Frequency-based IOR is not "True" IOR

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Abstract

Auditory frequency cues can influence attention orienting in auditory frequency space; cues that match targets in frequency have a facilitatory effect on reaction time and accuracy for cue-target intervals of up to two seconds (Ward, 1997). Mondor, Breau, and Milliken (1998) found that this facilitatory effect can reverse to an inhibitory effect at cue-target intervals longer than 450 msec under some conditions. Mondor et al. referred to this effect as frequency-based Inhibition of Return (IOR). The present work demonstrates that inhibitory effects are not found in frequency target-target experiments (Experiment 1) or in cue-target experiments in which the experimental task reduces the probability that response inhibition to the cue will affect reaction time (Experiment 2). These results show that frequency-based IOR can be empirically distinguished from spatial IOR and that inhibitory effects in frequency cue-target experiments may arise from response inhibition to the cue. The present work, as well as functional and neurophysiological arguments, support the position that the term IOR should be reserved for inhibitory spatial effects.

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Introduction

At any given moment an individual may be exposed to a multitude of stimuli from all sensory modalities. Researchers have identified a number of facilitatory and inhibitory mechanisms that allow people to select relevant information for further processing. A number of experimental paradigms have been developed to study how people process and respond to stimuli. One such paradigm that has been used extensively is the cue-target paradigm. In this paradigm participants are presented with a cue stimulus followed by a target to which a response is required. This paradigm has been used with both symbolic cues (e.g., arrows indicating a location) and stimulus cues (e.g., luminance transients, sudden sounds). In the stimulus cue case, the cues and targets vary along a feature of interest (e.g., spatial location, color, auditory frequency). Trials on which the cue and target match on the feature of interest are called *valid-cue* trials and trials on which the cue and target differ on that feature are called *invalid-cue* trials. When the proportion of valid trials is greater than that of invalid trials, the cues are said to be informative. When valid and invalid cues are equally likely the cues are said to be uninformative. In the case of spatial cueing, it has been found that uninformative stimulus cues often have a biphasic effect on response latencies. If the time interval between cue and target is short (<300 msec), participants respond more rapidly on valid-cue trials relative to 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 early facilitation is followed 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 has been labeled Inhibition of Return (IOR).

Inhibition of Return

Inhibition of return was first observed in visual spatial orienting by Posner & Cohen (1984). They demonstrated that IOR occurs when a stimulus cue is used but not when attention is covertly oriented in a voluntary (endogenous) manner in response to a symbolic cue. They also demonstrated that IOR occurs with both covert shifts of attention and overt eye movements. Further research has revealed many of the properties of the IOR phenomenon. 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 and Khoe, 1997). Like attention, IOR has been shown to affect target detection accuracy (Handy, Jha, & Mangun, 1999) and early ERP components (McDonald, Ward & Kiehl, 1999). IOR has also been associated with the oculomotor system. Rafal et al. (1989) have demonstrated 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 et al., 1985) and latency (Abrams & Dobkin, 1994) of saccadic responses.

IOR is not an exclusively visual phenomenon and the effect has been observed in other spatial modalities, including audition (e.g., Schmidt, 1996; McDonald & Ward, 1999; Reuter-Lorenz & Rosenquist, 1996) and somatosensation (e.g., Tassinari & Campara, 1996). In addition to these within modal effects, IOR has also been found in cross-modal studies in which the cues and targets are presented in different sensory modalities (e.g., McDonald & Ward, 2000; 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) labeled the inhibitory cue effect found by Posner and Cohen (1984) Inhibition of Return they were naming the empirically observed phenomenon after their theoretical explanation. Posner et al. explained the biphasic pattern of cue effects 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 cued location. These authors suggested that this mechanism would be useful by biasing the visual system to acquire novel information at new locations. Although this attentional explanation of IOR remains popular, other mechanisms have been proposed (for reviews see Taylor & Klein, 1998a; Reuter-Lorenz, Jha & Rosenquist, 1996; Spence & Driver, 1998a; Klein, 2000). Based on evidence that links IOR to saccadic programing, it has been proposed that IOR is generated by the oculomotor system (e.g., Rafal et al., 1989; Rafal & Henik, 1994; Tassinari et al., 1987). It has also been suggested that IOR is the result of a motor bias against responding to stimuli at the cued location (Taylor & Klein, 1998a). Current evidence does not unequivocally support any one of these mechanisms. In fact, it is possible, even probable, that IOR is produced by a number of 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 if the tone is of an expected frequency than if the tone frequency is uncertain (e.g., Greenberg & Larkin, 1968). Providing a cue that indicates the frequency of the target tone improves detection performance to about the level obtained when there is no frequency uncertainty (Johnston & Hafter, 1980; Scharf et al. 1987). Frequency cueing has also been shown to improve performance on discrimination tasks with suprathreshold stimuli. Informative frequency cues improve accuracy (higher d') in intensity discrimination tasks (Ward & Mori, 1996) and improve reaction time for discriminating sound duration (Mondor & Bregman, 1994). Most relevant for the present work, Ward (1997) demonstrated that uninformative stimulus frequency cues can reflexively orient attention within auditory frequency space. Intensity discrimination responses were faster and more accurate (higher d') for validly cued targets than for invalidly cued targets. As with studies of spatial shifts of attention, the greatest reaction time (RT) benefit was present at 100 msec post cue and decreased with increasing cue-target intervals. By contrast, the effect of cue validity did not interact with cue-target stimulus onset asynchrony (SOA) and discrimination accuracy was facilitated for SOAs as long as two seconds. However, unlike spatial shifts, no inhibitory cue effects were found for either dependent measure at any cue-target interval.

In a series of experiments, Mondor, Breau and Milliken (1998) further explored the parallels between spatial and frequency cueing. They used the cue-target paradigm to examine the effect of uninformative auditory stimulus cues on response times. In two spatial cueing experiments the cues and targets were broadband noise bursts that varied in their spatial location and the participants were required to detect or localize the target. In a second

pair of frequency cueing experiments the cues and targets were pure tones that varied in frequency and the participants were required to detect or discriminate the frequency of the target. In all experiments, Mondor et al. observed a biphasic pattern of RT data. Valid location and frequency cues facilitated performance at the shortest SOA (150 msec) and inhibited performance 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. As mentioned previously auditory spatial IOR has been observed in other experiments (although not for a simple detection task, see McDonald & Ward (1999)). However Mondor et al.'s (1998) study was the first time a biphasic pattern has been observed in a frequency cue-target 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 that attempts to explain the observed facilitatory and inhibitory cue effects in both location and frequency cueing. This model is an extension of an earlier model presented by Mondor, Zatorre and Terrio (1998) that provided an account of only the facilitatory effect. In the first stage of the Dual-Process model selection of stimuli for high level processing is achieved by comparing the stimulus representation (an auditory stream constructed by auditory scene analysis (e.g., Bregman, 1990)) to an attentional template. The template can be set endogenously or exogenously. The speed of selection is determined by the degree to which the stimulus representation matches the attentional template. Importantly, Mondor proposed that the attentional template is specified by sound location and frequency. The basis for this proposal is evidence provided by Mondor et al. (1998) that location and frequency information cannot be used independently to guide selection (for evidence that the effects of

