

# Interaction between location- and frequency-based inhibition of return in human auditory system

Qi Chen · Ming Zhang · Xiaolin Zhou

Received: 4 April 2006 / Accepted: 19 July 2006 / Published online: 18 August 2006  
© Springer-Verlag 2006

**Abstract** Using a cue–target paradigm, this study investigated the interaction between location and frequency information processing in human auditory inhibition of return (IOR). The cue and the target varied in terms of location and frequency and participants were asked to perform a target detection, localization or frequency discrimination task. Results showed that, when neither location nor frequency of auditory stimuli was particularly relevant to the target detection task, there was a location-based IOR only if the cue and the target were identical in frequency and there was a frequency-based IOR only if the cue and the target were presented at the same location. When a particular feature of auditory stimuli, whether location or frequency, was directly relevant to the current task, the IOR effect was evident for this feature only if the cue and the target differed on the task-irrelevant feature, while the IOR effect was eliminated for the task-relevant feature

when the cue and the target had the same task-irrelevant feature. Similarly, the IOR effect based on the task-irrelevant feature was evident when the cue and the target differed on the task-relevant feature, and was eliminated or reversed when the cue and the target shared the task-relevant feature. Theoretical implications of these findings for auditory IOR are discussed.

**Keywords** Auditory inhibition of return · Sound localization · Frequency discrimination · Dual-process model · Response inhibition · Constructive retrieval account

## Introduction

Studies of visual attention and orientation have long observed a phenomenon in which response to a target appearing at a precued peripheral location is slowed down compared with response to a target appearing at a novel location if the SOA between the uninformative cue and the target is longer than 300 ms (Maylor and Hockey 1985; Posner and Cohen 1984; see Klein 2000 for a review). This bias towards novel location is called “inhibition of return” (IOR) and is believed to be reflexive and involuntary, generated by exogenous stimuli. The IOR effect has been repeatedly observed in a number of different experimental tasks, including target detection (e.g. Posner and Cohen 1984; Maylor and Hockey 1985; Kwak and Egeth 1992), localization (e.g. Maylor 1985; Pratt et al. 1997), and discrimination (e.g. Lupiáñez et al. 1997; Pratt 1995; Pratt and Abrams 1999; Pratt et al. 1997). Its underlying mechanism, however, remains controversial. It is suggested that the IOR effect is associated with attentional modulation on

---

Q. Chen · X. Zhou (✉)  
Department of Psychology, Peking University,  
Beijing 100871, China  
e-mail: xz104@pku.edu.cn

M. Zhang  
Department of Psychology, Northeast Normal University,  
Changchun 130024, China

X. Zhou  
State Key Laboratory of Cognitive Neuroscience  
and Learning, Beijing Normal University,  
Beijing 100875, China

X. Zhou  
Learning & Cognition Laboratory,  
Capital Normal University, Beijing 100037, China

perceptual processing (Handy et al. 1999; Lupiáñez et al. 1997; Posner and Cohen 1984; Pratt et al. 1997; Reuter-Lorenz et al. 1996), with the activity of the oculomotor system (Rafal et al. 1989; Rafal and Henik 1994; Tassinari et al. 1987; Taylor and Klein 1998; Kingstone and Pratt 1999), or with manual response bias (Havey 1980; Khatoun et al. 2002; Taylor and Klein 1998, 2000). It is possible that IOR has both attentional and motor components and that it can be produced by different mechanisms operating at different stages of information processing (Abrams and Dobkin 1994; Hunt and Kingstone 2003; Kingstone and Pratt 1999; Klein 2000; Lupiáñez et al. 2004; Prime and Ward 2002; Taylor and Klein 2000).

Investigation into IOR has spread into the auditory domain (McDonal and Ward 1999; Reuter-Lorenz and Rosenquist 1996; Schmidt 1996; Spence and Driver 1998a, b; Tassinari et al. 2002) and into the cross-modal link between visual and auditory information processing (Spence and Driver 1997, 1998b; Spence et al. 2000). Most of the studies employed the cue–target paradigm used in visual IOR research and established that the IOR effect can be found for a variety of properties of auditory stimuli, although somewhat different patterns of effects were also found in other paradigms (e.g. Prime and Ward 2002; Spence and Driver 1998b). Mondor and his colleagues observed both frequency-based and location-based IOR (Mondor 1999; Mondor and Breau 1999; Mondor et al. 1998a). Listeners were asked to detect, localize, or identify the frequency of the target. The location or the frequency of the cue and the target could be the same or different. It was found that at longer SOAs (e.g. 750 ms), listeners' performance was better when the cue and the target differed in location or frequency than when they were in the same location or of the same frequency, in contrast with the reversed, facilitatory pattern of effects at short SOAs (e.g. 150 ms). A recent study by Mondor and Lacey (2001) extended the scope of IOR in auditory attention by showing that IOR can also be observed for subordinate features of sound, such as duration, intensity, and timbre.

Mondor (1999) and Mondor and Lacey (2001) proposed a dual-process model to account for the earlier facilitatory (at short SOAs) and late inhibitory (at longer SOAs) cueing effects in various tasks. This model assumes that there are two separate processes interactively responsible for the facilitatory and inhibitory effects. The first process controls the transmission of acoustic information to auditory short-term memory, and the second process is involved in differentiation of memory representations and response assignment. The sound input establishes an attentional

template or filter which governs the speed at which auditory information is passed on to memory. In the typical cue–target paradigm, the template may be set in accordance with the properties of the cue. If the subsequent target matches the template, it will be transmitted quickly to auditory short-term memory. If the target does not match the template, it will be transmitted more slowly. However, in the short-term memory, accurate response assignment requires accurate and distinctive memory representation of the target. The similarity between the cue and the target will make the differentiation of memory representations of the cue and the target more difficult and hence slow down the response to the target. Therefore, the facilitatory and inhibitory effects in the cue–target paradigm are determined by the tradeoff in importance of these opposing influences. Because the specific settings of the parameters of the cue template are assumed to dissipate over the time course of about 300–400 ms, the inhibitory effect (IOR) will appear at longer SOAs, reflecting the fact that the time required to differentiate memory representations for the cue and the target depends on their similarity.

