## Auditory frequency-based inhibition differs from spatial IOR

## DAVID J. PRIME and LAWRENCE M. WARD University of British Columbia, Vancouver, British Columbia, Canada

Uninformative auditory frequency cues have a facilitatory effect on reaction time and accuracy of detection and intensity discrimination of target tones for cue–target intervals of up to 3 sec (Green & McKeown, 2001; Ward, 1997). Under some conditions, however, this facilitatory effect can reverse to an inhibitory effect at cue–target intervals longer than 450 msec (Mondor, Breau, & Milliken, 1998). The present work demonstrates that such inhibitory effects are not found in target–target experiments (Experiment 1) or in cue–target experiments requiring a go–no-go discrimination of the target (Experiment 2), whereas they do appear in the paradigm used by Mondor et al. (1998, Experiment 3), albeit unaffected by the similarity of cue and target. Thus, the frequency-based inhibitory effects sometimes found in auditory cuing tasks can be distinguished empirically from those characterizing spatial inhibition of return (IOR), which are found in both target–target and go–no-go cue–target paradigms. The present work and functional and neurophysiological arguments all support the position that different mechanisms underlie spatial IOR and the inhibitory effects sometimes found in auditory frequency processing.

In spatial location cuing studies, it has been found that uninformative stimulus cues can have different effects on response latencies at different cue–target intervals. For relatively short cue–target intervals (<300 msec), subjects respond more rapidly on valid-cue trials than on invalid-cue trials. This facilitatory effect has been attributed to an automatic (exogenous) covert orienting of attention to the cued location that results in more efficient processing of the target (for a review, see Wright & Ward, 1998). In some cases, this facilitation at shorter cue–target intervals is accompanied in the same experiment by an inhibitory effect at longer cue–target intervals in which subjects respond more slowly on valid-cue trials than on invalid-cue trials. This latter effect is called inhibition of return (IOR).

IOR was first observed in visual spatial orienting by Posner and Cohen (1984). In their study, IOR occurred when attention was oriented exogenously by a direct cue, but not when attention was oriented endogenously (voluntarily) in response to a symbolic cue. They also found that IOR occurred with both covert shifts of attention and overt eye movements. Further research has revealed many other properties of visual IOR. The inhibitory effect has been found to last for several seconds after cue onset (Tassinari & Berlucchi, 1995) and to affect simple detection responses (e.g., Posner & Cohen, 1984), localization responses (e.g., Maylor, 1985), and nonspatial discrimination responses (e.g., Pratt, 1995; Pratt, Kingstone, & Khoe, 1997). Like attention, IOR has been shown to affect target detection accuracy (Handy, Jha, & Mangun, 1999) and short-latency ERP components (McDonald, Ward, & Kiehl, 1999). IOR has been associated with the oculomotor system. Rafal, Calabresi, Brennen, and Sciolto (1989) showed that an endogenously prepared saccade can produce IOR even if the saccade is not executed. In addition to its effect on manual responses, IOR can affect the direction (Posner, Rafal, Choate, & Vaughan, 1985) and latency (Abrams & Dobkin, 1994) of saccadic eye movements.

IOR is not an exclusively visual phenomenon. It has been observed in other spatial modalities, including hearing (e.g., McDonald & Ward, 1999; Reuter-Lorenz & Rosenquist, 1996; Schmidt, 1996) and touch (e.g., Tassinari & Campara, 1996). In addition to these within-modality effects, IOR has also been found in cross-modal studies in which the cues and the targets are presented in different sensory modalities (e.g., McDonald & Ward, 2002; Spence & Driver, 1998a). The ubiquitous nature of IOR across many tasks and sensory modalities indicates that the processes underlying IOR are important and general mechanisms in the spatial selection of information.

When Posner et al. (1985) coined the label *inhibition of return* they were naming the empirically observed phenomenon after their theoretical explanation. Posner et al. (1985) explained the opposite cue effects found at shorter and longer cue-target intervals by assuming that the cue causes a transient shift of attention to its location and that, after returning to fixation, attention is subsequently inhibited from returning to the previously cued location. This would bias the visual system to acquire novel information

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at new locations. Although this attentional explanation of IOR remains popular, other mechanisms have been proposed (for reviews, see Klein, 2000; Reuter-Lorenz, Jha, & Rosenquist, 1996; Spence & Driver, 1998a; Taylor & Klein, 1998b). On the basis of evidence that links IOR to saccadic programming, it has been proposed that IOR is generated by the oculomotor system (e.g., Rafal et al., 1989; Rafal & Henik, 1994; Tassinari, Aglioti, Chelazzi, Marzi, & Berlucchi, 1987). It has also been suggested that IOR is the result of a motor bias against responding to stimuli at a previously cued location (Taylor & Klein, 1998b). Current evidence does not unequivocally support any one of these mechanisms. It is possible, even probable, that IOR is produced by several mechanisms that operate at multiple stages of information processing. This theoretical uncertainty is paralleled by inconsistency in the usage of the term IOR; sometimes IOR is used to refer to the empirical effect, and sometimes it used to refer to the underlying mechanism(s).

## Auditory Frequency Orienting and Frequency-Based "IOR"

Given the evidence that IOR is closely related to the spatial attention system, it is possible that an IOR mechanism may exist for any domain in which people are capable of orienting their attention. Although the majority of research on attention orienting has focused on the spatial domain, it has been established that it is possible to selectively attend to a region of auditory frequency space. Detection of a near-threshold pure tone is easier when the listener knows the tone frequency in advance (Greenberg & Larkin, 1968; Johnson & Hafter, 1980; Scharf, Quigely, Aoki, Peachey, & Reeves, 1987). Similarly, informative frequency cues also improve intensity discrimination (Ward & Mori, 1996) and speeded duration discrimination (Mondor & Bregman, 1994) of suprathreshold sounds. Most relevant for the present work, Ward (1997) demonstrated that uninformative direct frequency cues can reflexively orient attention within auditory frequency space. Intensity discrimination responses were faster and more accurate (higher d') on valid-cue trials (cue and target of same frequency) than on invalid-cue trials (cue and target of different frequencies). As with studies of spatial shifts of attention, the greatest reaction time (RT) facilitation was present at the 100msec cue-target stimulus onset asynchrony (SOA), and it decreased with increasing SOA, although facilitation was present even at the longest SOA of 2,050 msec. By contrast, the effect of cue validity on discrimination accuracy did not interact with cue-target SOA; thus, discrimination accuracy was facilitated roughly equally for all SOAs, from 100 to 2,050 msec. Unlike in spatial studies, no IOR was found for either dependent measure at any SOA.

