

RESEARCH ARTICLE

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**Auditory cues and inhibition of return:
the importance of oculomotor activation**

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Abstract We studied the effects of eccentric auditory cues to clarify the conditions that evoke inhibition of return (IOR). We found that auditory cues positioned 12° to the left or right of midline failed to produce IOR whereas visual cues produced IOR under the same experimental conditions. The eccentric auditory cues elicited automatic orienting as evidenced by more rapid detection of cued than uncued visual targets at short stimulus onset asynchrony. Yet these same cues did not produce IOR unless observers were required to saccade to the cue and back to center before generating a manual detection response. Thus, under the conditions examined herein automatic orienting was not sufficient to evoke IOR, but oculomotor activation appeared to be essential. The functional significance of IOR and the question of modality-specific orienting processes are considered.

Key words Attention · Eye movements · Inhibition of return · Modality specificity · Human

Introduction

The ability to search efficiently and to respond effectively to objects and events in the environment is crucial to our survival. Efficient search and action require the integration of information from different sensory modalities and spatial maps that code relevant locations in viewer-centered and environment-centered coordinate frames. Moreover, information must be integrated across time so that the results of search at one moment can properly influence the choice of where to go next.

The precueing paradigm, in which a cue precedes the occurrence of an imperative signal to which the observer responds, is a particularly useful tool for studying the mechanisms that underlie our ability to meet these requirements (Eriksen and Hoffman 1972; Posner 1980; Van der Heijden 1992). It is well established that cues

can be used to direct covert attention, leading to more accurate discrimination and rapid detection of events occurring at the cued location (e.g., Hawkins et al. 1990; for a review see Van der Heijden 1992). Attention can be directed via a symbolic/endogenous cue, typically presented at the fovea, which informs the observer where the target event is most likely to occur. Peripheral cues, such as an eccentric flash of light, can also be used to direct attention. In fact, an abrupt luminance change in the periphery can summon attention automatically, even when that signal does not predict the location of a subsequent target (e.g., Yantis and Jonides 1984).

One fascinating consequence of peripheral cueing is a paradoxical inhibition of processing that is evident at the cued location after the initial facilitation dissipates (Posner and Cohen 1984). There is reason to believe that this inhibition is due, at least in part, to a bias against returning attention to that location, and it is this idea that gave rise to the term “inhibition of return” or IOR (Posner and Cohen 1984; Maylor and Hockey 1985; Reuter-Lorenz et al. 1996). It has been proposed that IOR is a mechanism that facilitates the exploration of novel locations (Posner and Cohen 1984). That is, once orienting has been directed to a particular location, either overtly or covertly, new locations will be given priority, thus ensuring more effective search. Reuter-Lorenz et al. (1996) have recently reported that at least one of the ways in which IOR operates is by inhibiting sensory/perceptual processing at previously attended locations.

The conditions that lead to a particular location or object (Tipper et al. 1994) being “tagged” by IOR are not fully understood. IOR is a reliable and robust consequence of peripheral visual cues. However, IOR does not result when attention is directed to a location in response to a central (endogenous) cue (Posner and Cohen 1984; Rafal et al. 1989). This outcome has been taken to indicate that covert orienting per se is not sufficient to evoke IOR. On the other hand, IOR has been found when observers saccade to a location designated by an endogenous cue, or program a saccade but refrain from executing it (Rafal et al. 1989). These results have led a number

of researchers to posit a role for the saccade system in IOR, although there are differing views about the precise nature of oculomotor involvement in IOR (e.g., Berlucchi et al. 1989; Rafal et al. 1989; Tassinari 1989). Since IOR does occur in response to peripheral visual cues, without any explicit instructions that invoke the eye movement system, it is assumed that peripheral visual cues *automatically* engage or prime the oculomotor system in a manner that is sufficient to induce IOR (Klein and Pontefract 1994; Rafal et al. 1989) whereas endogenous cues do not.

With these ideas in mind, it is of interest to consider the potential for peripheral auditory cues to evoke IOR. On the basis of subjective experience, one might think that auditory events in the periphery are particularly effective stimuli for evoking a directional orienting response. Sudden sounds not only elicit startle but seem naturally to evoke head and eye turning as well. Indeed, laboratory experiments indicate that sounds can effectively facilitate the detection of subsequent visual events (Posner 1978; Buchtel and Butter 1988; Farah et al. 1989). It seems reasonable to expect, then, that the reflexive orienting evoked by auditory events could lead to IOR.