However, the generality of the dual-process model in accounting for the auditory IOR effect has been questioned and as Prime and Ward (2002) pointed out, this model has difficulty in explaining several empirical findings. For example, according to the dual-process model, the amount of IOR is affected by cue–target similarity and inhibition will be reduced when cues and targets are easier to distinguish. But by manipulating the distinguishability between the cue and the target, Prime and Ward (2002) did not find any interaction between cue–target similarity and the inhibitory effect. Furthermore, the dual-process model assumes that both spatial and nonspatial IOR arise from the operation of the same mechanisms, which is also identical, or analogous to the mechanism producing IOR in the visual domain (Mondor and Lacey 2001). However, as far as auditory IOR is concerned, Prime and Ward (2002) found dissociation between location-based and frequency-based IOR in a target–target paradigm and in the cue–target paradigm requiring go–no-go discrimination of the target: the location-based IOR effect was observed in such paradigms but the frequency-based effect was not. This dissociation suggests that location- and frequency-based IOR may be subserved by different cognitive and neural mechanisms.

Another popular account of IOR in the cue–target paradigm is in terms of response inhibition to the cue (e.g. Harvey 1980; Spence and Driver 1998b; see also Prime and Ward 2002 for a discussion). According to this account, the presentation of a cue induces automatically

a response tendency which participants have to inhibit. This inhibition may persist and slow the response to the subsequently presented target. The inhibitory effect is stronger if the cue and the target belong to the same category (e.g., having the same location or frequency) than if they do not. However, by comparing IOR in the auditory cue–target paradigm and target–target paradigm, Tassinari et al. (2002) demonstrated that although refraining from responding to the cue in the cue–target paradigm contributed some amount of IOR, IOR could nevertheless appear in both cue–target and target–target paradigms, indicating that auditory IOR may depend on both motor inhibition and other factors, such as covert attention or oculomotor control. We will return to these accounts of IOR in the [Discussion](#) section.

So far almost all studies on auditory IOR were conducted separately for different properties of auditory stimuli, such as location, frequency, or duration. To examine directly whether they have the same underlying mechanisms and how they possibly interact in contributing to attentional or response bias, we may need to co-vary different properties of the auditory signal. According to the additive factor method logic (Sternberg 1969; Miller 1988; Sanders 1990), if different properties of auditory signals interact in producing IOR, they must share some common processing mechanisms. In fact, this rationale has been used in studies on visual IOR. A few studies reported that IOR can be observed for nonspatial attributes of visual stimuli, such as color (Law et al. 1995), shape (Riggio et al. 2004), length (Francis and Milliken 2003), and even semantic feature (Fuentes et al. 1999). Other studies tried to interpolate these nonspatial properties with location (e.g. Riggio et al. 2004). In particular, Tanaka and Shimojo (1996) and Pratt and Castel (2001) used a target–target procedure in which every stimulus in a pair served as a target. The targets were rectangles varying in terms of peripheral location (left or right), color (red or green), and orientation (vertical or horizontal). The same stimuli were used in experiments differing only in experimental tasks. In the detection experiment, observers were instructed to make a simple detection response to the appearance of the target, regardless of the location, color, and orientation of the target. In the localization experiment, observers were instructed to make a choice response based only on the location of the target. Likewise, the color discrimination experiment required a choice response based only on the color of the target, and the orientation discrimination experiment required a choice response based only on the orientation of the target, regardless of other attributes of the target. Pratt and Castel (2001) obtained interesting interactions between spatial and

nonspatial attributes. First, spatial-based IOR will be found if the task-relevant nonspatial attributes are different between the preceding and probe targets, while spatial-based facilitation of return will be found when the task-relevant nonspatial feature remains the same. Second, location-based IOR will be found if the nonspatial attributes are task-irrelevant. Third, neither constant facilitation nor IOR effects will be found when all of the nonspatial attributes differ between preceding and probe targets. It should be noted that Pratt and Castel (2001) focused on the effects of nonspatial attributes on location-based IOR and did not discuss the impact of the spatial attribute on nonspatial IOR.

In the auditory domain, a few previous studies have also demonstrated that attentional modulation of spatial and nonspatial auditory processing may interact and give rise to measurable behavioral consequences. Melara and Marks (1990) demonstrated that individual features of sound input, such as pitch, loudness, and timbre, are immediately and mandatorily accessed by the listener and these features interact, forming an integral stimulus. Mondor et al. (1998b) asked whether auditory attention can be allocated exclusively to spatial location or frequency regions and whether attentional selection can operate independently through location and frequency channels. The authors varied the location and frequency of the target simultaneously and asked participants either to categorize the target by location or frequency or to detect the target embedded within a sequence of distractors. In all the experiments, performance depended on both location and frequency information even though only one of these features was relevant to the task demand, suggesting strongly that selection of auditory information may not be guided independently via location or frequency and that selection of auditory information may be accomplished via an attentional template that normally incorporate both frequency and location information.

In the present study, we conducted three experiments similar to Pratt and Castel (2001), but with auditory stimuli and with the cue–target paradigm. Our main purpose was to investigate the potential interaction between location and frequency information in attentional modulation of auditory information processing. We manipulated concurrently the location and frequency of auditory cues and targets in three experiments, which had the same design but different tasks (detection, localization, and frequency discrimination). In the detection task, participants responded to the presence of a target, regardless its location or frequency. In the localization task, participants made

judgment to the spatial location of the target, disregarding its frequency. In the frequency discrimination task, participants made judgments to the frequency of the target, disregarding its spatial location. The variation of experimental tasks should allow us to examine the effect of task demand on the potential interaction between location and frequency information in auditory IOR. We did not employ the target–target paradigm, because auditory frequency-based IOR may not be observed in this paradigm (Prime and Ward 2002).