In another series of experiments, however, Mondor, Breau, and Milliken (1998) found more parallels between auditory spatial and frequency cuing. They used a cue– target paradigm to examine the effect of uninformative, direct auditory cues on RTs. In two spatial-cuing experiments, the cues and targets were broadband noise bursts that varied in spatial location, and the subjects were required to detect or to localize the later-occurring noise bursts. In two frequency-cuing experiments, the cues and targets were pure tones that varied in frequency, and the subjects were required to detect or discriminate the frequency of the second of the two tones. In all four experiments, Mondor et al. (1998) found that valid location and frequency cues speeded responses at the shortest SOA (150 msec) and slowed them at the longest SOA (750 msec). Given the parallel pattern of results, the authors interpreted this performance as indicating the operation of both location-based and frequency-based IOR at the longer SOAs. As was mentioned previously, auditory spatial IOR has been observed in other experiments (although not often for a simple detection task; see McDonald & Ward, 1999). However Mondor et al.'s (1998) study was the first to observe both response facilitation and response inhibition in a frequency-cuing experiment. Mondor and his colleagues have since replicated this finding (Mondor, 1999; Mondor & Breau, 1999).

Mondor (1999) proposed a dual-process model of auditory attention orienting to explain facilitatory and inhibitory cue effects in both location and frequency cuing. This model accounts for facilitatory cue effects by assuming that the cue establishes a transient attentional template that results in faster selection of targets on valid-cue trials for short cue-target intervals. The model accounts for inhibitory cue effects by assuming that responses to valid targets are delayed, relative to invalid targets, because of the relative difficulty in distinguishing between the memory representations of cues and targets in the former case. Critically, in order to account for both location and frequency effects, Mondor assumed that both location- and frequency-based inhibitory cue effects arise from the operation of the same mechanism. In addition, by labeling these effects location-based IOR and frequency-based IOR, Mondor implicitly assumed that these inhibitory effects arise from identical, or analogous, mechanisms to those that produce spatial IOR between and within other modalities. The finding that frequency-based IOR is based on identical or analogous mechanisms to those of spatial IOR would have important consequences for theories of attention orienting and IOR. For example, finding a nonspatial form of IOR would be evidence that oculomotor activity is not a necessary prerequisite for the occurrence of IOR. Such a finding would also have implications for explanations of the function of IOR. Because spatial domains and nonspatial domains, such as frequency or color, differ in the type of information they provide, the function of any common mechanism must be related to some function that can be performed within every domain in which the mechanism is found. Such a mechanism would require either a single neuronal system that is capable of serving each domain or multiple functionally equivalent neuronal systems. In order to address these theoretical implications, it is important to establish whether or not frequency-based IOR truly is identical, or at least analogous, to spatial IOR.

#### The Present Study

The purpose of the present study is to make a direct comparison between auditory frequency-based IOR and spatial IOR. If auditory frequency-based IOR and spatial IOR share a common mechanism, the former should respond in a similar way to experimental manipulations. In the first of three sets of experiments, we employed the targettarget paradigm. This paradigm has been used to exclude the possibility that the necessity of inhibiting the response to the cue influences the response to targets that are very similar to the cue. In this paradigm, subjects respond to a series of targets without any intervening cues. Performance on targets that are preceded by identical targets (repeat trials) is compared with performance on targets that differ from the preceding target (*change trials*). Because subjects do not have to withhold their response from targetlike cue stimuli, response inhibition cannot explain any slowing of responses on repeat trials, relative to those on change trials. Because the subject must respond to each target, the target-target SOAs are always long, usually a second or more. IOR is indicated when subjects respond faster on change trials than on repeat trials. Several studies using target-target experiments have demonstrated the existence of spatial IOR in vision (e.g., Maylor & Hockey, 1985, 1987; Posner et al., 1985; Rafal et al., 1989), audition (McDonald & Ward, 1999), touch (Roder, Spence, & Rosler, 2000), and cross-modally (McDonald & Ward, 2002; Spence & Driver, 1998a; Spence, Lloyd, McGlone, Nicholls, & Driver, 2000). In the second experiment, we required subjects to make a decision about whether or not to respond to the target, on the basis of its frequency, reasoning that subjects would have less inclination to prepare a response in advance under these conditions, thus decreasing the likelihood that they would inhibit a prepared response to a highly similar cue. Auditory spatial IOR appears at longer SOAs when subjects make the decision to respond or not on the basis of its spatial location (Mc-Donald & Ward, 1999). Finally, in the third experiment, we replicated Mondor et al.'s (1998) paradigm and manipulated the similarity of the cue and the target. There is also evidence indicating that spatial IOR can occur even when cues and targets greatly differ in their stimulus characteristics and are, therefore, easy to distinguish from one another (e.g., McDonald & Ward, 1999; Posner & Cohen, 1984). The results of these experiments and the existing literature on attention orienting and IOR were used as the basis for comparison necessary to address the following question: Do auditory frequency-based IOR and spatial IOR share the same mechanisms?

## **EXPERIMENTS 1A, 1B, AND 1C**

Some authors have argued that the target–target paradigm provides a definitive test for distinguishing between inhibitory effects arising from the necessity of inhibiting a prepared response to the cue and those arising from spatial IOR (e.g., Maylor & Hockey, 1985; Posner & Cohen,

1984; Spence & Driver, 1998a, 1998b; Spence et al., 2000). In particular, Spence and Driver (1998a) argued that this paradigm is especially useful in auditory IOR studies. In Experiments 1A, 1B, and 1C, we used the target-target paradigm to determine whether the frequency-based inhibitory effect is unique to the cue-target paradigm. In order to avoid confounds resulting from subjects' adopting a response repetition strategy, in which they might be more prepared to make the same response to a current target than to the immediately previous one whenever the two were identical, the subjects were required to make the same simple detection response to the onset of all pure-tone targets. In target-target studies of spatial orienting, some authors have argued that inhibitory effects may be masked by facilitatory effects owing to sustained attention at a previous target location unless steps are taken to reorient attention away from that location before target onset (e.g., Posner & Cohen, 1984). For this reason, many targettarget studies employ a central reorienting event, a second stimulus, different from the targets and never responded to, that is always presented at fixation. Because potential target locations are always equidistant from fixation and reorienting events are never responded to, this location is considered to be neutral. However, there are several difficulties in applying this technique to an auditory frequency target-target experiment. First, there is no equivalent center location in frequency space. Should attention be oriented to another frequency region, or is it necessary for subjects to adopt an unfocused broadband listening state? Second, the logic of using a reorienting event assumes the existence of a unitary focus of attention. This has not been established for frequency orienting, and there is evidence from studies of endogenous frequency orienting that people are able to listen simultaneously to more than one frequency region (Macmillan & Schwartz, 1975; Schlauch & Hafter, 1991; Ward & Mori, 1996). Finally, if a puretone reorienting event is used along with pure-tone targets, the subject's task is no longer a simple detection task but, rather, a go-no-go frequency discrimination task. In order to address these issues, we conducted three different target-target experiments. In Experiment 1A, no reorienting event whatsoever was used between target pairs. In Experiment 1B, a visual warning signal was presented between target pairs. This experiment was used to examine the effect of an irrelevant stimulus in a frequency targettarget experiment. In Experiment 1C, an auditory reorienting event was also presented between the shorter SOA target pairs. The auditory reorienting event consisted of a pure tone, of a different frequency from those of the targets, embedded in broadband white noise. If the inhibitory cue effects observed in frequency cue-target experiments are the result of IOR, an inhibitory effect should be seen on repeat trials, relative to change trials, in these experiments.