auditory location cues are task dependent see McDonald & Ward (1999)). After a stimulus representation has been selected, it enters an auditory short term memory store from which processes that determine action can access it. The sooner the stimulus enters the memory store the sooner a response can be made. This model accounts for facilitatory cue effects by assuming that the cue establishes an attentional template which results in faster selection of validly cued targets. Moreover, because the attentional template decays rapidly (<300 msec) this facilitatory effect is transient. In the second stage of this model, memory representations must be differentiated from each other in order to make the appropriate response. The model accounts for the inhibitory cue effects by assuming that because cues and targets are more similar (or even identical) on valid-cue trials than on invalid-cue trials, distinguishing between the two takes longer on valid-cue trials. It is assumed that this effect is masked by the facilitatory effect of the attentional template for valid trials at short SOAs.

Critically, in order to account for both location and frequency effects, Mondor has presupposed that both the location and frequency based inhibitory cue effects that he has observed arise from the operation of the same mechanism. In addition, by labeling these effects location-based IOR and frequency-based IOR, Mondor has implicitly assumed that these inhibitory effects arise from the same, or analogous, mechanisms as those that produce spatial IOR between and within other modalities. If frequency-based IOR is based on identical or analogous mechanisms as spatial IOR, this finding has important consequences for the development of 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 the spatial domain and non-spatial 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 a form of IOR.

Although the biphasic pattern of RT performance found by Mondor and his colleagues has often been viewed as evidence of the occurrence of IOR, other explanations are possible. One possibility is that the inhibitory effect arises as a result of *response inhibition* to the cue (Harvey, 1980). In a typical cue-target experiment participants are instructed to respond as rapidly as possible to the target but to refrain from responding to the cue. The response inhibition hypothesis proposes that participants 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. If the degree of response inhibition to the target is greater when the cues and targets are more similar then responses to validly cued targets will be more inhibited than responses to invalidly cued targets. According to this account, the typical biphasic pattern of cue effects would be explained by assuming that a transient attention orientation facilitates performance at short SOAs but this initial facilitation dissipates, leaving only the influence of response inhibition at later 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 representations.

The response inhibition account of inhibitory cue effects is in many ways similar to that of Mondor's Dual-Process model. Both of these 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 cue-target 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 while 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 is not the result of response inhibition to the cue. This evidence mainly comes from the results of experiments using the target-target paradigm (also referred to as response-response or continuous-responding paradigms). Because subjects do not have to withhold their response from target-like cue stimuli, response inhibition cannot explain the results of target-target experiments. In this paradigm participants respond to a series of targets without any intervening cues. Performance on targets that are preceded by identical targets (match trials, equivalent to valid-cue trials) is compared to performance on targets that differ from the preceding target (change trials, equivalent to invalid-cue trials). Because the subject must respond to each target the SOAs are long. IOR is indicated when subjects respond faster on change trials than on repeat trials. Many 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) and crossmodally (McDonald & Ward, 2000; Spence & Driver, 1998a). There is also a great deal of evidence indicating that

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 Present Study

The purpose of the present study is to make a direct comparison between "frequency-based IOR" and spatial IOR. If frequency-based IOR is a form of IOR then it should respond in a similar way to experimental manipulations. In the first of three sets of experiments I employed the target-target paradigm to investigate the possibility that response inhibition could account for the inhibitory effects found in some frequency cue-target experiments. In the second and third experiments I employed the cue-target paradigm to further investigate the nature of frequency cueing. The existing literature on attention orienting and IOR was used as the basis for comparison necessary to address the question: Is frequency-based IOR "true" IOR?

Experiments 1A, 1B, 1C

Some authors have argued that the target-target paradigm provides a definitive test for distinguishing between inhibitory effects due to manual response inhibition and "true" IOR (e.g.; Maylor & Hockey, 1985; Posner & Cohen, 1984; Spence & Driver, 1998a, 1998b). In Experiments 1A, 1B, and 1C, I used the target-target paradigm to determine whether the inhibitory effect of frequency cues is unique to the cue-target paradigm. In order to avoid confounds resulting from participants adopting a response repetition strategy, participants were required to make a simple detection response to the onset of pure-tone targets. In studies of spatial orienting some authors have argued that inhibitory effects may be masked by facilitatory effects due to sustained attention at the cued location unless steps are taken to

reorient attention away from the cued location before target onset (e.g., Posner & Cohen, 1984). For this reason many studies employ a central "reorienting" event, a second stimulus 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 participants 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 at more than one frequency region (Macmillan & Schwartz, 1975; Schlauch & Hafter, 1991; Ward & Mori, 1996). Finally, if a pure tone reorienting event is used along with pure tone targets, the participant's task is no longer a simple detection task but rather a go-nogo frequency discrimination task. In order to address these issues I 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 target-target experiment. In Experiment 1C, an auditory reorienting event was presented between the short inter-stimulus interval (ISI) target pairs. The reorienting event consisted of a pure tone, of a different frequency from that of the targets, embedded in broadband white noise. If the inhibitory cue effects observed in frequency cue-target experiments are the result of IOR then an inhibitory effect should be seen on match trials relative to change trials in these experiments.

Method

Participants.

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 due to unacceptably high error rates (>40%) in one or more conditions. These high error rates appear to be the result of loss of concentration due to fatigue. All participants (ages 19-30 years; mean age 22 years) reported normal hearing and had normal or corrected to normal vision.

Stimuli and Apparatus.

Stimulus presentation and response recording were controlled by an x86-based microcomputer. All of the experiments were conducted in a darkened, sound-attenuating chamber (183 cm × 193 cm × 197 cm) with a background sound level of 35 dB SPL. A speaker was positioned 90 cm directly in front of a chin-rest, which was used to minimize head movements. A green light-emitting diode was positioned in the center of the speaker to serve as a fixation point. Eye movements were monitored by recording the horizontal electrooculogram (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 continuously digitized at a rate of 256 Hz. Electrode impedance was kept below 5 kΩ. Participants 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.