## Materials and methods

### Subjects

A total of 79 participants were tested, 27 for Experiment 1, 27 for Experiment 2 and 25 for Experiment 3. They were undergraduate students at Northeast Normal University in China, aged between 21 and 24 and all right-handed. None of them reported any hearing impairment. All participants gave informed consent according to the guidelines of the Department of Psychology, Northeast Normal University and were paid for their participation.

### Design and stimuli

Three experiments used essentially the same design and stimuli, with two within-subject factors designating the relations between the cue and the target. The first factor was whether the cue was ipsilateral or contralateral to the target (i.e., cue–target location correspondence or cue validity) and the second factor was whether the frequency of the cue was the same as or different from the frequency of the target (i.e., cue–target frequency correspondence). These two factors were crossed to yield four equiprobable conditions, i.e. same-location and same-frequency condition, same-location and different-frequency condition, different-location and same-frequency condition, and different-location and different-frequency condition. Each condition had 40 trials in the test.

The cue and the target were two pure tones, 555 and 869 Hz. These frequencies were chosen in accord with Mondor (1998a). These two tones served as the cue or the target in the four experimental conditions in equal probability. They were synthesized at a sampling rate of 16,000 Hz, using CoolEdit Pro 2.0. Both of the tones were 100 ms in duration, and they began and ended with 5-ms linear onset/offset amplitude ramps to eliminate clicks.

All of the experiments were conducted in a darkened, sound-attenuating chamber (300 × 100 × 200 cm) with a background sound level of lower than 35 dB SPL. A Pentium III/933 Sony portable computer running Windows XP and the experimental software DMDX (Forster and Forster 2003) was used to control the presentation of sound stimuli and to record responses. Cue and target tones were presented over Laus LA-6000 speakers located 45° to the left, 45° to the right of the listener's midline. These speakers were placed approximately 50 cm from the midline. The sound stimuli were presented to listeners at a comfortable intensity of approximately 65 dB.

### Procedure

On each trial, a cue sound was presented over either the left or the right speaker, followed by a target sound presented at either the same or different location with either the same or different frequency. There were no predictive relations between the cue and the target along either the location or the frequency dimension. The target was presented 750 ms after the onset of the cue. That is, the SOA between the cue and the target was fixed at 750 ms. The cue sound of the next trial was presented 1,000 ms after participants responded to the target of the previous trial. Depending on the experiment, participants were asked either to detect the presence (Experiment 1) or the location (Experiment 2) of the target, or to discriminate the high or low of the target frequency (Experiment 3). In Experiment 1, they were asked to respond by pressing one of the buttons on the joystick with the index finger of their dominant hand. In Experiment 2, about half of the participants were asked to respond by pressing the upper button on the joystick with the index finger of their dominant hand if the target was sounded from the left speaker and the lower button with the middle finger of their dominant hand if the target was sounded from the right speaker. About another half of the participants used the reversed button-to-speaker assignment to respond. In Experiment 3, the upper and lower buttons of the joystick were used to represent respectively the high and low of the frequency. Again, assignment of button-to-frequency was counterbalanced over participants.

The presentation of the cue and the target on the ipsilateral and contralateral sides and the combination of the same or different frequencies as cues and targets were completely balanced. Participants were instructed to respond as rapidly as possible without making anticipatory responses. If participants made an anticipatory response before target onset or failed to make a

response 2,000 ms after target onset, a feedback signal was presented. There were also 20 catch trials in each experiment in which no target was presented. Participants were also instructed to look at the fixation on the screen directly in front of them through an adjustable chinrest and to refrain from moving their heads or eyes.

In each experiment, each participant completed a total of 32 practice trials and 180 experimental trials. Trials for the four experimental conditions were randomly mixed and divided into two testing blocks between which participants had a 2-min break.

**Results**

One participant in Experiment 1 was excluded from data analyses because he made too many false responses to catch trials and his mean reactions in two experimental conditions were shorter than 100 ms. Median reaction times (RTs) on correct trials for each of the four conditions were computed for each participant in each experiment. Calculating mean reaction times in other ways does not change the pattern of effects. The inter-participant means of these, together with response error rates in Experiments 1, 2 and 3, are shown in Table 1.

**Experiment 1: detection task**

Analyses of variance (ANOVAs) were conducted for RTs, with cue–target location and frequency correspondences as two within-participant factors. In the simple detection task, the main effect of the location correspondence was significant,  $F(1, 25) = 14.10$ ,

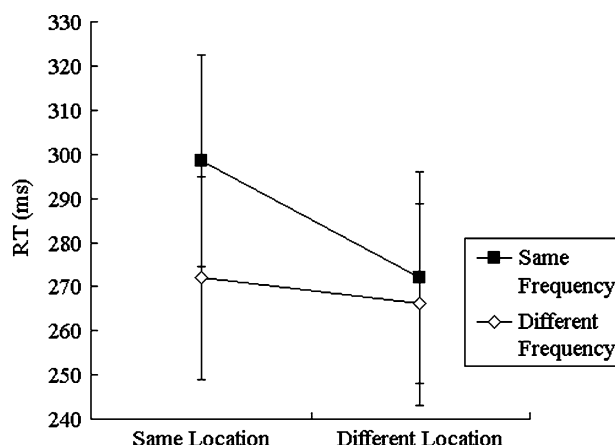
$P < 0.005$ , indicating that participants were generally slower in responding to targets appeared at the same location as cues (285 ms, collapsed over the RTs at the “same location” in Table 1 and Fig. 1) than to targets appeared at the opposite location (269 ms, collapsed over the RTs at the “different location” in Table 1 and Fig. 1). This effect was the typical location-based auditory IOR. The main effect of frequency correspondence was also significant,  $F(1, 25) = 16.94$ ,  $P < 0.001$ . RTs on the same-frequency trials (285 ms, collapsed over the RTs at the “same frequency” in Table 1 and Fig. 1) were significantly slower than RTs on the different-frequency trials (269 ms, collapsed over the RTs at the “different frequency” in Table 1 and Fig. 1), manifesting a typical frequency-based auditory IOR. More importantly, the interaction between cue location and frequency correspondence was significant,  $F(1, 25) = 10.11$ ,  $P < 0.005$  (see Fig. 1). Further analysis on simple effects revealed that the location-based IOR existed only when the cue and the target had the same frequency,  $F(1, 25) = 21.54$ ,  $P < 0.001$ . The frequency-based IOR existed only when the cue and the target were presented on the same location,  $F(1, 25) = 20.10$ ,  $P < 0.001$ . There was no effect for either location or frequency if the cue and target differed in the other feature. The analyses of error rates (i.e., anticipatory responses and failures to respond within time limit) did not find anything significant.