#### Method

**Subjects**. Fourteen students (9 female, 5 male) attending the University of British Columbia were paid for their participation. Four

subjects (all female) were excluded from data analysis owing to unacceptably high error rates ( $\sim 25\% - 40\%$ ) in one or more conditions. These high error rates appear to be the result of loss of concentration owing to fatigue. All the subjects (ages, 19–30 years; mean age, 22 years) reported normal hearing and had normal or corrected-tonormal vision.

Stimuli and Apparatus. Stimulus presentation and response recording were controlled by an Intel 486-based microcomputer. All of the experiments were conducted in a darkened, sound-attenuating chamber (183  $\times$  193  $\times$  197 cm) with a background sound level of 35 dB SPL. A speaker was positioned 105 cm directly in front of a chinrest, which was used to minimize head movements. A green light-emitting diode (LED) was positioned in the center of the speaker to serve as a fixation point. Eye movements were monitored by recording the horizontal electro-oculogram (EOG), using tin electrodes placed 1 cm lateral to the left and right outer canthi. The EOG activity was amplified with a bandpass of 0.1-30 Hz and was continuously digitized at a rate of 256 Hz. Electrode impedance was kept below 5 k $\Omega$ . The subjects responded to the onset of a target by pressing a microswitch placed under the index finger of their dominant hand. Response latencies were measured in milliseconds by a custom interval timer.

All of the auditory stimuli were generated by a custom sound generator and were presented from the speaker positioned directly in front of the subjects. Target stimuli were 75 dB (SPL; measured at the ears) pure tones (2000 or 5000 Hz) presented for 50 msec (2.5-msec rise/fall). The *reorienting* event consisted of a 50-msec, 500-Hz pure tone embedded in a background of broadband white noise (0– 10000 Hz), the entire sound at 75 dBA. A 200-msec darkening of the fixation LED served as the visual warning.

**Design and Procedure**. The subjects completed all three experiments in a single 1.5 h-session randomly in one of the three possible orders. Each experiment consisted of 15 blocks of 56 targets. The first block of trials in each experiment was treated as practice and was not analyzed. The subjects were instructed to respond by pushing the response button as quickly as possible to the onset of the targets without making anticipatory responses. In Experiments 1B and 1C, the subjects were informed that irrelevant stimuli that did not require a response would occur between target trials, and they were told to ignore these stimuli. In order to make the experimental task as similar as possible to those used in spatial orienting studies, the subjects were also instructed to fixate on the LED at all times during the block of trials and to blink between target pairs. The subjects' EOGs were monitored to ensure that they complied with these instructions. The sequence of events for Experiments 1A, 1B, and 1C are depicted in Figure 1. In all three experiments, the targets were presented in pairs. The presentation of each pair began with the presentation of the visual warning signal. After a random delay of 800-1,300 msec, the first target in the pair was presented. In Experiment 1A, the second target was presented 600-1,000 msec after the subject responded to the first target. In Experiment 1B, the visual warning signal was presented 300 msec after the subject's response to the first target. The second target in the pair was then presented after a further 100 to 500 msec delay. In Experiment 1C, the sequence of events was identical to that in Experiment 1B, except that the auditory reorienting event was also presented 300 msec after the subject's response to the first target. The presentation of the next pair began after a delay of 1,000 msec after the response to the second target of each pair. Thus, since the average RT was about 250 msec, the target-target SOA varied randomly between about 850 and 1,250 msec within each pair of targets (shorter SOA), and between 2,050 and 2,550 msec between the first trial of each pair and the second trial of the previous pair (longer SOA). Because of differences in RTs, we refer only to these approximate ranges of SOAs,



Figure 1. Sequence of events for a pair of targets in Experiments 1A, 1B, and 1C.

rather than to specific values. Notice that *all* SOAs are in the IOR range.

Target frequency was randomly varied between 2000 and 5000 Hz. RTs were separated for each target–target SOA according to the relationship between the frequencies of successive targets. A trial was classified as a *repeat* trial if the current and preceding targets were of the same frequency. A trial was classified as a *change* trial if the current and preceding targets were of different frequencies.

### Results

The subjects were allowed 600 msec to respond to a target tone; if the subject failed to respond in this interval, the trial was counted as an error and was excluded from analysis. In addition, RTs less than 100 msec or more than three SDs beyond the mean for each condition were also treated as errors. This procedure resulted in the exclusion of 3.1%of the trials in Experiment 1A, 3.7% in Experiment 1B, and 3.9% in Experiment 1C. Inspection of the EOG records showed that eye movements away from fixation rarely occurred and even more rarely coincided with targets (<1% of trials). This was expected, since all the stimuli were presented from the central speaker and no events whatsoever occurred anywhere else. For this reason, eye movements were not used as a basis for excluding trials. Mean RTs were calculated from the remaining data for each subject for all four SOA  $\times$  trial type conditions for each of the three experiments. The means across subjects of these mean RTs and the corresponding mean error rates are shown in Table 1 for both the included and the excluded participants. The mean RTs for included subjects are also depicted in Figure 2. As can be seen, at the shorter SOA in all three experiments, RT to a pure-tone target was shorter when it was of the same frequency as the previous target. No inhibition on repeat trials, relative to change trials, was observed. All of the rejected subjects also demonstrated this pattern of performance.

A 3  $\times$  2  $\times$  2 multivariate analysis of variance (MANOVA) for repeated measures was performed on the mean RT data from these three experiments. The withinsubjects factors were experiment, target-target SOA (shorter and longer), and trial type (repeat and change). This analysis revealed a significant main effect for trial type [F(1,9) = 12.73, p < .01] and a significant SOA  $\times$ trial type interaction [F(1,9) = 22.69, p < .001]. In all three experiments, the subjects responded more rapidly on repeat trials than on change trials at the shorter SOA (850-1,250 msec), but not at the longer SOA (2,050-2,550 msec). Planned comparisons (Bonferroni t tests, familywise error = 0.15) between mean RTs for repeat and change trials at each SOA revealed significant facilitatory effects at the shorter SOA (p < .001 in all three experiments), but not at the longer SOA. The main effects of experiment [F(2,18) = 3.36, p = .057] and SOA [F(1,9) = 4.05, p =.074] approached significance. RTs were longer in Experiment 1C and at the longer SOA in all three experiments. No other effects approached significance. An equivalent analysis conducted on the error rate data found no significant effects.