On the other hand, if we consider searching in natural settings, sounds are likely to be the first signal to indicate the potential relevance of a location in the environment. Since vision is the primary modality through which human beings verify the presence of relevant stimuli, an adaptive response might be to remain neutral or biased towards a sound source rather than being biased *against* it as in IOR.

This investigation aimed to clarify the conditions that lead to IOR and the functional significance of this phenomenon by studying the effectiveness of peripheral auditory precues. To foreshadow the results, we found no evidence for IOR to auditory precues, even though these cues induced automatic orienting. IOR occurred only when the oculomotor system was explicitly engaged by having observers saccade to the cue and back to center. These results reconfirm the importance of the saccade system in IOR and reveal a potentially important dissociation between visual and auditory orienting.

General methods

Apparatus

All the experiments were conducted in a sound-attenuated, echo-reduction chamber. An array of three light-emitting diodes (LEDs; 0.6° visual angle each) was positioned 47 cm in front of the observer. The central green LED was positioned directly in front of the chinrest used to minimize head movements. The outer bicolor LEDs were positioned 12° to the left and right of the central LED. A 3-inch (7.5-cm) speaker mounted on a Plexiglas panel was positioned behind each of the outer LEDs. The visual cues consisted of a 200-ms green flash of the left or right LED (0.10 footcandles, 1.08 lux). Auditory cues consisted of a 200-ms 100-Hz tone (60 dB). Visual targets consisted of a 200-ms red flash (0.30 ft. candles) delivered via the left or right bicolor LEDs. Auditory targets consisted of a 200-ms burst of white noise delivered via the left or right speaker (30 dB).

Stimulus presentation and data acquisition were controlled by a Macintosh IIx computer. Digital-to-analog and analog-to-digital conversion was done via National Instruments hardware. Data were acquired at a rate of 500 Hz.

Procedure

Each trial began with the onset of the centrally positioned green LED, which served as the fixation point. Subjects were instructed to keep their eyes on the fixation point for the duration of each trial. Following a 500-ms fixation interval, a 200-ms visual or auditory precue occurred, depending on the experiment, to the left or right of the fixation point. Five hundred milliseconds after the onset of the cue, the central fixation point flickered for approximately 300 ms. Flickering was generated by applying to the lamp a 60-ms square wave that pulsed off and on three times. The target was a 200-ms red flash or a 200-ms noise burst (depending on the experiment) which occurred randomly to the left or right of the fixation light with a stimulus onset asynchrony (SOA) of approximately 1000 or 1300 ms relative to the peripheral cue. The precue did not predict the location of the subsequent target. Each trial block consisted of 32 valid and 32 invalid trials and 8 catch trials. Within each trial block, SOA, target type and target location were counterbalanced and randomized.

Subjects were instructed to respond as quickly as possible when they detected the onset of the target by depressing a micro-switch, located directly in front of them, using their right index finger.

Experiment 1

The first experiment tested whether auditory cues could produce IOR when observers were required to detect visual targets. Separate blocks were run using visual cues in order to verify that the temporal parameters of the experiment and the intensity of the target (Reuter-Lorenz et al. 1996) were sufficient to measure IOR.

Method

Participants. Six undergraduates from Introductory Psychology participated in the experiment for course credit. All observers had normal or corrected-to-normal vision and no hearing abnormalities according to their self-report.

Procedure. Auditory or visual cues were presented in separate blocks. Block order was counterbalanced between subjects. Observers participated in a block of 20 practice trials before data collection began with each cue type. Each observer participated in six experimental blocks, three for each cue modality, with short breaks between blocks. The testing session lasted approximately 60 min.

Results and discussion

Latencies greater than 800 ms and less than 150 ms were eliminated from the analysis. In addition, responses falling more than 2.5 standard deviations from the mean were eliminated. This procedure resulted in the exclusion of 3.9% of all responses. Responses occurred on less than 1% of catch trials.

The latency data were submitted to an analysis of variance (ANOVA) with cue modality (visual/auditory),

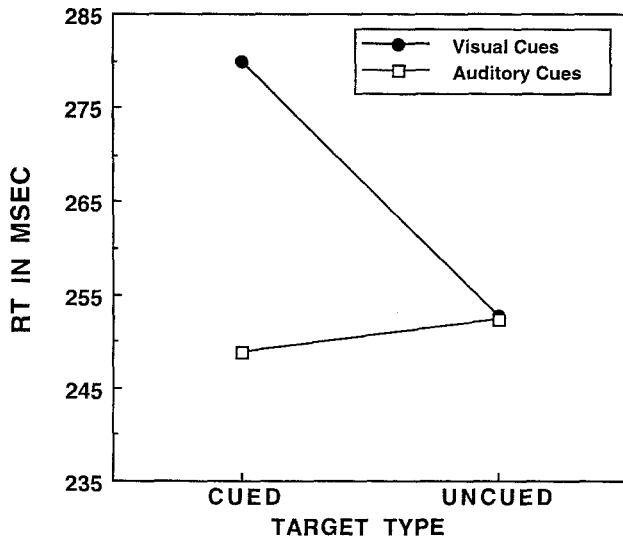


Fig. 1 Effects of auditory or visual cues on the latency to detect visual targets. RT reaction time