**Experiment 2: localization task**

In the localization task, the main effect of cue–target location correspondence was significant in RTs,  $F(1, 26) = 12.05$ ,  $P < 0.005$ , with RTs to the same-location targets (421 ms) being slower than RTs to the

**Table 1** Mean reaction times, standard errors and response error percentages in Experiments 1, 2, and 3

		Location Same		Location Different	
		Frequency Same	Frequency Different	Frequency Same	Frequency Different
Experiment 1 (detection)	RT (ms)	298	272	272	266
	SE	24	23	24	23
	Error (%)	3.9	2.9	2.8	1.8
Experiment 2 (localization)	RT (ms)	407	436	404	379
	SE	22	25	22	19
	Error (%)	1.5	3.8	2.9	3.2
Experiment 3 (discrimination)	RT (ms)	386	381	403	372
	SE	19	18	17	19
	Error (%)	1.4	2.9	2.5	2.6



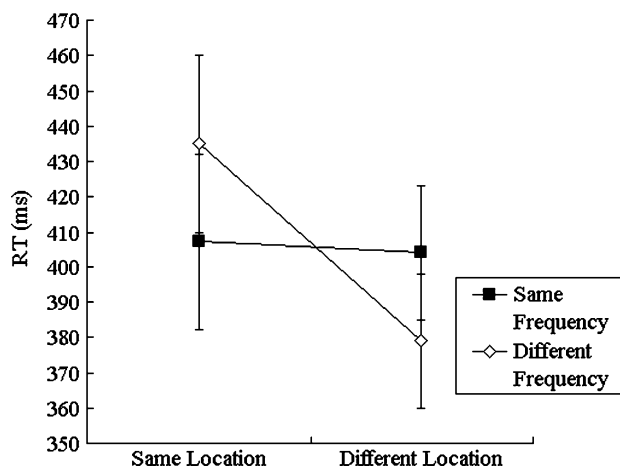
**Fig. 1** Mean reaction times (RTs; ms) in the detection task as the function of whether the cue and the target have the same frequency and/or location



opposite-location targets (391 ms). Unlike Experiment 1, the main effect of frequency correspondence was not significant,  $F(1, 26) < 1$ . The mean RT on the same-frequency trials (405 ms) was not different from the RT on the different-frequency trials (407 ms). The interaction between cue location and frequency correspondence was significant,  $F(1, 26) = 25.37$ ,  $P < 0.001$  (see Fig. 2). Analyses of simple effects revealed a significant location-based IOR (56 ms) when the cue and the target had different frequencies,  $F(1, 26) = 20.34$ ,  $P < 0.001$ . Responses to the same-location targets were slower than responses to the different-location targets. There was no location-based IOR when the cue and the target had the same frequency,  $F(1, 26) < 1$ . Thus, having the same task-irrelevant feature eliminated the expected IOR effect for the task-relevant feature while having different task-irrelevant features may have augmented the IOR effect for the task-relevant feature. On the other hand, there was a significant frequency-based facilitation of return (28 ms) for the same-location targets,  $F(1, 26) = 10.52$ ,  $P < 0.005$  and a significant frequency-based IOR (25 ms) for the different-location targets,  $F(1, 26) = 9.88$ ,  $P < 0.005$ . Thus, having the same task-relevant feature not only eliminated but also reversed the expected IOR effect for the task-irrelevant feature, while having different task-relevant features seems to have no dramatic influence on the IOR effect for the task-irrelevant feature. The analyses of error rates (i.e., incorrect responses to the targets) did not find anything significant.

### Experiment 3: frequency discrimination task

In the frequency discrimination task, the main effect of cue–target location correspondence was not significant

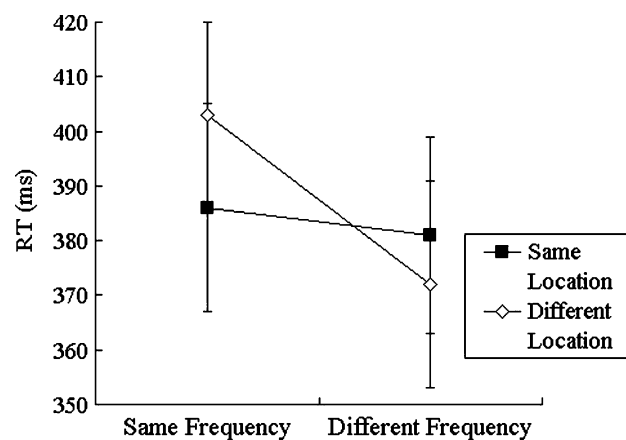


**Fig. 2** Mean RTs (ms) in the localization task as the function of whether the cue and the target have the same frequency (task-irrelevant) and/or location (task-relevant)

in RTs,  $F(1, 24) = 1.21$ ,  $P > 0.1$ , but the main effect of frequency correspondence was,  $F(1, 24) = 11.69$ ,  $P < 0.005$ . RTs on the same-frequency trials were longer (18 ms) than those on the different-frequency trials, exhibiting a frequency-based IOR. The interaction between location and frequency correspondences reached significance,  $F(1, 20) = 7.54$ ,  $P < 0.05$  (see Fig. 3). Further analyses on simple effects revealed that the frequency-based IOR was evident only when the cue and the target were in different locations (31 ms),  $F(1, 24) = 21.56$ ,  $P < 0.001$ . It was not present when the cue and the target were at the same location (5 ms),  $F(1, 24) < 1$ . Thus as in Experiment 2, having the same task-irrelevant feature eliminated the expected IOR effect for the task-relevant feature while having different task-irrelevant features may have augmented the IOR effect for the task-relevant feature. On the other hand, there was a significant location-based facilitation of return (17 ms) when the cue and the target shared the same frequency,  $F(1, 24) = 9.50$ ,  $P < 0.01$ , but a non-significant inhibitory trend (9 ms) when the cue and the target had different frequencies,  $F(1, 24) = 2.17$ ,  $P > 0.1$ . Thus, as in Experiment 2, having the same task-relevant feature not only eliminated but also reversed the expected IOR effect for the task-irrelevant feature, while having different task-relevant features caused an inhibitory trend for the task-irrelevant feature. The analyses of response error rates did not find anything interesting.