## Discussion

IOR was not observed in any of these three target-target experiments. In fact, a significant facilitatory effect was found for repeat trials at the shorter SOA. Because a simple detection response and long SOAs were used in these experiments, the results cannot be explained by response repetition effects.<sup>1</sup> The present results are consistent with reports from other auditory frequency attention-orienting studies that show that uninformative frequency cues can facilitate performance for SOAs of up to 2–3 sec (Green & McKeown, 2001; Ward, 1997). However, this result differs dramatically from those of Mondor et al.'s (1998)

Table 1 Mean Response Times (RTs, in milliseconds), Standard Errors (*SEs*), and Percentages of Errors (% E) as a Function of Target Frequency Relationship and Target–Target Stimulus Onset Asynchrony (SOA) in Experiments 1A, 1B, and 1C for Subjects Included in the Analysis (*n* = 10) and for Those Evoluded Owing to High Error Bates in One or More Conditions (*n* = 4)

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		Target–Target SOA						
		Shorter	(850-1,25	50 msec)	Longer (2,050–2,550 msec)			
Experiment	Target Relationship	RT	SE	%E	RT	SE	%E	
	Ι	ncluded (n	= 10)					
1A	repeat	224	11	2.7	243	10	3.4	
	change	241	12	2.8	246	10	3.5	
1B	repeat	218	10	3.2	238	11	2.8	
	change	233	10	3.5	239	11	5.4	
1C	repeat	253	17	4.1	271	21	4.1	
	change	271	18	4.3	279	20	3.2	
	I	Excluded (n	= 4)					
1A	repeat	267	57	11.7	279	67	17.7	
	change	292	65	12.5	284	67	18.5	
1B	repeat	295	66	16.5	315	69	18.0	
	change	310	70	20.0	323	75	21.0	
1C	repeat	290	52	17.2	273	41	11.5	
	change	305	53	19.2	285	44	7.0	



Figure 2. Mean reaction times (in milliseconds) for included subjects as a function of SOA for repeat and change trials in Experiments 1A, 1B, and 1C. Error bars are based on mean-squared error for the interaction from the analysis of variance reported in the text.

simple detection frequency cue–target experiment. These authors found a facilitatory effect at a 150-msec SOA, no significant effect at 450 msec, and an inhibitory effect at 750 msec. It is worth noting that this inhibitory effect was found without the use of a reorienting event. The present results also differ from those of spatial target–target experiments that have demonstrated IOR within vision and audition (e.g. Maylor & Hockey, 1985; McDonald & Ward, 1999). The failure to find inhibitory effects in an auditory frequency target–target experiment indicates that cue–target inhibitory effects arise from a different mechanism than that responsible for spatial IOR.

The experiment factor did not interact with the other factors, indicating that the presence of the visual warning and reorienting event did not affect reliably either the time course or the magnitude of the facilitatory effect. The introduction of an irrelevant visual event in Experiment 1B did not affect performance, but the introduction of the auditory reorienting event in Experiment 1C did result in an overall slowing of RT, indicating that the subjects did attend to the reorienting event. The finding of a facilitatory effect in Experiment 1C indicates that auditory frequency attention is resistant to being reoriented. Rather, it seems likely that the reorienting event established a second focus of attention, resulting in what has been called *multiband listening* in that experiment (e.g., Johnson & Hafter, 1980).

## **EXPERIMENTS 2A AND 2B**

In Experiments 2A and 2B, we introduced a change into the cue-target paradigm that we believed would alter the

tendency of subjects in simple RT tasks to prepare their response before the occurrence of the target. When this happens in cue-target paradigms, the necessity of inhibiting that prepared response when an identical stimulus, the cue, appears before the target does can lead to inhibition at longer SOAs that resembles spatial IOR (e.g., Spence & Driver, 1998a). In the present cue-target experiments, a go-no-go task was used in which the subjects were required to respond (press a button, always the same one) to tones of particular frequencies and to withhold responses to tones of other frequencies. No-go trials, on which no response whatsoever was made, occurred on one third of the trials. We reasoned that adding this implicit frequency discrimination task to the cue-target paradigm would lessen the tendency of subjects to prepare their response before the target had occurred, since they could not know whether they were to respond or not until that event, lessening the possibility of an inhibitory effect's arising from response inhibition to the cue. Moreover, auditory spatial IOR appears readily in this paradigm (McDonald & Ward, 1999), and so it should appear in similar frequency-cuing experiments if auditory frequency-based inhibitory effects share the same mechanism. However, if the two effects do not share the same mechanism, it is possible that inhibitory cue effects will not occur in these experiments.

#### Method

**Subjects**. Twenty-one students attending the University of British Columbia were paid for their participation. Ten subjects (6 female, 4 male) took part in Experiment 2A, and 11 (all female) took part in Experiment 2B. All the subjects (ages, 18–29 years; mean age,

22 years) reported normal hearing and had normal or corrected-tonormal vision.

Stimuli and Apparatus. The apparatus was the same as that used in Experiments 1A, 1B, and 1C. The cue and target stimuli were 75-dB pure tones (1000, 2236, or 5000 Hz) presented for 50 msec (2.5-msec rise/fall). A 500-msec pure tone (276 Hz) was used for error feedback.

Design and Procedure. Experiments 2A and 2B differed only in the specific SOAs used. The subjects completed each experiment in a single 1-h session consisting of 27 blocks of 27 trials. The first 5 blocks of trials in each experiment were treated as practice and were not analyzed. The subjects were instructed to fixate on the LED at all times during a block of trials and to blink between trials. They were also instructed to respond as quickly as possible to the onset of the go targets without making anticipatory responses. At the beginning of each experimental session, the three cue/target tones were presented to the subjects 10 times (5 times in order of ascending frequency and 5 times in descending order). Each trial began with a 150-msec flicker of the fixation LED. After a 550-msec delay, a pure-tone cue was presented, selected at random from the three possible frequencies. After a variable cue-target SOA (150, 550, or 950 msec in Experiment 2A; 150, 750, or 1,500 msec in Experiment 2B), a target tone was presented. The cue tone was completely uninformative with respect to target frequency (random coincidence of cue and target frequencies). The subjects were instructed to respond to the highfrequency (5000 Hz) or the low-frequency (1000 Hz) targets (go trials) but to withhold responses from middle-frequency (2236 Hz) targets (no-go trials). If the subjects responded to a no-go target or failed to respond to a go target within 2,000 msec, the error feedback tone was presented. The intertrial interval was 800 msec.

One third of the trials in each block were no-go trials. Go trials in which targets were preceded by cues of the same frequency were classified as valid-cue trials. Go trials in which targets were preceded by cues of the other go frequency were classified as invalid-cue trials. The remaining go trials, in which the targets were preceded by cues of the middle frequency, were classified as *middle-cue* trials.

#### Results

RTs less than 100 msec or more than three SDs beyond the mean for each condition were treated as errors and were excluded from analysis. This procedure resulted in the exclusion of 5.3% of the go trials in Experiment 2A and 5.7% of the go trials in Experiment 2B. Inspection of the EOG records showed that eye movements away from fixation rarely occurred and even more rarely coincided with targets (<1% of the trials). For this reason, eye movements were not used as a basis for excluding trials. The subjects responded to 11.8% of the no-go trials in Experiment 2A and to 9.9% of the no-go trials in Experiment 2B. Mean RTs were calculated from the remaining data for each subject for all nine SOA  $\times$  cue validity conditions for both experiments. The means across subjects of these mean RTs and the corresponding mean error rates are shown in Table 2. The mean RTs for Experiments 2A and 2B are also shown in Figure 3. No inhibitory effect was found at any SOA in either experiment.

