilateral versus contralateral, as between-subject variables. Thresholds were averaged over frequencies. The interaction of certainty and delay was just significant ($F_{3,3} = 2.84, p = 0.046$); delay did not interact with laterality ($F_{3,3} < 1$), and the triple interaction was not significant ($F < 1$). Since the differences between the measurements made in certainty and uncertainty—differences in listeners, precise frequencies and delays—render a statistical test such as ANOVA less meaningful, the interaction of certainty and delay may not be genuine. However, if indeed a cue interferes more with detection at short signal delays with certainty than with uncertainty, it follows that sluggish frequency focusing is even more strongly excluded as a possible explanation of the interference.
those of Hughes (1940), seem to contradict. Experimental differences probably account for this apparent discrepancy. In particular, most comparisons of binaural and monaural thresholds have been based on separate measurements of the two whereas we, in effect, required listeners to discriminate a binaural tone burst (cue plus signal) from a monaural burst (cue alone).

That frequency focusing appears to take place extremely rapidly is not entirely surprising. After all, the critical band appears to form all but immediately upon auditory stimulation (e.g., Wright and Dai, 1994). However, if frequency focusing is so rapid, why does a signal of uncertain frequency not lead to proper focusing right at or near onset? Why does uncertainty lead to higher thresholds in the first place? The critical difference may be that we presented the cues at least 4 dB above threshold. Hence, the cue was readily detected and could focus listening on the appropriate frequency. Experiments on frequency uncertainty have found that the rise in threshold ascribed to uncertainty is of the order of 3 or 4 dB. This estimation has been arrived at by presenting signals of uncertain frequency at levels some 4 dB higher than the thresholds for the same signals when always at the same, certain frequency. Set 3 or 4 dB higher, signals are strong enough to allow focusing on the correct frequency, thereby overcoming the detrimental effect of frequency uncertainty. Perhaps this is the reason why uncertainty does not lead to still higher thresholds as predicted by most signal-detection theories.

Another interesting outcome concerns the detrimental effect of contralateral cues. Although in the main experiment, the threshold elevation with contralateral cues was, in statistical terms, only marginally \((p=0.09)\) greater than with ipsilateral cues, it was greater at all but one signal delay. Moreover, the contralateral cues were more detrimental in two other experiments. It may well be that the contralateral cues raise threshold more because they draw attention to the wrong ear. Indeed, the contralateral effect could reflect an entirely different mechanism than the ipsilateral effect. However, the results of experiment 2 (see below) suggest that most of the detrimental effect of contralateral cues comes about in the same manner as that of ipsilateral cues.

The question arises as to the possibility that proximal interference is a form of forward masking. Our measurements with an ipsilateral cue are superficially like those of forward masking (e.g., Plack et al., 2006) in which threshold is measured as a function of the delay of a signal relative to a preceding masker (our cue). However, none of those measurements was made against a background of continuous noise as were ours. More important, we measured somewhat greater threshold shifts with a contralateral cue than with an ipsilateral cue whereas no forward masking has been reported at low to moderate masker levels when the masker and signal go to different ears (e.g., Lüscher and Zwislocki, 1949). Finally, little masking would be expected from cues as weak as 4 dB above threshold. In fact, Zwislocki et al. (1959), who appear to be the only investigators to have used maskers as weak as our cues, measured a 2-dB decrease in threshold following a masker at 15 dB SL. Their masker was a 40-ms, 1000-Hz tone; the signal was a 20-ms, 1000-Hz tone that came on 80 ms after masker onset. The decrease in threshold was found for a range of masker durations from 5 to nearly 100 ms, corresponding to signal delays from 45 to 140 ms. Zwislocki et al. (1959) ascribed the decrease in threshold to “sensitization.” This improvement in detection contrasts strongly with the 4- and 2-dB increases in threshold we measured at 500 and 1500 Hz with a 12-dB cue (comparable in level to their 15-dB masker) and a signal delay of 82 ms. Besides the absence of a background noise and the shorter signal duration (20 ms instead of our 40 ms), Zwislocki et al. (1959) used a tracking procedure in which the signal level varied up and down. It is unclear how these differences would lead to poorer detection in one case and to better detection in the other. Perhaps their low-level maskers served as temporal cues which were not otherwise provided, a suggestion made by Rubin (1959). In any case, we conclude that our results cannot be ascribed to forward masking in the traditional sense.