### Discussion

This study had two aims. The first aim was to investigate the interaction between location and frequency



**Fig. 3** Mean RTs (ms) in the frequency discrimination task as the function of whether the cue and the target have the same frequency (task-relevant) and/or location (task-irrelevant)

information processing in auditory IOR. The second aim was to examine the effect of task demand on the pattern of auditory IOR. Three experiments consistently observed interactions between location and frequency information, indicating that spatial and frequency IOR share some common mechanisms in auditory processing. However, the details of interaction changed with different task demands. Experiment 1 showed that, when neither location nor frequency was particularly relevant to the detection task, there was a location-based IOR only when the cue and the target were identical on frequency and there was a frequency-based IOR only when the cue and the target were at the same location (Fig. 1). Responses were the slowest when the cue and the target shared both features and the fastest when they shared neither. This pattern of interaction between location and frequency information, however, changed when the experimental task was particularly relevant to one feature and irrelevant to another. Taking into account the fact that the task-relevant and task-irrelevant features were reversed in Experiments 2 and 3, the patterns of effects in the two experiments closely mirrored each other (see Figs. 2, 3). When a particular feature of auditory stimuli, whether it was location (Experiment 2) or frequency (Experiment 3), was relevant to the current task, the IOR effect was evident for this feature when the cue and the target differed on the task-irrelevant feature. There was no effect for the task-relevant feature when the cue and the target had the same irrelevant feature. Similarly, for the task-irrelevant dimensions, frequency in Experiment 2 and location in Experiment 3, the IOR effect was evident for this feature when the cue and the target differed on the task-relevant feature, whilst the reverse was true when the cue and the target shared the task-relevant feature.

These findings, replicated in our study on auditory attention in congenitally blind people (Chen et al. 2006) and in a study with multiple SOAs between the cue and the target (unpublished data), are consistent with Melara and Marks (1990) and Mondor et al. (1998b) by showing that the task-irrelevant, uninformative dimension of auditory input affects participants' performance on the task-relevant feature and by showing that the effect is essentially the same, whether task-irrelevant feature is location or frequency. However, these findings also differ from Melara and Marks (1990) and Mondor et al. (1998b) in that the influence of task-irrelevant feature on participants' performance depends not only on whether this feature is shared between the cue and the target but also on the validity of the task-relevant feature in cueing the target. On the other hand, the pattern of effects found here is parallel

to those observed for visual IOR (Pratt and Castel 2001), even though these authors used a target–target paradigm. A careful examination of Fig. 2 in Pratt and Castel (2001) shows that when the nonspatial task-irrelevant features (orientation in the color discrimination task, color in the orientation judgment task, and color/orientation in the localization task) were kept constant, IOR for the task-relevant feature would be obtained if the two consecutive targets (in their target–target paradigm) differed on the task-irrelevant feature(s), but IOR for the task-relevant feature would be eliminated or reversed if the two consecutive targets shared the same task-irrelevant feature. Similarly, IOR for the task-irrelevant feature would be obtained if the two consecutive targets differed on the task-relevant feature, and it would be eliminated or reversed if the two consecutive targets shared the same task-relevant feature. Recently we replicated these findings with concurrent manipulation of color and spatial cueing in a study using the fMRI techniques (Q. Chen and X. Zhou, unpublished data).

In the following paragraphs, we discuss three potential accounts for the interaction between location and frequency information in auditory IOR. The dual-process account was proposed specifically for auditory IOR, but it has no flexibility to accommodate the present findings. Response inhibition accounts attribute all the effects to response inhibition to the cue, whether this inhibition is based on refraining from manually responding to the cue (Harvey 1980; Spence and Driver 1998b), the oculomotor suppression necessary to maintain fixation (Tassinari et al. 1987, 2002), or inhibitory tagging or disconnection of the link between perceptual processing and response activation (Fuentes et al. 1999; Klein 2000; Tipper et al. 1994; Vivas and Fuentes 2001). Although these response inhibition accounts could accommodate the findings in the detection task, they have difficulties in explaining the interactions between task-relevant and task-irrelevant features in the localization and discrimination tasks. The third account, the constructive retrieval account, seems to provide a better and parsimonious account for such interactions.

#### The dual-process account

The dual-process account can easily account for the results of Experiment 1 here. According to this model, IOR is not indicative of attentional inhibition but reflects mainly the time to differentiate memory representations for the cue and the target. The more similar the cue and the target, the more time needed to differentiate their representations (but see Prime and Ward 2002). If the target is the same as the cue on both

location and frequency, the response time to the target would be the longest; if the target is different from the cue on both location and frequency, the response time would be the shortest. Sharing one dimension between the cue and target would prolong the differentiation of memory representations and delay the detection response to the target.