A custom sound generator was used to produce all of the auditory stimuli. Target stimuli were 75-dB (SPL; measured at the ears) pure tones (2000 Hz or 5000 Hz) presented

for 50 msec (2.5-msec rise/fall). The "reorienting" event consisted of a 50ms pure tone (500

Hz) embedded in a background of broadband white noise (0-10,000 Hz). A 200 ms darkening

of the fixation LED served as the visual warning.

Design and Procedure

Participants completed all three experiments in a single 1.5 hour session. The order of

experiments was partially counterbalanced across participants. 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. Participants were instructed to respond as quickly as possible to the

onset of the targets without making anticipatory responses. In order to make the experimental

task as similar as possible to those used in spatial orienting studies, participants were also

instructed to fixate on the LED at all times during the block of trials and to blink between

target pairs. The participants' EOG was 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 800-1300

ms the first target in the pair was presented. In Experiment 1A the second target was

presented 600-1000 ms after the participant responded to the first target. In Experiment 1B,

the visual warning signal was presented 300 ms after the participant's response to the first

target. The second target in the pair was then presented after a 100-500 ms delay. In

Experiment 1C the sequence of events was identical to Experiment 1B except that the

auditory reorienting event was also presented 300 ms after the participant's response to the

first target. The presentation of the next pair began after a delay of 1000 ms. Thus, the

response-stimulus interval (RSI) varied randomly between 600-1000 ms within each pair of

targets, and between 2000-2500 ms between different pairs of trials.

Target frequency was randomly varied between the two possible values. Reaction times (RTs) were separated for each RSI according to the relationship between the frequencies of successive targets. An RT was classified as a Repeat trial if both the current and preceding target were of the same frequency. An RT was classified as a Change trial if the current and preceding trial were of different frequencies.

Results

Participants were allowed 600 msec to respond to a target tone; if the participant failed to respond in this interval the trial was counted as an error and excluded from analysis. In addition, RTs less than 100 msec or more than 3 SDs beyond the mean for each condition were also treated as errors. This procedure resulted in the exclusion of 3.1% of 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. For this reason eye movements were not used as basis for excluding trials. Mean RTs were calculated from the remaining data for each participant for all 4 RSI x Trial Type conditions for each of the three experiments. The means across participants of these mean RTs and the corresponding mean error rates are shown in Table 1. The mean RTs are also depicted in Figure 2. As can be seen, at the short RSI in all three experiments, RT to a pure-tone target was facilitated when it was of the same frequency as the previous target. No inhibition on match trials relative to change trials was observed.

A 3x2x2 multivariate analysis of variance (MANOVA) was performed on the mean RT data from these three experiments. The within-participant factors were experiment, RSI (short and long), and trial type (match and change). This analysis revealed a significant main

effect for trial type [$F(1,9) = 12.73$, $p < .01$] and a significant RSI x trial type interaction [$F(1,9) = 22.69$, $p < .001$]. In all three experiments participants responded more rapidly on match trials than on change trials at the short RSI but not at the long. Planned comparisons (Bonferroni t-tests, familywise error = .15) between mean RTs for match and change trials at each RSI revealed significant facilitatory effects at the short RSI ($p < .001$ in all three experiments) but not at the long RSI. The main effects of experiment [$F(2,18) = 3.36$, $p = .057$] and RSI [$F(1,9) = 4.05$, $p = .074$] approached significance. RTs were longer in Experiment 1C and at the long RSI in all three experiments. No other effects approached significance. An equivalent analysis conducted on the error rate data found no significant effects.

Discussion

The results of these experiments demonstrate that uninformative frequency cues do not cause inhibitory effects in a simple detection target-target experiment. In fact a significant facilitatory effect was found for match targets at the short RSI. This result is consistent with reports from other frequency attention studies that show that uninformative frequency cues can facilitate performance for SOAs of up to 2 seconds (Ward, 1997). Moreover, these results contrast strongly with those of Mondor et al.'s simple detection frequency cue-target experiment. These authors found a facilitatory effect at 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 current 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 a frequency target-target experiment indicates that these effects arise from a different

mechanism than that responsible for spatial IOR. These results are consistent with a response inhibition explanation for the inhibitory effect found in some frequency cue-target experiments.

The experiment factor did not interact with the other factors indicating that the presence of the visual warning and reorienting event did not affect 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 auditory reorienting event in Experiment 1C did result in an overall slowing of RT indicating that the participants 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, possibly because the reorienting event established a second focus of attention.

Experiment 2A-2B

The purpose of Experiments 2A and 2B was to test the response inhibition hypothesis by using an experimental task that would be less susceptible to this effect. Because button pressing is not an instinctual response to the sudden onset of tones, participants would only have had to actively inhibit responding to cue stimuli if they had adopted a strategy of being highly prepared to respond to auditory stimuli. This strategy could increase performance on tasks requiring a speeded response. In these cue-target experiments a go-nogo task was used in which participants were required to respond to tones of certain frequencies and to withhold responses to tones of other frequencies. I expected that participants would be less likely to adopt a strategy that would require them to inhibit their responses to cue stimuli in this task for two reasons. First, participants did not know if they would be required to respond on a given trial until after the target was presented and they had discriminated its frequency.

Second, because participants were required to respond to only 2/3 of the targets and none of the cues they would only have responded to 1/3 of the tones presented in these experiments. If this is the case, inhibitory cue effects due to response inhibition should not be found.

Method

Participants

Twenty-one students attending the University of British Columbia were paid for their participation. Ten participants (6 female, 4 male) took part in Experiment 2A and 11 (all female) took part in Experiment 2B. All participants (ages 18-29 years; mean age 22 years) reported normal hearing and had normal or corrected to normal 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 Hz, 2236 Hz 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. Participants completed each experiment in a single 1 hour 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. Participants were instructed to fixate on the LED at all times during the block of trials and to blink between trials. They were also instructed to respond as quickly as possible to the onset of the targets without making anticipatory responses. At the beginning of each experimental session the three cue/target tones were presented to the participants 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 SOA (150, 550, 950 msec in Experiment 2A; 150, 750, 1500 msec in Experiment 2B), a target tone was then presented. The cue tone was completely uninformative with respect to target frequency (random coincidence of cue and target frequencies). Participants were instructed to respond to the high (5000 Hz) or low (1000 Hz) frequency targets (go trials) but to withhold responses from middle (2236 Hz) frequency targets (no-go trials). If subjects responded to a no-go target or failed to respond to a go target within 2000 msec the error feedback tone was presented. The inter-trial 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

Reaction times less than 100 ms or more than 3 SDs beyond the mean for each condition were treated as errors and excluded from analysis. This procedure resulted in the exclusion of 5.3% of go trials in Experiment 2A and 5.7% of go trials in Experiment 2B. Inspection of the EOG records showed that eye movements away from fixation rarely occurred. For this reason eye movements were not used as basis for excluding trials. Participants responded to 11.8% of the no-go trials in Experiment 2A and to 9.9% of no-go trials in Experiment 2B. Mean RTs were calculated from the remaining data for each participant for all 9 SOA x Cue Validity conditions for both experiments. The means across participants of these mean RTs and the corresponding mean error rates are shown in Table 2.