SOA (1000/1300 ms) and target type (cued/uncued) as repeated factors. Cued targets were on the same side as the cue, uncued targets were on the opposite side. The effect of SOA was not reliable [$F(1,5)=2.13$; $P>0.20$; short SOA: reaction time (RT)=262 ms, long SOA: RT=252 ms]. A significant main effect for target type, $F(1,5)=11.95$; $P<0.018$, indicates the presence of IOR: responses to uncued targets were faster than responses to cued targets (252 ms and 264 ms, respectively). Responses were generally faster with auditory than with visual cues, [$F(1,5)=27.5$; $P<0.003$] (251 ms and 266 ms, respectively). However, the significant interaction between cue modality and cue validity indicated that this effect was due primarily to the absence of IOR with auditory cues [$F(1,5)=28.57$; $P<0.003$]. Figure 1 illustrates this interaction.

The data from this experiment reveal an absence of IOR with auditory cues, whereas the same targets and temporal parameters yield pronounced IOR when the cues are visual.¹ One potential reason for the failure of auditory cues to produce IOR could be that observers do not actually orient (covertly) to the cue in the first place. Since some form of reflexive orienting is, by some accounts, assumed to be a prerequisite for IOR (e.g., Maylor 1985; Rafal et al. 1989), it seemed important to establish that the auditory cues employed in this investigation are capable of eliciting an automatic orienting response. This was examined in the following experiment which presented visual targets at varying SOAs following an auditory cue. Both short and long SOAs were used so

¹ Although we did not monitor eye position in the present experiment, we did so in our previous investigation in which the same visual cues were used (Reuter-Lorenz et al. 1996). In that study we eliminated trials in which saccades were made to the cue. Because such trials were so rare and eliminating them had no effect on the magnitude of IOR, we believe that it is unlikely that greater IOR from visual than from auditory cues in the present study was due to a greater incidence of overt saccades to visual than to auditory cues

that the potential early facilitation could be compared with the IOR expected at later SOAs (Posner and Cohen 1984; Maylor and Hockey 1985).

Experiment 2

Method

Participants. Seven undergraduates, participating for Introductory Psychology course credit, had normal or corrected-to-normal vision and no hearing abnormalities according to their self-report.

Apparatus. See General methods.

Procedure. The duration of the auditory cue was shortened to 50 ms so that there was no overlap between cue and target presentation at the short SOAs. Five SOAs were used: 100, 150, 200, 600 and 1000 ms. There were 66 trials per block, including six catch trials. The brightening of the center LED following cue onset was eliminated from this experiment. Observers participated in a block of 20 practice trials followed by seven experimental blocks, with short breaks between blocks. The testing session lasted approximately 60 min.

Results and discussion

The trimming procedure was the same as in experiment 1 and resulted in the exclusion of 3.1% of all responses. Responses occurred on less than 1% of catch trials.

A repeated-measures ANOVA with target type and SOA as factors revealed main effects for target type [$F(1,6)=8.08$; $P<0.029$] and for SOA [$F(4,24)=15.90$; $P<0.0001$]. Overall, cued targets were responded to faster than uncued targets (301 and 307 ms respectively) and responses were faster at SOAs of 200 and 600 ms than at the other SOAs, which did not differ from one another (SOA/mean RT: 100/314 ms, 150/313 ms, 200/287 ms, 600/292 ms, 1000/314 ms). The important outcome of this experiment was the significant interaction between SOA and target type [$F(4,24)=5.96$; $P<0.0018$]. As can be seen in Fig. 2, cued targets were associated with faster responses than uncued targets at early SOAs [LSD test (Kirk 1968): SOA 100: $t(6)=3.59$; $P<0.02$; SOA 150: $t(6)=8.26$; $P<0.0001$; SOA 200: $t(6)=4.13$; $P<0.01$] but at longer SOAs where IOR was expected to occur, latencies to cued and uncued targets did not differ [SOA 600: $t(6)=1.03$; ns; SOA 1000: $t(6)=1.02$; NS]