This account, however, has problems in accounting for the results of Experiments 2 and 3. Why was IOR for the task-relevant feature influenced differentially by the task-irrelevant feature? According to Mondor et al. (1998b), location and frequency are integral perceptual dimensions because they cannot be attended or selected independently from each other. Therefore, in the second process of differentiating memory representations, the task-irrelevant feature would function in essentially the same way as the task-relevant feature. Task demand should play no significant role in determining the pattern of cueing effects. Clearly, the patterns of effects in the localization and discrimination tasks observed here (Figs. 2, 3) do not fit with this prediction. Moreover, the augmenting of the IOR effect for the task-relevant feature when the cue and the target had different task-irrelevant features was found to be due to both the slowdown of responses to the target when it had the same task-relevant feature as the cue and the increase of efficiency in response to the target when it had a different task-relevant feature from the cue. Whether the task-irrelevant feature increased or decreased the RTs to the target depended not only on whether the target and the cue had the same or different task-irrelevant feature, but also on the cue validity of the task-relevant feature. The dual-process model has no mechanism for such an interaction.

#### The response inhibition accounts

Another possible mechanism for IOR appearing in the cue–target paradigm is response inhibition in which participants must suppress their natural tendency to respond to the cue (Harvey 1980; Prime and Ward 2002; Tassinari et al. 2002; De Jong et al. 1994). This suppression or inhibition may persist and slow down the later response to the target. When applying this account to the present data, however, we find that this account will meet the same problems as the dual-processes account does. The response inhibition account assumes that, the more similar the cue and the target, the greater the persisting inhibition affecting the response to the target. However, although this hypothesis can explain the results of Experiment 1 in which the RTs to the target were the slowest when the cue and the target shared both the location and the fre-

quency and the fastest when the cue and the target differed on both features, it cannot account for the results of Experiments 2 and 3, as we discussed above.

Another form of the response inhibition account of IOR, suppression of oculomotor activity, assumes that IOR is due to the conflict between maintenance of fixation and the natural tendency to move the eyes to the cue (Rafal et al. 1989; Tassinari et al. 1987, 2002; Taylor and Klein 1998). Oculomotor suppression necessary to maintain fixation may retard subsequent oculomotor responses to the ipsilateral targets, either because it reduces the allocation of attentional resources to target processing, due to the functional links between oculomotion and spatial attention, or because it biases the general set controlling motor output (Tassinari et al. 2002). However, it is not clear how the effect of task demand and the interaction between task-relevant and task-irrelevant features in producing IOR can be incorporated into this account, as there is no mechanism for the maintenance of eye fixation being differentially affected by task-relevant and irrelevant features.

The third form of the response inhibition account assumes that the presence of a cue establishes “inhibitory tagging” for the subsequently presented target sharing the manipulated feature with the cue. Although inhibitory tagging may not affect the accumulation of information and perceptual processing of the target, it temporarily disconnects the link between perceptual processing and response activation (Fuentes et al. 1999; Tipper et al. 1994; Vivas and Fuentes 2001) or shifts the criterion for initiating a response to the target (Ivanoff and Klein 2001; Taylor and Klein 1998). Clearly this form of response inhibition account has no difficulties in explaining the location- or frequency-based auditory IOR (e.g. Mondor et al. 1998a). Processing of an auditory cue impairs the subsequent response activation for the manipulated feature of the target. Nor does this account have difficulties in accounting for the IOR effect when the response to the target (i.e. the experimental task) is irrelevant to the manipulated cue–target relation (Mondor and Breaux 1999), because the inhibited responses can be based on target properties rather than on the shared relations between the cue and the target. However, this account has no mechanism in explaining the present interaction patterns between task-relevant and task-irrelevant features.

#### A constructive retrieval account

Although the response inhibition accounts could be saved for the present findings by adding further



assumptions concerning response activation for the task-irrelevant feature, our favorite account is the constructive retrieval account (Lupiáñez et al. 1997, 2001a, b; Milliken et al. 2000). In order to explain the finding that IOR emerges at longer SOAs in perceptual discrimination tasks than in the target detection task and the finding that the more difficult the discrimination task, the longer the SOA at which IOR emerges, Lupiáñez et al. (1997, 2001a, b) propose a constructive retrieval account in which the process of integrating current perceptual information with memory representations of prior experience determines when and how IOR emerges in attentional orienting. Kahneman et al. (1992) suggested that the onset of a visual target initiates the retrieval of memory representation of similar prior events, which they called object files. The spatiotemporal information from the current target is then compared to that for the prior event. If this process reveals a spatiotemporal match, the object file for a prior event is updated with information from the current target; if there is no spatiotemporal match with an existing object file, a new object file is created for target. Borrowing this framework, Milliken et al. (2000) and Lupiáñez et al. (2001a, b) proposed further that whether an existing object file is updated or a new object file is created is determined not only by the physical spatiotemporal correspondence between the present and past events, but also by the attentional set that participants adopt in a particular task context. In an attentional cueing task, an attentional set favoring integration of present and past is assumed to facilitate integration of the cue and a subsequent target sharing the same critical feature; an attentional set favoring encoding of new event representations, on the other hand, would delay the response to the target. Different tasks may induce different attention sets. Participants tend to create a new object file for the target in the detection task and tend to integrate the target with the cue (i.e. updating the existing file created by the cue) in the localization or discrimination task.

According to this constructive retrieval account, the only thing that participants need to do in the detection task is to detect and encode the abrupt onset of a new object. So in this task integration of visual information across events (i.e. the cue and the target) serves no useful function and the best strategy or attentional set for participants is to encode new perceptual events and use whatever information available to differentiate the target from the cue. Any differences between the cue and the target will make it easier to recognize when the second event arrives. This explains why in Experiment 1 responses to the target were the fastest when the target differed from the cue in both location and

frequency and the slowest when the target had the same location and frequency as the cue.

In the localization or discrimination task, efficient performance depends less on the encoding of new perceptual events, as the mere appearance of a new object is not sufficient to determine its location or identity. Instead the accumulation of featural information for each event is most critical to task performance. In other words, the localization or discrimination task is performed at the object level after feature integration has taken place. Therefore, when the cue and the target are repeated on the task-relevant dimension (location in Experiment 2 and frequency in Experiment 3), the most parsimonious attentional set adopted by participants should be integrating the target with the cue and updating the object file created by the cue. By using this attentional set, participants will be most efficient in performing the task when the cue and the target are repeated on the task-irrelevant dimension, which will make the process of updating the old object file easier and produce a faster response. In contrast, having different task-irrelevant features will delay the integration and slow down the response. Thus, when the cue and the target share the same task-relevant feature, participants' localization or discrimination responses could be either enhanced or delayed, depending on whether the target and the target have the same task-irrelevant feature.