The mean RTs for Experiments 2A and 2B are shown in Figure 3. No inhibitory effect was found at any SOA in either experiment.

Separate 3x3 repeated-measures MANOVAs were performed on the mean RT data from Experiments 2A and 2B. Within-participant factors were SOA (Experiment 2A: 150, 550, and 950 msec; Experiment 2B: 150, 750, and 1500 msec) and cue type (valid, invalid, and middle).These analyses showed a significant main effect for SOA in both Experiment 2A [$(F(2,18) = 21.9, p < 0.0001$] and Experiment 2B [$F(2,20 = 13.52, p < 0.001$]. 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 [$F(2,18) = 15.2, p < 0.001$] and Experiment 2B [$F(2,20) = 12.3, p <0 .001$]. In both experiments, participants 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 [$F(4,40) = 14.6, p < .000001$]) showing that frequency cueing 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 = .10) were made between the mean RTs for valid-cue and invalid-cue or middle-cue trials at each of the three SOAs used in the two experiments. A note of caution must be made with regards to 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 they also differed in that the cued frequency is a frequency that participants were not required to respond to. In Experiment 2A, significant facilitation (shorter RTs on valid-cue trials), relative to both invalid-cue 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 150 msec SOA. In addition, valid-cue trials were significantly faster than invalid-cue trials at the 750 SOA. No significant effects were found at the longest SOA (1500 msec) in Experiment 2B.

An equivalent MANOVA run on the error rates for Experiment 2A revealed no significant effects for SOA [$F(2,18) = 2.4$, $p = 1.2$], cue validity [$F(2,18) = 1.7$, $p = .20$] or their interaction [$F(4,36) = 1.6$, $p = .20$]. Analysis of the error rates from Experiment 2B revealed a significant effect of cue validity [$F(2,20) = 7.2$, $p < .01$]. Participants made significantly fewer errors on valid-cue trials. No significant effects were found for SOA [$F(2,20) = 2.89$, $p = .08$] or the SOA x cue type interaction [$F(4,40) = 1.14$, $p = .35$]. Pairwise comparisons revealed that subjects made significantly fewer errors on valid-cue trials than on invalid-cue trials at the 150 msec SOA in both experiments. These results indicate that the RT results are not due to a speed accuracy trade-off.

Discussion

As in the previous set of experiments no inhibitory effects were found at any SOA. Even at the 1500 msec SOA there was a non-significant facilitatory effect observed between valid-cue and invalid-cue trials. Again, these results contrast strongly with those of Mondor et al. (1998). In their frequency discrimination experiment Mondor et al. found an early facilitatory effect that reversed to an inhibitory effect by 750 msec SOA. The facilitatory effects at 150 msec SOA (163 msec in Experiment 2A, 141 msec in Experiment 2B) in the current experiments are of roughly the same magnitude as the effect found by Mondor et al. (143 msec). For this reason it is unlikely that the facilitatory effect of attention is masking the

inhibitory effect in these experiments. However, overall RTs were slower in these experiments compared to the frequency discrimination experiment of Mondor et al. Because the latency of IOR onset has been shown to increase with task difficulty (Luipiáñez et al., 1997; Klein, 2000) it is possible that IOR would have been detected if longer SOAs had been used. This possibility is unlikely. Studies of visual spatial IOR indicate that the SOAs used in these experiments should have been sufficient to detect IOR (see Figure 4 in Klein, 2000) if the same relationship holds between RT and IOR onset latency in frequency cueing experiments as in location cueing studies. This assumption seems reasonable if frequency-based IOR is truly IOR.

It is difficult to see how Mondor's Dual-Process model can account for the results of these two experiments. According to this model, inhibition is observed because participants must distinguish the cue from the target. The fact that participants do not know if they are required to respond until after they have determined the target frequency should be irrelevant. However, in accordance with prediction, the results of the experiments do support the response inhibition hypothesis in that no inhibition was found when the decision to respond was based on a discrimination of a characteristic of the target.

Experiments 3A, 3B and 3C

The final set of experiments was designed to serve two purposes. First, I attempted to replicate Mondor et al.'s finding of inhibitory cue effects in a simple detection cue-target experiment. Experiment 3A is a replication of Mondor et al.'s frequency detection experiment in all relevant aspects (e.g. tone frequencies and duration, SOAs). The second purpose of these experiments was to examine the effect of cue-target similarity on the inhibitory cue effect. Mondor's Dual-Process model would predict that inhibition would be

reduced when cues and targets are easier to distinguish. It is also possible that response

inhibition to the cue would affect target responses less when the cue and target differ.

Experiment 3B is identical to 3A except that the targets were 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 then 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

Participants.

Sixteen students (14 female, 2 male) attending the University of British Columbia

were paid for their participation. All participants (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 Hz 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 duration were the same as in

Experiment 3B but the cue stimuli were embedded in a background of broadband white noise

(0-10,000 Hz). A 500 msec pure tone (276 Hz) was used for error feedback.

Design and Procedure.

Participants completed all three experiments in a single 1.5 hour session. The order of

experiments was partially counterbalanced across participants. Each experiment consisted of

16 blocks of 40 trials. To discourage anticipatory responding, on 10% of trials no target was present and participants were required to refrain from responding on these catch trials. Three 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. Participant instructions were essentially the same as those in Experiments 2A and 2B with the exception that participants were required to respond to the onset of a target regardless of its frequency (a simple detection task). Trials in which targets were preceded by cues of the same frequency were classified as valid-cue trials and trials in which cues and targets differed in frequency were classified as invalid-cue trials. As in the previous experiments, eye movement was monitored to ensure subjects maintained fixation during trial presentation.