IV. EXPERIMENT 2. THE EFFECT OF IPSILATERAL AND CONTRALATERAL “DISTRACTORS” ON DETECTION AS A FUNCTION OF SIGNAL DELAY.

As shown by the results of experiment 1 with a cue and a following signal always at the same frequency, a weak cue that comes on some 200 ms before signal onset makes the signal more difficult to detect. The difficulty increases as the signal delay decreases so that with a delay of 52 ms, the threshold is as much as 5 dB higher than with a delay of 352 ms. As discussed above, the effect is not some kind of low-level forward masking. Moreover, the interference is the same whether measured with frequency certain, as in experiment 1, or uncertain. Could it be that the cue interferes with the processing of the signal by drawing attentional resources to itself? If so, then replacing the cue by a distractor, i.e., a preceding tone burst that differs in frequency from the signal, may also result in “proximal interference.” On the other hand, if the interference requires close similarity—both spectral and temporal—between cue/distractor and signal, then distractors should raise threshold less than cues whether frequency is certain or uncertain. To test these possibilities, we repeated experiment 1 (frequency certainty) with distractors in place of cues.

A. Method

The yes/no procedure was the same as in experiment 1, as were the durations and signal frequencies, which were set to 500, 1500, and 4000 Hz and tested on different days. The delay of the signal relative to the distractor was also the same with an additional signal delay of 0 ms with ipsilateral distractors. (At 0-ms delay, the distractors and signals were simultaneous.) Accordingly, we tested six delays from 0 to 352 ms with both ipsilateral and contralateral distractors. Whereas in experiment 1 the cue and signal always had the same frequency, which was constant throughout a session, in experiment 2 the distractor frequency changed from trial to trial and differed from that of the constant-frequency signal by at least one critical band. The distractor frequency was chosen at random on each trial from the following ranges:

Five of them had also served in experiment 1. The sixth normal hearing were paid to participate in this experiment. Ipsilateral distractor was presented first. Six women with presented in the first six blocks, and for the other three, the three of the six listeners, the contralateral distractor was pre-

tractor was presented to the same—ipsilateral—ear as the signal was set 1 dB above its 2AFC threshold. A session comprised 12 blocks of 64 trials each. Each block had one of the three signal frequencies which were constant throughout a session both with distractors and cues. Ipsilateral and contralateral presentations have been averaged. Distractors and cues were at 4 dB SL. (N.B. Thresholds at 500 Hz have not been corrected for binaural unmasking.)

TABLE II. SPL (in dB) at threshold measured with the 352-ms signal delay for each of the three signal frequencies which were constant throughout a session both with distractors and cues. Ipsilateral and contralateral presentations have been averaged. Distractors and cues were at 4 dB SL. (N.B. Thresholds at 500 Hz have not been corrected for binaural unmasking.)

<table>
<thead>
<tr>
<th>Signal frequency (Hz)</th>
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<th>1500</th>
<th>4000</th>
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<tbody>
<tr>
<td>Distractor</td>
<td>30.1</td>
<td>35.5</td>
<td>38.8</td>
</tr>
<tr>
<td>Cue</td>
<td>30.0</td>
<td>34.7</td>
<td>37.4</td>
</tr>
</tbody>
</table>

FIG. 4. Threshold as a function of signal delay for 4-dB distractors (frequency is different from that of signal) and for 4-dB cues (frequency is the same as that of signal). Thresholds have been averaged across ipsilateral and contralateral presentations for both cues and distractors. Cue thresholds have been normalized to the distractor thresholds at a signal delay of 352 ms.

265–412 and 602–1132 Hz for a signal at 500 Hz; 570–1163 and 1855–3400 Hz for a signal at 1500 Hz; 2184–3289 and 4720–6800 Hz for a signal at 4000 Hz. To accommodate these ranges, the frequency limits of the continuous masking noise were set for the 500-Hz, 1500-Hz, and 4000-Hz signals respectively to 150–3000 Hz, 300–6000 Hz, and 600–12000 Hz. These bandwidths were chosen to raise the thresholds at all cue frequencies above the levels in the quiet. To have a noise strong enough to raise thresholds at the lowest frequencies, the low-frequency noise was set to 57 dB SPL (spectrum level of 22.44 dB) compared to 50 dB SPL (spectrum level of 12.44 dB) at 1500 Hz. The high-frequency noise was set inadvertently 0.5 dB higher than intended, to 53.5 dB SPL (spectrum level of 12.94 dB).