When the cue and the target differ on the task-relevant dimension, however, participants may adopt an attentional set of creating a new object file for the target because integrating the distinctively different (on the task-relevant dimension) cue and target would incur costs to the task performance. In this context, having different task-irrelevant features between the cue and the target would make easier the creation of a new object file for the target while having the same task-irrelevant feature would make the creation of the new object file more difficult. In other words, when the cue and the target have different task-relevant features, having different task-irrelevant features between the cue and the target would facilitate the response to the target while having the same task-irrelevant feature between the cue and the target would delay the response to the target.

Therefore, the constructive retrieval account can explain how the task-irrelevant dimension can have contrasting influences on participant's performance, depending on whether the cue and the target share the same feature on the task-relevant dimension. By the same token, this account could also accommodate the complex interactions between task-relevant and task-irrelevant dimensions in visual IOR (e.g., Pratt and Castel 2001).

## Conclusion

This study has provided novel information concerning the interaction of task-relevant and task-irrelevant features in auditory IOR and its modulation by task demands. Results demonstrate that different features (location vs. frequency) of auditory signal cannot be selected independently from each other (Mondor et al. 1998b) and the way they interact can be highlighted by task demand, such that the pattern of IOR in the cue–target paradigm is not determined by the feature per se but by which feature is directly relevant to the task. The processing of frequency and location information in auditory signals must share some common cognitive mechanisms. Obviously our data here are not completely compatible with Prime and Ward (2002) who found dissociation between location and frequency information in auditory IOR in some particular task contexts. Whether this discrepancy is due to difference in paradigms (cue–target vs. target–target, but see Pratt and Castel 2001) or other factors needs further investigation.

The present findings provide support to the constructive retrieval account of IOR although they do not necessarily exclude other accounts, if additional assumptions are added. Nevertheless, it seems that, because the constructive retrieval account incorporates the concept of attentional set, which can be endogenously modulated by task demand or other setups (Lupiañez et al. 2001a, b), it is powerful in its ability to account for a number of phenomenon, including the present interaction between location- and frequency-based IOR in auditory information processing.

**Acknowledgments** The research reported here was supported by National Pandeng Project (95-special-09) and by grants from the China National Science Foundation (30070260, 30470569, 60435010) and the Ministry of Education of China (2002/53, 01002, 02170). We thank Dr. Juan Lupiañez and two anonymous reviewers for their comments on early versions of this paper.

## References

- Abrams RA, Dobkin RS (1994) Inhibition of return: Effects of attentional cuing on eye movement latencies. *J Exp Psychol Hum Percept Perform* 20:467–477
- Chen Q, Zhang M, Zhou X (2006) Spatial and nonspatial peripheral auditory processing in congenitally blind people. Neuroreport (in press)
- De Jong R, Liang C-C, Lauber E (1994) Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *J Exp Psychol Hum Percept Perform* 20:731–750
- Forster KI, Forster JC (2003) DMDX: a Windows display program with millisecond accuracy. *Behav Res Methods Instrum Comput* 35:116–124
- Francis L, Milliken B (2003) Inhibition of return for the length of a line? *Percept Psychophys* 65:1208–1221
- Fuentes LJ, Vivas AB, Humphreys GW (1999) Inhibitory tagging of stimulus properties in inhibition of return: effects on semantic priming and flanker interference. *Q J Exp Psychol A* 52:149–164
- Handy TC, Jha AP, Magnun GR (1999) Promoting novelty in vision: inhibition of return modulates perceptual-level processing. *Psychol Sci* 10:157–161
- Harvey N (1980) Non-informative effects of stimuli functioning as cues. *Q J Exp Psychol* 32:413–425
- Hunt AT, Kingstone A (2003) Inhibition of return: dissociating attentional and oculomotor components. *J Exp Psychol Hum Percept Perform* 29:1068–1074
- Ivanoff J, Klein RM (2001) The presence of a nonresponding effector increases inhibition of return. *Psychon Bull Rev* 8:307–314
- Kahneman D, Treisman A, Gibbs S (1992) The reviewing of object files: object specific integration of information. *Cogn Psychol* 24:175–219
- Khatoun S, Briand KA, Sereno AB (2002) The role of response in spatial attention: direct versus indirect stimulus-response mappings. *Vis Res* 42:2639–2708
- Kingstone A, Pratt J (1999) Inhibition of return is composed of attentional and oculomotor processes. *Percept Psychophys* 61:1046–1054
- Klein RM (2000) Inhibition of return. *Trends Cogn Sci* 4:138–147
- Kwak H, Egeth H (1992) Consequences of allocating attention to locations and to other attributes. *Percept Psychophys* 57:455–464
- Law MB, Pratt J, Abrams RA (1995) Color-based inhibition of return. *Percept Psychophys* 57:402–408
- Lupiañez J, Decaix C, Sieroff E, Chokron S, Milliken B, Bartolomeo P (2004) Independent effects of endogenous and exogenous spatial cueing: inhibition of return at endogenously attended target locations. *Exp Brain Res* 159:447–457
- Lupiañez J, Milan EG, Tornay F, Madrid E, Tudela P (1997) Does IOR occur in discrimination tasks? Yes, it does, but later. *Percept Psychophys* 59:1241–1254
- Lupiañez J, Milliken B (1999) Inhibition of return and the attentional set for integrating versus differentiating information. *J Gen Psychol* 126:392–418
- Lupiañez J, Milliken B, Solano C, Weaver B, Tipper SP (2001a) On the strategic modulation of the time course of facilitation and inhibition of return. *Q J Exp Psychol* 54A:753–773
- Lupiañez J, Weaver B, Tipper SP, Madrid E (2001b) The effects of practice on cueing in detection and discrimination task. *Psicologica* 22:1–23
- Maylor EA (1985) Facilitatory and inhibitory components of orienting in visual space. In: Posner MI, Marin OSM (ed) *Attention and performance*, vol XI. Erlbaum, Hillsdale, pp 189–204
- Maylor EA, Hockey R (1985) Inhibitory component of externally controlled covert orienting in visual space. *J Exp Psychol Hum Percept Perform* 11:777–787
- McDonald JJ, Ward LM (1999) Spatial relevance determines facilitatory and inhibitory effects of auditory covert spatial orienting. *J Exp Psychol Hum Percept Perform* 25:1234–1252
- Melara RD, Marks LE (1990) Perceptual primacy of dimensions: support for a model of dimensional interaction. *J Exp Psychol Hum Percept Perform* 16:398–414
- Miller J (1988) Discrete and continuous models of human information processing: theoretical distinctions and empirical results. *Acta Psychol* 67:191–257
- Milliken B, Tipper SP, Houghton G, Lupiañez J (2000) Attending, ignoring, and repetition: on the relation between