Results

The error removal procedure was the same as in Experiments 2A and 2B, resulting in the removal of less than 1% of trials. The rate of false alarm errors on catch trials was also less than 1%. Due to the low error rate in these experiments, error rates were not analyzed. Mean RTs and error rates for all 6 SOA x Cue Validity conditions in each experiment are shown in Table 2. Mean RTs for Experiments 3A, 3B, and 3C are depicted in Figure 4. A 3x3x2 within participant repeated measures MANOVA (experiment x SOA x validity) was performed on the mean RTs. The main effects of cue validity [$F(1,15) = 16.09$, $p < .002$] and SOA [$F(2,30) = 42.69$, $p < .000001$] significant. The frequency cues had an inhibitory effect on performance, participants responded more rapidly on invalid-cue trials than on valid-cue trials. RTs increased with increasing SOA, the opposite pattern to that usually obtained in the cue-target paradigm. 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 compared to the shortest SOA. Planned comparisons (Bonferroni t-tests, familywise error = .15) revealed significant inhibitory cue effects at both the 450 and 750 msec SOAs (p < .01 for 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 3C. The main effect of experiment as well as the experiment x validity and 3-way interactions were not significant (p > .30 for all comparisons). However the experiment x SOA interaction was found to be significant [$F(4,60) = 8.27$, $p < .0001$].

Discussion

All of these experiments replicated the inhibitory effect found by Mondor et al. (1998) in a simple detection frequency cueing study. However, none of these three experiments were successful in replicating the biphasic pattern of performance obtained by Mondor et al. (1998). The lack of a facilitatory effect at 150 msec SOA is interesting given that very similar cues produced large facilitatory effects in discrimination experiments and, as targets, the facilitatory effect found in Experiments 1A, 1B, and 1C. This result suggests that the inhibitory effect present in a simple detection cue-target experiment is strong enough to mask the facilitatory effect of attention orienting and that this inhibition is present at least as early as 150 msec SOA. The fact that inhibitory effects were found at the late 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 participant instructions. 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. However, no firm conclusions can be drawn on this issue on the basis of the

current data.

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 experiments resembled those of spatial cue-target experiments. The

results of the first two series of experiments in this study clearly demonstrate that frequency-

based IOR can be distinguished empirically from spatial IOR. In particular, the failure to

obtain an inhibitory effect using the target-target paradigm (Experiments 1A, 1B, 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. (1998). In fact, the facilitatory effect found in

this study is the opposite to the results 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;

McDonald & Ward, 1999; Spence & Driver, 1998a). The results of Experiments 2A and 2B

provide additional support for the response inhibition explanation for frequency-based

inhibition. When the nature of the experimental task does not encourage the use of a strategy

that would require inhibiting a tendency to respond to the cue, 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 2050 msec and Green and

McKeown (2000) found significantly better detection accuracy in a two alternative forced

choice (2AFC) task for valid relative to invalid cues for SOAs of more than three seconds.

These results converge in demonstrating that exogenous frequency orienting 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 sometimes followed by inhibition.

Is frequency-based IOR "true" IOR?

It is difficult to determine which empirical inhibitory effects are due to IOR and which are not because it has not yet been established what IOR is. If IOR functions by biasing attention orienting then 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 the term not be overgeneralized to describe many different effects with different underlying causes. I propose that three criteria should be used to evaluate whether or not frequency-based IOR exists. First, the empirically observed frequency-based inhibitory effects should closely resemble the effects of spatial IOR under a variety of experimental conditions. Second, if frequency-based IOR exists, it should serve the same purpose as spatial IOR. Finally, the inhibitory frequency and spatial effects should be produced by the same, or analogous, brain mechanisms. The results of the current study demonstrate that empirical frequency-based inhibitory effects do not closely parallel spatial IOR. In the following I will address the second and third criteria.

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 to avoid reinspecting previously

attended locations. Klein (1988) tested this proposal by examining detection responses to probe stimuli presented after the participants had searched an array of items. Participants responded more slowly to probes presented at previously searched locations relative to locations that had not contained a search item. The magnitude of this difference was greater when the search task required a serial allocation of attention to each item than when the task could be performed in a parallel manner. These results indicate 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). Klein and MacInnes (1999) have provided additional support for the foraging facilitation hypothesis. Participants searched a complex visual scene for a camouflaged target and were required to detect and foveate probe stimuli presented during the search. More time was required to fixate probes that were presented near a previously fixated location relative to other locations.

There are several differences between audition and vision that make a frequency foraging mechanism unlikely. Although the visual scene changes over time, a great deal of information about an object can be obtained in a single fixation. This includes such dynamic characteristics as rate and direction of motion. Conversely, acquiring information from auditory sources often requires sustained attention over time (e.g.; speech). Bregman (1990) proposed that auditory information from multiple sources is grouped into auditory streams over time. Sequences of sounds in the same frequency region are often generated by a single environmental event. The processing of sounds in such an auditory stream will be more efficient if the initial sound in the stream attracts attention to the appropriate frequency region. Because auditory information is often conveyed by changes over time attention must

be sustained for some time before the relevance of the sound source becomes evident. For this reason it is not surprising that, under some circumstances, exogenous frequency orienting can result in a long-lasting facilitation of both accuracy and RT. In fact a mechanism, such as frequency-based IOR, that reduces the efficiency of processing stimuli of the same frequency would seem to be disadvantageous. In addition, any utility that frequency-based IOR might have would be severely reduced if the listener is able to monitor several different frequency regions at one time. Indeed, as mentioned previously, there is evidence that listeners are capable of monitoring at least four different frequency regions (Schlauch & Hafter, 1991). This ability has a great deal of utility because natural auditory sources typically produce sound at several different frequencies. For example, speech sounds typically contain three or formants. Moreover, the cost of misallocating attention to one frequency region would be substantially reduced if the listener is able to simultaneously attend to other frequency regions.

The case for the existence of frequency-based IOR would also be weakened if it could be demonstrated that the neural mechanisms involved in spatial IOR are not involved in producing inhibitory effects in frequency space. Although the neural basis of IOR has not yet been determined there is converging evidence that the superior colliculus (SC) is involved in the production of IOR. The SC is a midbrain oculomotor structure that is part of the retinotectal pathway. In addition to its role in producing saccadic eye movements, evidence indicates that the SC is also 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, normal and brain damaged adults, and single cell recordings in monkeys. Studies of infants have demonstrated that visual IOR is presented

before complete cortical development (Valenza, Simion, & Umilta, 1994). In addition, SC involvement in IOR is indicated by temporal versus nasal hemifield asymmetries in the magnitude of IOR. Under monocular viewing conditions the IOR effect is larger in the temporal hemifield for both adults (Rafal et al., 1989) and infants (Simion et al., 1995). SC involvement is implicated by these studies because the nasal portion of the retina, corresponding to the temporal portion of the visual field, has more input to the SC than the temporal portion of the retina. Furthermore, IOR is reduced or eliminated in individuals with damage to the SC (Posner et al., 1985; Rafal et al., 1988). Finally, Dorris et al. (1998; cited in Klein, 2000) have found that neurons in the monkey SC responded much less vigorously to targets presented at previously cued locations than to targets presented at uncued locations.