Separate  $3 \times 3$  repeated measures MANOVAs were performed on the mean RT data from Experiments 2A and 2B. Within-subjects factors were SOA (Experiment 2A, 150, 550, and 950 msec; Experiment 2B, 150, 750, and 1,500 msec) and cue type (valid, middle, and invalid). These analyses showed a significant main effect for SOA in both Experiment 2A [F(2,18) = 21.9, p < .0001] and Experiment 2B [F(2,20 = 13.52, p < .001]. In both experiments, RT decreased with increasing SOA. This pattern of performance has previously been interpreted as reflecting a general alerting effect produced by the cue. A main effect of cue validity was found in both Experiment 2A [F(2,18) = 15.2, p < .001] and Experiment 2B [F(2,20) = 12.3, p < .001]. In both experiments, the subjects responded more rapidly on valid-cue trials than on invalid-cue trials and middle-cue trials. The interactions between SOA and cue validity were also significant [Experiment 2A, F(4,36) = 7.9, p < .001; Experiment 2B, F(4,40) = 14.6, p < .001], showing that frequency cuing

Mean Respo as a Function	onse Times (RT of Cue Validity	fs, in Mill and Stin	lisecond 1ulus On	s), Standa set Asynch	rd Errors 1rony (SO	s (SEs), A) in Ex	and Perce	ntages of s 2A, 2B, 3	Errors 3A, 3B,	(% E) and 3C
			Cue–Target SOA							
		150		550			950			
Experiment	Cue Type	RT	SE	%E	RT	SE	%E	RT	SE	%E
2A	valid	610	38	4.3	575	33	3.4	591	34	4.5
	middle	763	41	8.4	654	45	4.5	627	43	4.3
	invalid	773	54	8.4	679	38	5.9	642	37	4.1
			150	750				1,500		
		RT	SE	%E	RT	SE	%E	RT	SE	%E
2B	valid	675	36	5.1	677	30	5.1	667	25	5.4
	middle	818	49	5.6	687	36	3.5	638	28	2.7
	invalid	816	45	10	742	36	6.4	691	34	7.6
		150		450			750			
		RT	SE	%E	RT	SE	%E	RT	SE	%E
3A	valid	327	19	0.6	351	21	0.8	390	22	0.8
	invalid	322	21	0.2	339	21	0.8	372	21	0.8
3B	valid	314	10	0.8	332	13	0.6	367	15	1.0
	invalid	304	11	0.8	320	13	0.6	353	16	0.8
3C	valid	327	12	0.6	330	14	0.8	364	17	0.8
	invalid	331	14	0.6	319	14	0.8	354	16	1.0

Table 2



Figure 3. Mean reaction times (in milliseconds) as a function of stimulus onset asynchrony (SOA) for valid-cue, middle-cue, and invalid-cue trials in Experiments 2A and 2B. Error bars are based on mean-squared error for the interaction from the analysis of variance reported in the text.

affected RTs differently, depending on SOA. In both experiments, the facilitatory effect of cue validity decreased with increasing SOA. To further examine this interaction, planned comparisons (Bonferroni t tests, experimentwise error = 0.10) were made between the mean RTs for validcue and invalid-cue or middle-cue trials at each of the three SOAs used in the two experiments. Caution should be used in interpreting the effect of middle cues on RTs. Middle-cue trials not only differed from valid-cue trials in the relationship between cue and target frequencies, but also differed in that, on middle-cue trials, the cue frequency was a frequency to which the subjects were never required to respond. In Experiment 2A, significant facilitation (shorter RTs on valid-cue trials), relative to both invalidcue and middle-cue trials, was found at all three SOAs. In Experiment 2B, significant facilitation, relative to both invalid-cue and middle-cue trials, was found at the 150msec SOA. In addition, responses on valid-cue trials were significantly faster than those on invalid-cue trials at the

750-msec SOA. No significant effects were found at the longest SOA (1,500 msec) in Experiment 2B.

An equivalent MANOVA run on the error rates for Experiment 2A revealed no significant effects for SOA [F(2,18) = 2.4, p = .12] or cue validity [F(2,18) = 1.7, p = .20] and no interaction [F(4,36) = 1.6, p = .20]. Analysis of the error rates from Experiment 2B revealed a significant effect of cue validity [F(2,20) = 7.2, p < .01]. The subjects made significantly fewer errors on valid-cue trials. No significant effect was found for SOA [F(2,20) = 2.89, p = .08], and there was no significant SOA × cue type interaction [F(4,40) = 1.14, p = .35]. Pairwise comparisons revealed that the subjects made significantly fewer errors on valid-cue trials at the 150-msec SOA in both experiments. These results indicate that the RT results are not due to a speed–accuracy tradeoff.

## Discussion

As in Experiments 1A, 1B, and 1C, no inhibitory effects were found at any SOA in these experiments. Even at the 1,500-msec SOA in Experiment 2, there was a nonsignificant facilitatory effect of the cue. Again, these results differ dramatically from those of Mondor et al. (1998). In their frequency discrimination experiment, Mondor et al. found a facilitatory effect at the 150-msec SOA and an inhibitory effect at the 750-msec SOA. The facilitatory effects at the 150-msec SOA in the present experiments (163 msec in Experiment 2A, 141 msec in Experiment 2B) are of roughly the same magnitude as the effect found by Mondor et al. (143 msec) at the same SOA. For this reason, it is unlikely that a stronger, longer-lasting facilitatory effect of attention is masking the inhibitory effect in our experiments. However, overall RTs were slower in these experiments than they were in the frequency discrimination experiment of Mondor et al. Because the latency of IOR onset has been shown to increase with task difficulty (Klein, 2000; Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997), it is possible that IOR would have been detected if longer SOAs had been used. This is unlikely, however. Studies of visual spatial IOR indicate that the SOAs used in our experiments should have been sufficient to detect IOR if the same relationship holds between RT and IOR onset latency in frequency-cuing experiments as in location-cuing studies (see Figure 4 in Klein, 2000). This assumption seems reasonable if frequency-based IOR shares the mechanism of spatial IOR.

## **EXPERIMENTS 3A, 3B, AND 3C**

The final set of experiments was designed to serve two purposes. First, we wanted to replicate Mondor et al.'s (1998) finding of inhibitory cue effects in a simple detection cue-target experiment. Thus, Experiment 3A is a replication of Mondor et al.'s variable-frequency simple tone detection experiment in all relevant aspects (e.g., tone frequencies and durations, SOAs). The second purpose of these experiments was to examine the effect of cue-target



Figure 4. Mean reaction times (in milliseconds) as a function of stimulus onset asynchrony (SOA) for valid-cue and invalid-cue trials in Experiments 3A, 3B, and 3C. Error bars are based on mean-squared error for the interaction from the analysis of variance reported in the text.

similarity on the inhibitory cue effect. Mondor's (1999) dual-process model predicts that inhibition will be reduced when cues and the targets are easier to distinguish. It is also possible that inhibition of a prepared response when the cue occurs would affect target responses less the more the cue and the target differ. Experiment 3B was identical to 3A, except that cues and targets were made more dis-

tinguishable by making the targets twice the duration of the cues. In Experiment 3C, cues and targets were made even more distinguishable by embedding the cue tones in a background of low-intensity white noise. If the inhibitory cue effect is affected by cue–target similarity, the magnitude of the effect should be progressively reduced in Experiments 3B and 3C. Finding such an effect would further distinguish frequency-based IOR from spatial IOR.