Each distractor was presented 4 dB above 2AFC thresholds measured in the same way as in experiment 1. The signal was set 1 dB above its 2AFC threshold. A session comprised 12 blocks of 64 trials each. Each block had one of the six signal delays throughout. In half the blocks, the distractor was presented to the same—ipsilateral—ear as the signal; in the other half, it went to the contralateral ear. For three of the six listeners, the contralateral distractor was presented in the first six blocks, and for the other three, the ipsilateral distractor was presented first. Six women with normal hearing were paid to participate in this experiment. Five of them had also served in experiment 1. The sixth listener had served in earlier psychoacoustical experiments.

**B. Results and discussion**

Performance was assessed in the same manner as in experiment 1, by calculating the SPL at which d’ would equal 1.0. Figure 4 gives thresholds from this experiment with distractors (filled symbols) and from experiment 1 with cues (unfilled symbols), at 4 dB SL, as a function of signal delay for the three signal frequencies. (No data are shown here at a delay of 0 ms because measurements were not made with ipsilateral cues.) Results at each signal frequency have been averaged across all distractor frequencies since threshold did not vary consistently as a function of distractor frequency. For example, distractors at frequencies above a 1500-Hz signal raised thresholds on average 0.28 dB more than distractors below, an insignificant difference as shown by a repeated-measures ANOVA (F₁,₅ < 1). Results for ipsilateral and contralateral distractors (and for cues) have been combined; a repeated-measures ANOVA showed no effect of distractor lateralization (whether in the contralateral or ipsilateral ear) on threshold (p = 0.25). For clarity, thresholds at 500 Hz have not been corrected for binaural unmasking as was done for Figs. 1 and 2. Thus, the values shown in Fig. 4 at 500 Hz are approximately 3 dB lower than in the previous figures. Furthermore, to facilitate the comparison of distractors with cues, at each signal frequency we have normalized the cue thresholds to the corresponding distractor thresholds at a delay of 352 ms; these adjustments were small, increasing from 0.1 dB at 500 Hz to 1.4 dB at 4000 Hz, as can be inferred from the actual thresholds in Table II.

Figure 4 shows the same overall relation between threshold and signal delay for distractors as for cues; the closer a preceding distractor is to signal onset, the higher the threshold (F₅,₂₅ = 8.75, p < 0.001 by repeated measures ANOVA). Nonetheless, for the five listeners who served in both experiments 1 and 2, the interference is significantly greater with cues than with distractors (F₁,₄ = 12.77, p = 0.023) as is the dependence of interference on signal delay as shown by the interaction between cue type and delay (F₄,₁₆ = 8.68, p < 0.001).

Table III presents the results of Fig. 4 as the difference between the threshold at a given signal delay and the corresponding threshold at a delay of 352 ms. The results at a delay of 0 ms are now included. Table III shows that thresholds tend to increase more at the 0-ms delay than at the 52-ms delay, but the effect is small and inconsistent. In the discussion of experiment 1, we pointed out that the interpretation of the results with the signal and contralateral cue presented simultaneously, i.e., with a signal delay of 0 ms, is complicated by the role of binaural interaction. Nonetheless, the similarity between the threshold increases at 0 ms and at 52 ms and even at 82 ms suggest that the interference may be based on essentially the same mechanism when cue and signal are simultaneous as when they come within approximately 100 ms of each other.