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 crossmodal 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. The question currently under consideration is whether or not the SC could also contribute to the production of a frequency-based IOR. Neurophysiological evidence indicates that it could not. 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 frequency-based IOR 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.

Implications for Theories of IOR and Auditory Attention

Spatial IOR can be distinguished from frequency-based IOR empirically, functionally and on neurophysiological grounds. For these reasons the term frequency-based IOR may be a misnomer. This conclusion is concordant with other research that has failed to find convincing evidence for nonspatial IOR in vision (Kwak & Egeth, 1992; Taylor & Klein, 1998b; but see Law, Pratt, & Abrams, 1995). IOR appears to be a multimodal but solely spatial mechanism. This evidence that inhibitory cue effects found in auditory frequency and location cueing experiments may arise from different mechanisms is incompatible with the Dual-Process model proposed by Mondor (1999). This model is based on the assumption that inhibitory effects in both location and frequency cueing experiments arise from difficulties in distinguishing between the memory representations of the cues and targets. However, this mechanism remains a plausible explanation for the inhibitory effects found in some frequency cueing studies and may also contribute to inhibitory effects found in auditory spatial cueing studies when identical cue and target stimuli are used. Nonetheless the Dual-

Process model, as proposed by Mondor (1999), 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 go-nogo localization task with cues and targets that were highly distinguishable from each other (cues and targets differed in intensity, duration, and spectral make up). 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 current 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 co-dominant in guiding selection). However, McDonald and Ward (1999) found that uninformative auditory spatial cues influenced RTs for spatial but not for simple detection nor for frequency discrimination tasks. The same cue and target stimuli were used in all three types of experiments, only the participants' task differed.

The response inhibition hypothesis also provides a plausible explanation for the inhibitory effect on RT found in some frequency cue-target experiments. Response inhibition could occur in both simple detection and discrimination cue-target experiments but not in target-target experiments. Response inhibition should also be reduced or eliminated in cue-target experiments that require a go-nogo discrimination. It is also possible that this effect contributes to inhibitory cue effects found in spatial cueing studies in which cue and target

stimuli are highly similar. However, Mondor and Breau (1999) have reported inhibitory effects in both location and frequency cueing experiments using both RTs and errors as dependent measures. In these experiments participants 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 (2000) 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 (1999) error rate results indicate that the inhibitory effects on RT found in these experiments are not due to response biases. If, as originally conceived, response inhibition slows RT because the activation of a motor program is delayed, then accuracy should not be affected. However, accuracy measures may reflect 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 participants were slower and made more errors when a keypress response was required compared to 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. Similarily, 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 representation of the cue and target will be more similar on valid than on invalid trials, response selection may be more delayed in the valid-cue 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 due to difficulties in distinguishing cue and target memory representations. However, the Dual-Process model and the response inhibition hypothesis 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 non-speeded 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 non-speeded responses. The non-speeded accuracy results obtained by Green and McKeown (2000) 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.

Conclusion

Although considerably more research will be required to determine the mechanisms responsible for inhibitory effects in frequency cueing studies, the present work clearly demonstrates that this effect can be empirically distinguished from spatial IOR. These results, and the functional and neurophysiological arguments presented above, support the position that the term IOR should be reserved for inhibitory spatial effects. Although, other explanations are possible, the response inhibition hypothesis provides a plausible explanation for the presence, and absence, of inhibitory effects in the frequency orienting data currently available.

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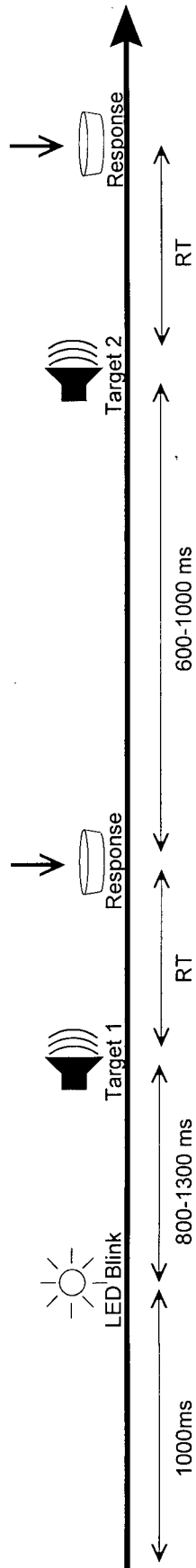
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Table 1

Mean Response Time (RT; in milliseconds), Standard Error (SE) and Percent Errors (%E) as a Function of Target Frequency Relationship and Response-Stimulus Interval (RSI) in Experiments 1A, 1B, 1C.
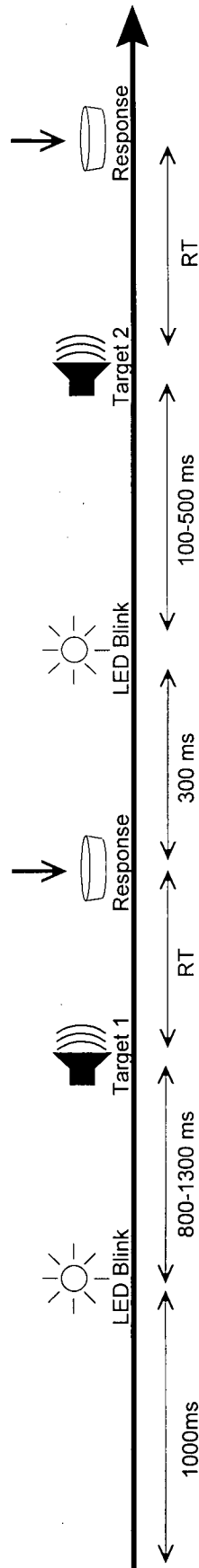
		Response-Stimulus Interval					
		Short			Long		
Experiment	Target Relationship	RT	SE	%E	RT	SE	%E
1A	Match	224	11	2.7	243	10	3.4
	Change	241	12	2.8	246	10	3.5
2A	Match	218	10	3.2	238	11	2.8
	Change	233	10	3.5	239	11	5.4
3A	Match	253	17	4.1	271	21	4.1
	Change	271	18	4.3	279	20	3.2