## Method

**Subjects**. Sixteen students (14 female, 2 male) attending the University of British Columbia were paid for their participation. All the subjects (ages, 18–23 years; mean age, 19 years) reported normal hearing and had normal or corrected-to-normal vision.

**Stimuli and Apparatus**. The apparatus was the same as that used in the two previous sets of experiments. In Experiment 3A, cue and target stimuli were 75-dB pure tones (555 or 869 Hz) presented for 100 msec (2.5-msec rise/fall). In Experiment 3B, cue duration was 60 msec, and target duration was 120 msec. In Experiment 3C, cue and target durations were the same as those in Experiment 3B, but the cue stimuli were embedded in a background of broadband white noise (0–10000 Hz) at 75 dBA. A 500-msec pure tone (276 Hz) was used for error feedback.

Design and Procedure. The subjects completed all three experiments in a single 1.5-h session, randomly in one of the three possible orders. Each experiment consisted of 16 blocks of 40 trials. To discourage anticipatory responding, on 10% of the trials no target was presented, and the subjects were required to refrain from responding on these catch trials. Three cue-target SOAs were used in these experiments: 150, 450, and 750 msec. The first block of trials in each experiment was treated as practice and was not analyzed. Subjects' instructions were essentially the same as those in Experiments 2A and 2B, with the exception that the subjects were required to respond as quickly as possible to the onset of a target, regardless of its frequency (a simple detection task). Trials on which targets were preceded by cues of the same frequency were classified as valid-cue trials, and trials on which cues and targets differed in frequency were classified as invalid-cue trials. As in the previous experiments, eye movement was monitored to ensure that the subjects maintained fixation during trial presentation.

#### Results

The error removal procedure was the same as that in Experiments 2A and 2B, resulting in the removal of fewer than 1% of the trials. The rate of false alarm errors on catch trials was also less than 1%. Owing to the low error rate in these experiments, error rates were not analyzed. Mean RTs and error rates for all six SOA  $\times$  cue validity conditions in each experiment are shown in Table 2. Mean RTs for Experiments 3A, 3B, and 3C are also depicted in Figure 4. A  $3 \times 3 \times 2$  within-subjects repeated measures MANOVA (experiment  $\times$  SOA  $\times$  validity) was performed on the mean RTs. There were significant main effects of cue validity [F(1,15) = 16.09, p < .002] and SOA [F(2,30) = 42.69, p < .001]. Overall, the frequency cues had an inhibitory effect on performance; the subjects responded more rapidly on invalid-cue trials than on validcue trials. RTs increased with increasing SOA, the opposite pattern to that usually obtained in the cue-target paradigm, but similar to the pattern found by Mondor et al. (1998). McDonald (1996) also found a slowing of RT with increasing SOA in auditory spatial-cuing experiments. McDonald found that the magnitude of this effect increased with the number of catch trials and proposed that it was due to a strategic suppression of responses on long SOA trials. Because the probability that any particular trial will be a catch trial increases with SOA, subjects may begin inhibiting their tendency to respond in order to avoid false alarm errors. The interaction between SOA and validity also reached significance [F(2,30) = 4.23,p < .03]. As can be seen in Figure 4, the inhibitory effect was larger at the two longer SOAs, as compared with the shortest SOA. Planned comparisons (Bonferroni t tests, familywise error = 0.15) revealed significant inhibitory cue effects at both the 450- and 750-msec SOAs (p < .01for all comparisons) for all three experiments. A significant 10-msec inhibitory effect was found at the 150-msec SOA in Experiment 3B. The effect of cue validity at 150 msec did not approach significance in either Experiment 3A or Experiment 3C. The main effect of experiment and the experiment  $\times$  validity and the three-way interactions were not significant (p > .30 for all comparisons). However, the experiment  $\times$  SOA interaction was significant [F(4,60) = 8.27, p < .001].

### Discussion

Each of Experiments 3A, 3B, and 3C replicated the inhibitory effect found by Mondor et al. (1998) at the 750msec SOA in a simple detection frequency-cuing study. However, none of these three experiments were successful in replicating the facilitation obtained by Mondor et al. at the 150-msec SOA, although the inhibition in our experiments was significantly smaller at that SOA. The same pattern of performance was also obtained in an earlier pilot study that used the same tone stimuli as those that served as the high and low cues and targets in Experiments 2A and 2B.<sup>2</sup> The lack of a facilitatory effect at the 150msec SOA is interesting, given that very similar cues produced large facilitatory effects in Experiments 2A and 2B and, as targets, the facilitatory effect found in Experiments 1A, 1B, and 1C. This result suggests that the inhibitory effect we found in our simple detection cue-target experiment was strong enough to mask the facilitatory effect of attention orienting and that this inhibition was present at least as early as a 150-msec SOA. The fact that inhibitory effects were found at the longer SOAs in these experiments precludes the possibility that the failure to obtain inhibitory effects in the first two sets of experiments resulted from some unknown aspect of the experimental setup or the subject instructions. Finally, the lack of significant interaction effects between Experiments 3A, 3B, and 3C does not provide support for the role of cue-target similarity in modulating the inhibitory effect.

## **GENERAL DISCUSSION**

## Empirical Characteristics of Inhibitory Effects in Frequency Orienting

Mondor et al. (1998) coined the term *frequency-based IOR* because the data from their frequency cue-target ex-

periments resembled those from spatial cue-target experiments. The results of the first two series of experiments in our study clearly demonstrate that frequency-based IOR can be distinguished empirically from spatial IOR. In particular, the failure to obtain an inhibitory effect when the target-target paradigm was used (Experiments 1A, 1B, and 1C) means that response inhibition to the cue cannot be ruled out as a possible mechanism of the inhibitory cue effect found by Mondor et al. In fact, the facilitatory effect found in Experiment 1 is the opposite of the IOR typically found in spatial target-target experiments. Similar visual and auditory spatial-orienting experiments, using both simple detection and localization tasks, have found either no effect or IOR (e.g., Maylor & Hockey, 1985, 1987; Mc-Donald & Ward, 1999; Spence & Driver, 1998a). The results of Experiments 2A and 2B provide additional support for the dissociation of frequency-based IOR and spatial IOR. When the experimental task in a cue-target paradigm requires an implicit frequency discrimination in order to decide whether to respond to a target tone, no inhibitory effect is found. The long-lasting facilitatory effect on RT found in these experiments is consistent with the results of other studies of exogenous frequency orienting that have used accuracy as a dependent measure. Ward (1997) found that uninformative frequency cues improved intensity discrimination accuracy (higher d') for SOAs up to 2,050 msec, and Green and McKeown (2001) found significantly better detection accuracy in a twoalternative forced-choice (2AFC) task for valid, relative to invalid, cues for SOAs of more than 3 sec. These results converge in demonstrating that exogenous frequency orienting usually results in a robust and long-lasting facilitation in processing at the attended frequency. This contrasts with the effects of uninformative spatial cues, which produce a transitory facilitation that is usually followed by inhibition at longer SOAs.