- negative priming and inhibition of return. *Percept Psychophys* 62:1280–1296
- Mondor TA (1999) Predictability of the cue–target relation and the time-course of auditory inhibition of return. *Percept Psychophys* 61:1501–1509
- Mondor TA, Breau LM (1999) Facilitative and inhibitory effects of location and frequency cues: evidence of a modulation in perceptual sensitivity. *Percept Psychophys* 61:438–444
- Mondor TA, Breau LM, Milliken B (1998a) Inhibitory processes in auditory selective attention: evidence of location-based and frequency-based inhibition of return. *Percept Psychophys* 60:296–302
- Mondor TA, Lacey TE (2001) Facilitative and inhibitory effects of cuing sound duration, intensity, and timbre. *Percept Psychophys* 63:726–736
- Mondor TA, Zatorre RJ, Terrio NA (1998b) Constraints on the selection of auditory information. *J Exp Psychol Hum Percept Perform* 24:66–79
- Posner MI, Cohen Y (1984) Components of visual orienting. In: Bouma H, Bouwhuis DG (eds) *Attention and performance*, vol X. Erlbaum, Hillsdale, pp 531–556
- Pratt J (1995) Inhibition of return in a discrimination task. *Psychon Bull Rev* 2:117–120
- Pratt J, Abrams RA (1999) Inhibition of return in discrimination tasks. *J Exp Psychol Hum Percept Perform* 24:229–242
- Pratt J, Castel AD (2001) Responding to feature or location: a re-examination of inhibition of return and facilitation of return. *Vis Res* 41:3903–3908
- Pratt J, Kingstrone A, Khoe W (1997) Inhibition of return in location- and identity-based choice decision tasks. *Percept Psychophys* 59:964–971
- Prime DJ, Ward LM (2002) Auditory frequency-based inhibition differs from spatial IOR. *Percept Psychophys* 64:771–784
- Rafal RD, Henik A (1994) The neurology of inhibition. Integrating controlled and automatic processes. In: Dagenbach D, Carr T (eds) *Inhibitory Processes in attention, memory and language*. Academic, San Diego, pp 1–50
- Rafal RD, Calabresi PA, Brennen CW, Sciolto TK (1989) Saccade preparation inhibits reorienting to recently attended locations. *J Exp Psychol Hum Percept Perform* 15:673–685
- Reuter-Lorenz PA, Jha A, Rosenquist JN (1996) What is inhibited in inhibition of return? *J Exp Psychol Hum Percept Perform* 22:367–378
- Reuter-Lorenz PA, Rosenquist JN (1996) Auditory cues and inhibition of return: the importance of oculomotor activation. *Exp Brain Res* 112:119–126
- Riggio L, Patteri I, Umiltà C (2004) Location and shape in inhibition of return. *Psychol Res* 68:41–54
- Sanders AF (1990) Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychol* 74:123–167
- Schmidt WC (1996) “Inhibition of return” without visual input. *Neuropsychologia* 34:943–952
- Spence CJ, Driver J (1997) Audiovisual links in exogenous covert spatial orienting. *Percept Psychophys* 59:1–22
- Spence CJ, Driver J (1998a) Auditory and audiovisual inhibition of return. *Percept Psychophys* 60:125–139
- Spence CJ, Driver J (1998b) Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision. *Percept Psychophys* 60:544–557
- Spence CJ, Lloyd D, McGlone F, Nicholls MER, Driver J (2000) Inhibition of return is supramodal: a demonstration between all possible pairing of vision, touch and audition. *Exp Brain Res* 134:42–48
- Sternberg S (1969) The discovery of processing stages: extensions of Donder’s method. *Acta Psychol* 30:276–315
- Tanaka Y, Shimojo S (1996) Location vs. feature: reaction time reveals dissociation between two visual functions. *Vis Res* 36:2125–2140
- Tassinari G, Aglioti S, Chelazzi L, Marzi CA, Berlucchi C (1987) Distribution in the visual field of the costs of voluntarily allocated attention and of the inhibitory after-effects of covert orienting. *Neuropsychologia* 25:55–71
- Tassinari G, Campara D, Benedetti C, Berlucchi C (2002) The contribution of general and specific motor inhibitory sets to the so-called auditory inhibition of return. *Exp Brain Res* 146:523–530
- Taylor TL, Klein RM (1998) On the causes and effects of inhibition of return. *Psychon Bull Rev* 5:625–643
- Taylor TL, Klein RM (2000) Visual and motor effects in inhibition of return. *J Exp Psychol Hum Percept Perform* 26:1639–1656
- Tipper SP, Weaver B, Jerreat LM, Burak AL (1994) Object-based and environment-based inhibition of return of visual attention. *J Exp Psychol Hum Percept Perform* 20:478–499
- Vivas AB, Fuentes LJ (2001) Stroop interference is affected in inhibition of return. *Psychon Bull Rev* 8:315–323