Table 2
Mean Response Time (RT; in milliseconds), Standard Error (SE) and Percent Errors (%E) as a Function of Cue Validity and Stimulus Onset Asynchrony (SOA) in Experiments 2A, 2B, 3A, 3B, 3C.
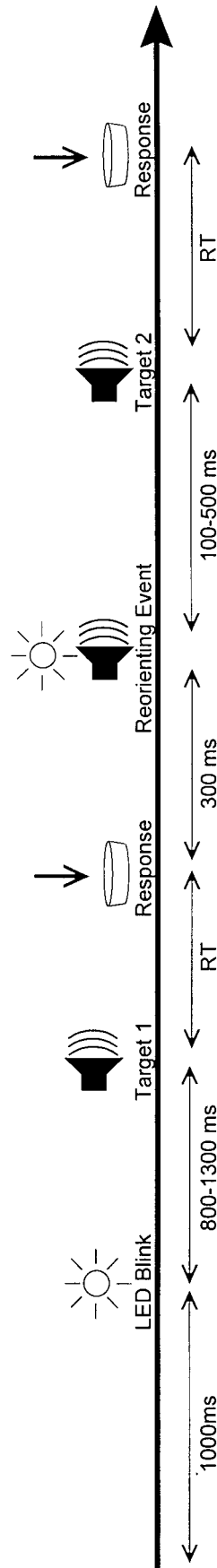
Experiment	Cue Type	SOA 150 RT	SE	%E	SOA 550 RT	SE	%E	SOA 950 RT	SE	%E
2A	Valid	610	38	4.3	575	33	3.4	591	34	4.5
	Middle	763	41	8.4	654	45	4.5	627	43	4.3
	Invalid	773	54	8.4	679	38	5.9	642	37	4.1

Experiment	Cue Type	SOA 150 RT	SE	%E	SOA 750 RT	SE	%E	SOA 1500 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

Experiment	Cue Type	SOA 150 RT	SE	%E	SOA 450 RT	SE	%E	SOA 750 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

Figure 1. Sequence of events for a pair of targets in Experiments 1A, 1B, and 1C.
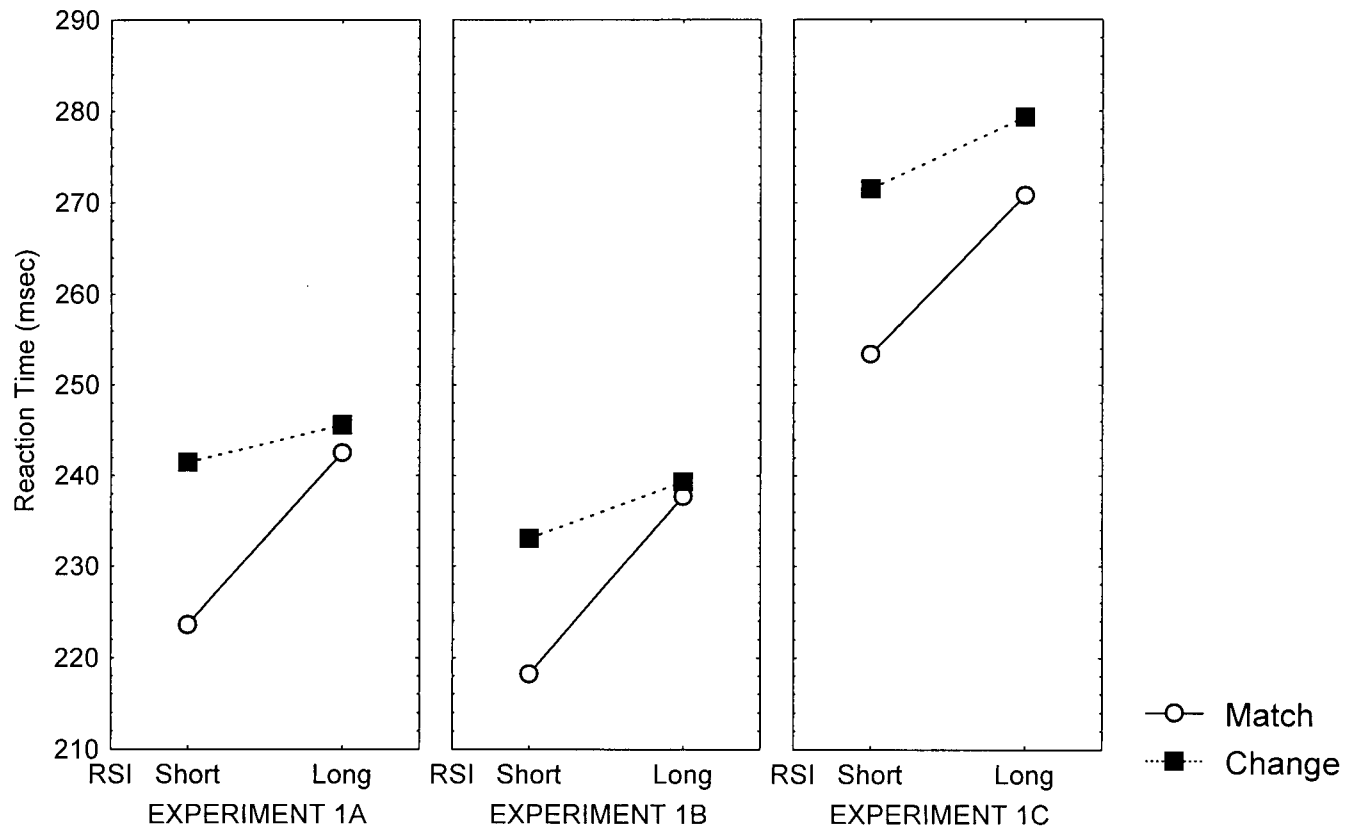
Figure 2. Mean reaction times (in milliseconds) as a function of response-stimulus interval (RSI)
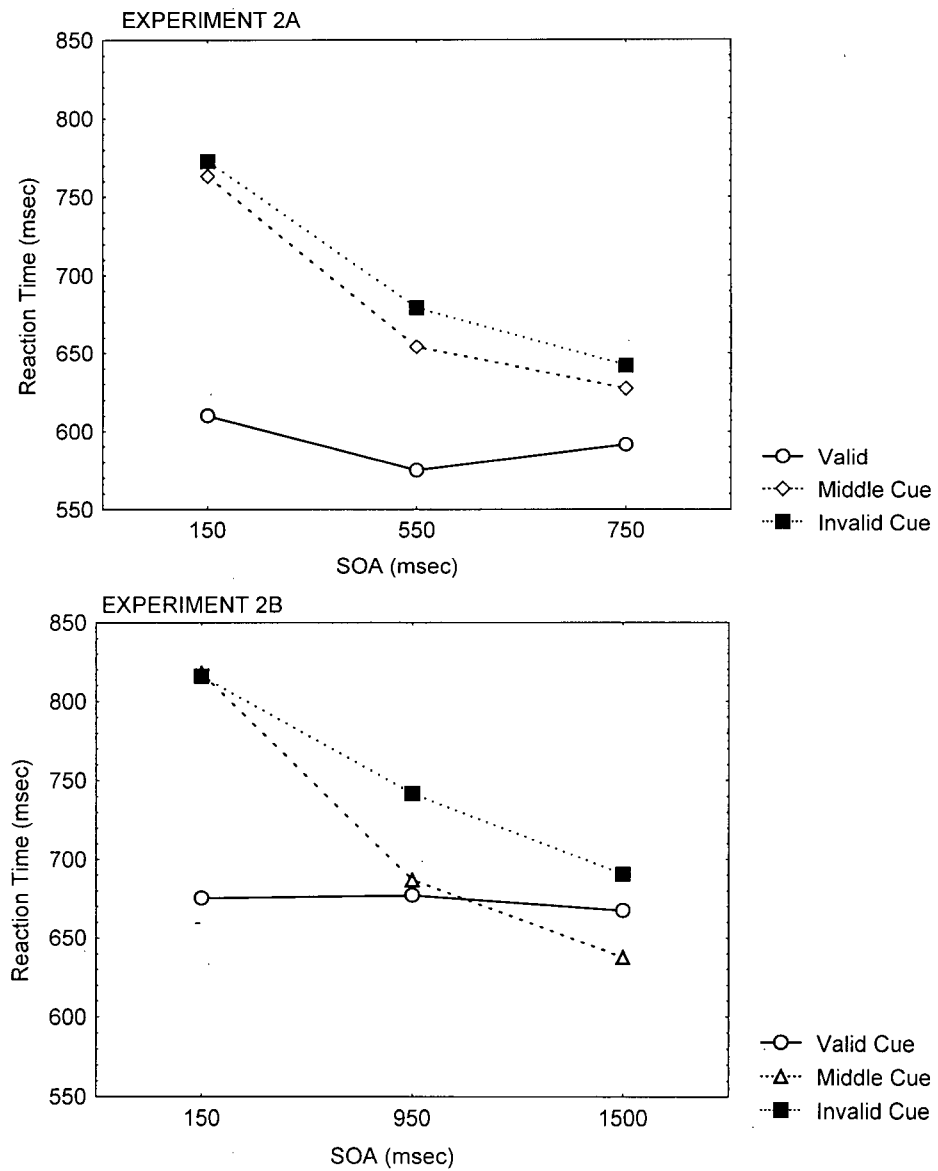for match and change trials in Experiments 1A, 1B, and 1C.