One of the reviewers suggested that a possible reason that inhibition was not found in Experiment 2 is that the subjects could have been using a matching strategy to inform their responses. In this strategy, subjects would classify the *cue* as to whether, had it been a target, it would have been a go or a no-go target. Then, when the target appeared, if it was identical to the cue, a fast response would be made, but if it was not identical to the cue, further processing would be necessary to determine whether it was the other go target or the no-go target. This would produce faster responses on go trials in which the cue and the target frequencies were the same than on trials in which they were different. We believe this strategy was unlikely to have given rise to the results of Experiment 2, for the following reasons. First, the subjects were told to ignore the cue. Second, the frequency discrimination is a difficult one; the RTs are relatively long, around 600-800 msec. There would not be time to categorize the cue before the target occurred at the two shorter SOAs. Because the strategy would not work for most trials and because the subjects could not know which kind of trial it would be at the time the cue was presented, it seems unlikely that they would have adopted such a strategy at all. Finally, the same type of strategy could potentially be used when cues and gono-go task are spatial, but IOR has been found in this case (McDonald & Ward, 1999). Moreover, when cues are spatial and the task is frequency discrimination, no spatial cue effects have been found (McDonald & Ward, 1999; Spence & Driver, 1994). Thus, we contend that the absence of inhibitory effects in Experiment 2 converges with their absence in Experiment 1 in the implication that frequencybased inhibitory effects do not arise from the same mechanism as does spatial IOR.

# Possible Mechanisms for Inhibitory Effects in Frequency-Cuing Experiments

Frequency-based IOR can be distinguished empirically from spatial IOR. This conclusion is concordant with other research that has failed to find convincing evidence for nonspatial IOR in vision (Kwak & Egeth, 1992; Taylor & Klein, 1998a; but see Law, Pratt, & Abrams, 1995). This evidence that inhibitory cue effects found in auditory frequency-cuing and location-cuing experiments may arise from different mechanisms is incompatible with the dual-process model proposed by Mondor (1999). That model is based on the assumption that inhibitory effects in both location- and frequency-cuing experiments arise from difficulties in distinguishing between the memory representations of the cues and the targets. However, this mechanism remains a plausible explanation for the inhibitory effects found in some auditory frequency-cuing studies and may also contribute to inhibitory effects found in auditory spatial-cuing studies when identical cue and target stimuli are used. Nonetheless, the dual-process model, as proposed by Mondor, has difficulty explaining several empirical findings. First, it is unclear why listeners should have to distinguish between cue and target memory representations in a simple detection experiment. Because the listener gives the same response on each trial, a simple counting strategy should suffice (i.e., respond to the second sound on each trial). Second, McDonald and Ward (1999) obtained auditory spatial IOR, using a gono-go localization task with cues and targets that were highly distinguishable from each other (cues and targets differed in intensity, duration, and spectral composition). This finding suggests that neither response inhibition nor cue-target similarity are necessary to obtain auditory spatial IOR. Third, no inhibitory effect was found in Experiments 2A and 2B in the present study despite the fact that cues and targets were pure tones of identical duration and intensity and, therefore, difficult to distinguish from each other. Finally, the dual-process model states that auditory selection is always based on both location and frequency (location and frequency are codominant in guiding selection). However, McDonald and Ward (1999) found that uninformative auditory spatial cues influenced RTs for spatial tasks, but not for simple detection or for frequency discrimination tasks. The same cue and target stimuli were used in all three types of experiments; only the subjects' task differed.

As was mentioned above, another possible source of inhibitory effects in a cue-target experiment is response inhibition to the cue (Harvey, 1980). In a typical cue-target experiment, subjects are instructed to respond as rapidly as possible to the target but to refrain from responding to the cue that precedes it at various SOAs. The response inhibition hypothesis proposes that subjects must voluntarily inhibit their tendency to make a motor response to the cue and that this inhibition may persist and slow the response to the target. It is assumed that the amount of persisting response inhibition affecting the response to the target is greater the more similar the cues and the targets are, leading to slower responses on valid-cue trials, in which cues and targets are more similar, than on invalid-cue trials, in which they differ in a critical feature. According to this account, the typical pattern of opposite cue effects at shorter and longer SOAs would be explained by assuming that a transient attention orientation facilitates performance at shorter SOAs but that this initial facilitation dissipates, leaving only the influence of response inhibition at longer SOAs. As originally proposed, response inhibition was assumed to involve the vetoing of a motor preparation program. However, response inhibition could potentially operate at any stage of processing between perception and response production. For example, it is possible that response inhibition could operate by inhibiting a link between perceptual representations and motor processes.

The response inhibition account of inhibitory cue effects is, in many ways, similar to that of Mondor's (1999) dual-process model. Both models assume that inhibitory cue effects arise because subjects must rapidly distinguish between cues, which must be ignored, and targets, which must be responded to. For both models, the degree of cuetarget similarity is the critical factor in determining performance on long SOA trials. However, they differ with respect to when this inhibition first occurs. The response inhibition account proposes that the inhibition starts during processing of the cue, whereas the dual-process model proposes that the inhibitory effect is caused by processes that occur after target presentation.

Although there is evidence that response inhibition can cause inhibitory cue effects (e.g., Spence & Driver, 1998a), there is abundant evidence that spatial IOR does not arise from this mechanism alone. This evidence comes mainly from the results of experiments using the target-target paradigm (see the introduction). The response inhibition hypothesis, however, does provide a plausible explanation for the inhibitory effect on RT found in some frequency cue-target experiments. Inhibition of a prepared response to the cue could occur in both simple detection and discrimination cue-target experiments but should not occur in target-target experiments, as we found in the present study. Response inhibition should also be reduced or eliminated in cue-target experiments that require a go-no-go discrimination, again as we found here. It is also possible that this effect contributes to inhibitory cue effects found in spatial-cuing studies in which cue and target stimuli are