Experiment 2 makes it clear that a preceding tone burst raises threshold for a signal that is at a fixed frequency and


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that follows within 200 ms even when the preceding burst and the signal are at different frequencies (i.e., the preceding burst is a distractor). However, the interference is notably less than when the preceding burst is a cue, at the same frequency as the signal, as in experiment 1. Since all the distractors in experiment 2 were outside the signal’s critical band, it may be that interference is greater when the distractor frequency falls within the same critical band as the signal. Indeed, several earlier reports do suggest that distractors presented simultaneously with the signal and in the same critical band raise threshold considerably \cite{Chocholle1960, Ingham1959, Sherrick1961}. However, their contralateral tones were generally much louder than ours, a factor that \cite{Chocholle1960} reported to be important; the negative effect of a simultaneous contralateral sound becomes smaller as its level decreases so that at 10 dB SL even distractors near in frequency to the signal caused threshold to increase only 1 to 3 dB, not unlike what we found at 4 dB SL with distractors far from the signal frequency. Moreover, some of our own preliminary results suggest that weak distractors very close in frequency to the signal interfere with detection no more than far distractors. The question of just how near distractors, especially at low levels, affect detection requires more research. On the whole, it is clear from the results in the literature and from those of experiment 2 that in general weak distractors interfere relatively little with detection.

### V. GENERAL DISCUSSION

The results of experiment 1 show that even with signal frequency the same throughout a block of trials, a weak cue begins to interfere with detection when the delay between cue onset and signal onset shortens to less than approximately 200 or 300 ms. The interference is much the same as measured with signal frequency changing randomly from trial to trial \cite{Scharf2007}, as seen in Fig. 3 above. Given the close similarity under frequency certainty and uncertainty, the threshold increase almost surely results from interference by the cue and not from sluggishness in frequency focusing. Accordingly, we interpret these results as showing that frequency focusing requires less than 52 ms (which is the shortest delay at which measurements were made both with frequency certainty and uncertainty), probably considerably less, but that determination requires additional measurements.

What is the basis for proximal interference? Why does a near-threshold tone burst reduce the detection of its repetition at a lower level when the signal delay is less than around 200 ms? As noted above, the finding that the interference is as bad if not worse when the cue is in the contralateral ear excludes any peripheral explanation referring to interaction on the basilar membrane. An explanation in terms of the allocation of attention seems also to be excluded, although less radically, by the finding that the rise in threshold is much smaller when the preceding tone bursts differ in frequency from the signal (at a fixed frequency) than when at the same frequency. In other words, “frequency distractors” do little distracting. Without this result, the finding in experiment 1 that contralateral cues at the same frequency as the signals seem to raise threshold more than ipsilateral cues at the same frequency could have been ascribed to “ear distraction.” Focusing on the wrong ear, the listener is less sensitive to signals in the correct ear. However, the overall contralateral effect is less than 1 dB so that, on the whole, attentional resource allocation appears to play a minor role in our results.

It is also possible that proximal interference has little to do with some kind of active interference but reflects a problem of discrimination. A cue presented alone and a cue presented with a closely following signal become more difficult to distinguish from each other when the cue and signal share the same interval of temporal integration. A cue at 4 dB SL plus a signal at threshold (0 dB SL) would summate to give a sound whose total intensity differs from that of the cue alone by less than a jnd. Presumably, the closer in time the cue and signal, the greater the integration and hence the poorer the detection. The duration of the interval of integration at threshold has usually been taken to be around 200 ms and applies to dichotic as well as to monotic signals (e.g.,

### TABLE III. Increases (in dB) in threshold relative to threshold at a delay of 352 ms, as a function of signal delay at each of three frequencies, for cues and distractors. Signal frequencies were fixed throughout a session at one of the three frequencies indicated, for both cues and distractors. Cues and distractors were at 4 dB SL. Ipsilateral and contralateral presentations have been averaged except for cues (frequency certainty) at a delay of 0 ms where no ipsilateral presentations were tested and so the data are italicized.

<table>
<thead>
<tr>
<th>Signal freq. (Hz)</th>
<th>Signal delay (ms)</th>
<th>Cues</th>
<th>Distractors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>52</td>
<td>82</td>
</tr>
<tr>
<td>500</td>
<td>4.4</td>
<td>5.5</td>
<td>3.2</td>
</tr>
<tr>
<td>1500</td>
<td>7.0</td>
<td>4.3</td>
<td>2.8</td>
</tr>
<tr>
<td>4000</td>
<td>3.5</td>
<td>3.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal freq. (Hz)</th>
<th>Cues</th>
<th>Distractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>1500</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4000</td>
<td>1.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Zwislocki, 1960, 1969. Given that both interference and integration occur within about 200 ms suggests that the two are related.

ACKNOWLEDGMENTS

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