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.
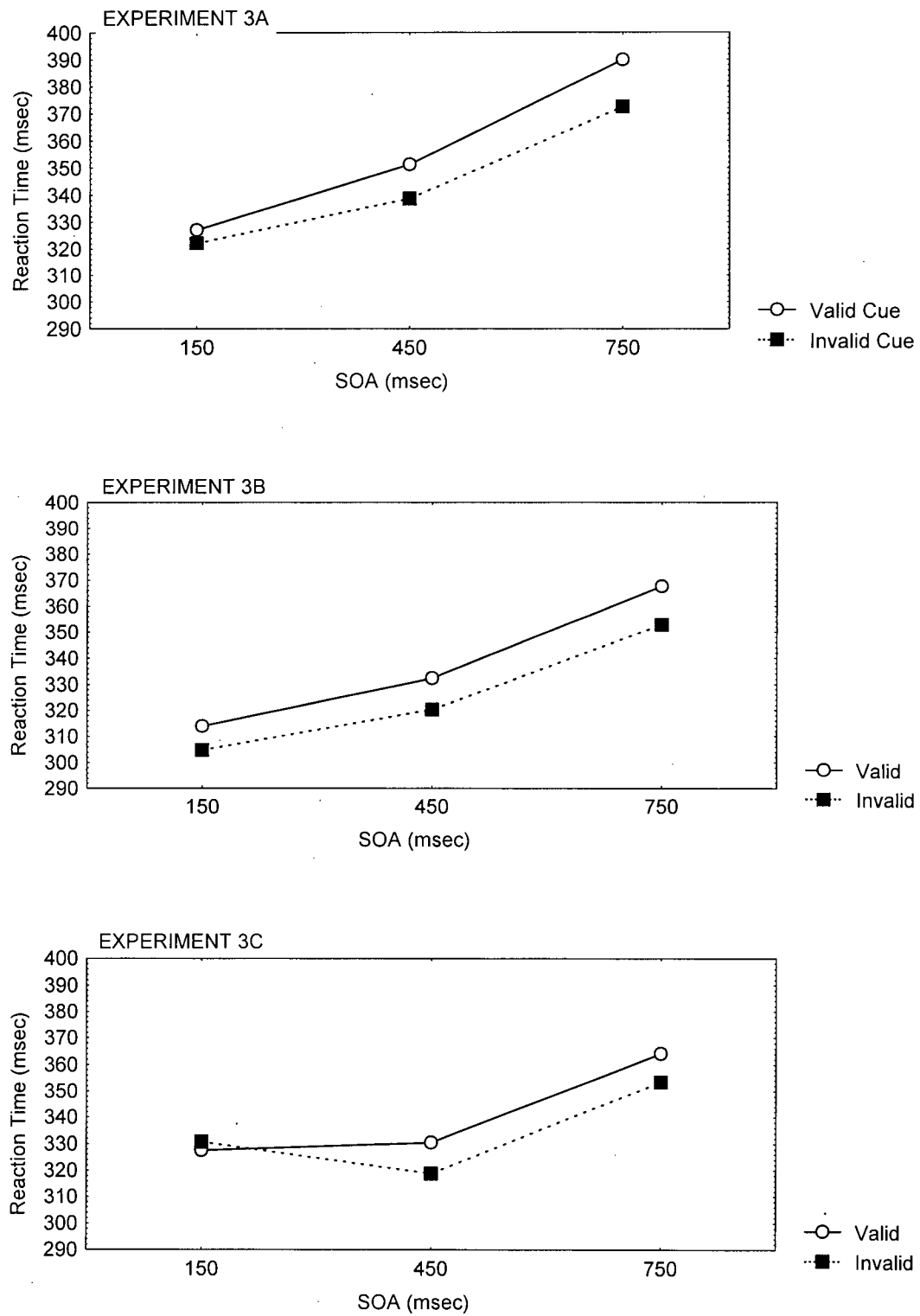
Figure 4. Mean reaction times (in milliseconds) as a function of stimulus onset asynchrony (SOA) for valid-cue and invalid-cue trials in Experiments 3A, 3B, and 3C.