highly similar. However, Mondor and Breau (1999) reported inhibitory effects in both location- and frequencycuing experiments, using both RTs and errors as dependent measures. In these experiments, subjects responded more slowly and made more errors on valid-cue trials, relative to invalid-cue trials, at an SOA of 750 msec. These results contrast with those of Ward (1997) and Green and McKeown (2001), who found that valid uninformative frequency cues increased accuracy even at much longer SOAs. It is unclear why the results of these studies differ, but Mondor and Breau's error rate results indicate that the inhibitory effects on RT found in their experiments are not due to response biases. If, as originally conceived, response inhibition slows RT because the activation of a motor program is delayed, accuracy should not be affected. However, accuracy measures may reflect the processing involved in decision making and responding when speeded responses are required (Santee & Egeth, 1982). For example, Tipper, MacQueen, and Brehaut (1988) found, in a study of negative priming, that subjects were slower and made more errors when a keypress response was required than when a verbal response was required. Tipper et al. interpreted their results as indicating that the inhibition associated with negative priming is confined to processing stages linking perception and action. Similarly, if listeners in cue-target experiments inhibit their response to cue stimuli by inhibiting the link between the cue's perceptual representation and later decision-making processes that initiate the manual response, accuracy could be affected. Because the perceptual representations of the cue and the target will be more similar on valid trials than on invalid trials, response selection may be more delayed in the validcue case than in the invalid-cue case. When response selection is delayed, the targets' perceptual representations may decay (see Luck et al., 1994)-the longer the delay, the more accuracy will be decreased. Although Mondor (1999) did not directly address this issue, a similar argument may be made with respect to response selection delays arising from difficulties in distinguishing cue and target memory representations. The dual-process model and the response inhibition hypothesis, however, do make different predictions regarding the results of accuracy measures in experiments that do not require speeded responses. The dual-process model predicts that discrimination accuracy should be equally affected in experiments requiring both speeded and nonspeeded responses. In both cases, listeners must distinguish between cue and target representations, and therefore, response selection will be equally delayed in the two situations. By contrast, the response inhibition hypothesis predicts that no inhibitory effect on accuracy should be found in experiments requiring nonspeeded responses. The nonspeeded accuracy results obtained by Green and McKeown, using a 2AFC detection task, are consistent with the response inhibition explanation. The response inhibition hypothesis also predicts that no inhibitory effect on accuracy (or RT) should be found in frequency-orienting target-target discrimination experiments.

Both the response inhibition account and the dualprocess model explanations of frequency-based inhibitory effects in cue–target experiments also predict that inhibitory effects should decrease as overall similarity between cues and targets decreases. However, this effect was not found in Experiment 3. Thus, we do not feel that there is any definitive explanation of inhibitory cue effects in auditory frequency-cuing experiments at this time.

## **Implications for Theories of IOR**

Inhibitory effects have been observed for some nonspatial attributes of irrelevant cues (e.g., color IOR, Law et al., 1995; semantic inhibition, Fuentes, Vivas, & Humphreys, 1999; auditory features, Mondor & Lacey, 2001). If IOR functions by biasing attention orienting, it is possible that a form of IOR may exist for every domain in which people are able to selectively orient attention. However, if research is going to converge in uncovering the mechanisms responsible for the IOR effect, it is important that different effects with different underlying causes be distinguished from each other. The approach taken in the present study was to compare spatial IOR and frequencybased inhibitory effects under a variety of experimental conditions. The lack of correspondence between the frequency and spatial effects indicates that these effects do not arise from the same underlying mechanism.

Psychological phenomena can also be distinguished from each other on the basis of their brain mechanisms and purpose. The case for the existence of nonspatial IOR also would be weakened if it could be demonstrated that the neural mechanisms involved in spatial IOR are not involved in producing nonspatial inhibitory effects. Although the neural basis of spatial IOR has not yet been determined, there is converging evidence that the superior colliculus (SC) is involved. The SC is a midbrain oculomotor structure that seems to be involved in producing covert shifts of attention (Posner & Petersen, 1990). Evidence for SC involvement in the production of IOR comes from many sources, including studies of infants (Simion, Valenza, Umiltà, & Dalla Barba, 1995; Valenza, Simion, & Umiltà, 1994), normal and brain-damaged adults (Posner et al., 1985; Rafal et al., 1989; Rafal, Posner, Friedman, Inhoff, & Bernstein, 1988; Sapir, Soroker, Berger, & Henik, 1999), and single-cell recordings in monkeys (Dorris, Everling, Klein, & Munoz, 1998; cited in Klein, 2000).

Although research into the neural basis of IOR has provided considerable evidence that the SC is involved in the production of visual spatial IOR, the neural mechanisms responsible for auditory, tactile, and cross-modal IOR remain relatively unexplored. Despite the lack of direct evidence, several authors have proposed that the SC may also be involved in the production of nonvisual IOR (e.g., McDonald & Ward, 1999; Reuter-Lorenz & Rosenquist, 1996; Spence & Driver, 1998a). These arguments are based on the results of neurophysiological research into the structure and function of the SC (for a review, see Stein & Meredith, 1993). This research has demonstrated in several species that visual, auditory, and somatosensory

signals converge in the deeper layers of the SC. In addition to separate maps for each modality, the deeper layers of the SC contain multimodal maps in which inputs from different sensory modalities interact. The sensory receptive fields in these different maps are roughly aligned with each other, and together, these maps form a comprehensive representation of multimodal space. This multimodal architecture makes the SC a likely candidate for a common neural substrate responsible for all spatial IOR effects. Could the SC also contribute to the production of nonspatial inhibitory effects? Neurophysiological evidence indicates that it could not. For example, auditory neurons in the SC specialize in encoding location and are very broadly tuned for frequency (Stein & Meredith, 1993). Given these response characteristics, it is unlikely that SC neurons could selectively modulate processing of auditory signals in sufficiently narrow frequency ranges to account for frequency-based inhibitory effects. Even if spatial IOR and nonspatial inhibitory mechanisms were to share some other neural substrate, they would still be different phenomena to the extent that the nature of IOR depends on the characteristics of the SC.

Regarding the functional purpose of IOR, Posner and colleagues (Posner & Cohen, 1984; Posner et al., 1985) proposed that IOR maximizes the acquisition of novel information by encouraging the sampling of new locations in the visual field. Klein (1988) extended this position by proposing that IOR may function to facilitate visual search by aiding the observer in avoiding reinspecting previously attended locations. Klein's (1988) results indicated that an inhibitory tag was associated with the searched locations. This functional interpretation is supported by evidence that IOR can be observed at more than one location (Danziger, Kingstone, & Snyder, 1998; Wright & Richard, 1996). Klein and MacInnes (1999) have provided additional support for this *foraging facilitation* hypothesis. At the present time, there is no evidence indicating that nonspatial forms of inhibition aid search processes.

#### Conclusion

Although considerably more research will be required to determine precisely the mechanisms responsible for inhibitory effects in auditory frequency-cuing studies, the present work clearly demonstrates that this effect can be empirically distinguished from spatial IOR. A major issue for future empirical and theoretical work is to determine which inhibitory effects arise from the same underlying mechanisms.

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#### NOTES

1. Facilitatory response repetition effects can occur when choice RT tasks are used; that is, RTs to stimuli that are the same as the preceding stimulus, requiring the same response, are faster than those to stimuli that are different, requiring a different response. In addition, when the response–stimulus interval is greater than 1 sec, an alternation effect is often found; the RTs to stimuli that are the same as the preceding stimulus are slower than RTs to those that are different (e.g., Kirby, 1976).

2. In this pilot study (n = 9), the cue and target stimuli were 75-dB pure tones (1000, 2236, or 5000 Hz) presented for 50 msec (2.5-msec rise/fall). In all other respects, this experiment was identical to Experiments 3A, 3B, and 3C. An equivalent analysis to that performed on Experiments 3A, 3B, and 3C revealed significant main effects for both SOA (p < .001) and validity (p < .03) and a significant interaction between these two factors (p < .001). Paired comparisons revealed a significant inhibitory effect at both the 450- and the 750-msec SOAs (p < .001 for both comparisons). The 2-msec inhibitory effect at 150 msec was not significant (p > .65).

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