The data from this experiment indicate the following: First, our auditory cues evoked an automatic tendency to orient attention towards the sound source that was evident by 100 ms after cue onset and was no longer apparent 600 ms following the onset of the cue. Second, there was no evidence for IOR with these cues – an outcome that replicates the results from the first experiment using a slightly different paradigm to uncover IOR. This experiment also demonstrates that the auditory cues were clearly localizable. If they had not been, cueing should not have affected performance at early SOAs. It is worth noting that cue localization in the other experiments included in this report may have been even easier because cue duration was 200 ms rather than 50 ms as it was in

Fig. 2 Effects of stimulus onset asynchrony (SOA) between auditory cue and visual target

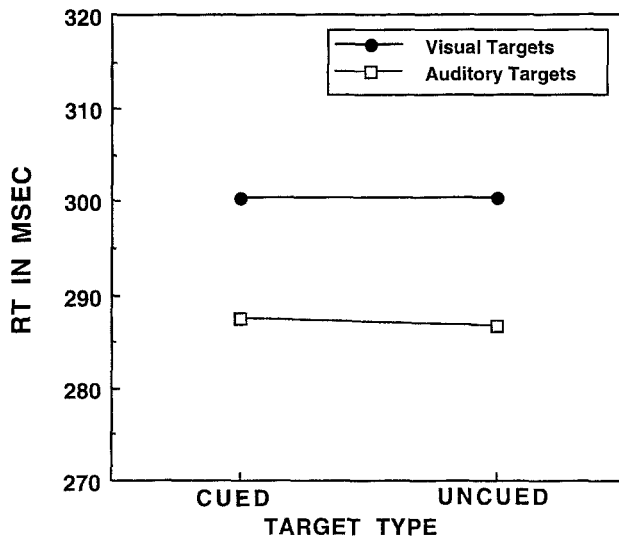
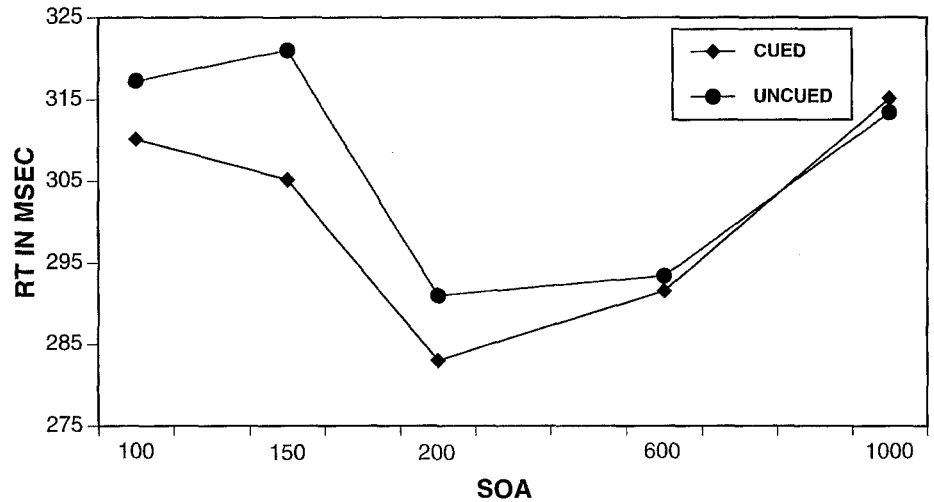


Fig. 3 Effects of auditory cues on the latency to detect auditory or visual targets

experiment 2. We should also point out that while we do not have direct evidence that visual cues would have evoked IOR under the present conditions, similar manipulations of SOA have successfully produced IOR in previous studies (e.g., Posner and Cohen 1984; Maylor and Hockey 1985; Tassinari et al. 1989).

The first experiment demonstrated that our experimental parameters were adequate to detect IOR with visual cues and visual targets. It is conceivable, however, that our failure to find IOR with auditory cues was due to the use of visual targets and that IOR would emerge from auditory cues if the target was also auditory. This possibility is suggested by our previous work which indicated that with visual cues IOR was greater for visual than for auditory targets (Reuter-Lorenz et al. 1996). This outcome was taken to reflect a greater role for location coding in visual than auditory target detection (cf. Rhodes 1987). However, it could have been due in part to the modality difference between the cue and the tar-

get, which could also underlie the absence of IOR in the present experiments. If the magnitude of IOR depends upon the cue and target being in the same modality, then we should find greater IOR from auditory cues when the target is auditory as well. The next experiment tested this possibility by comparing the effects of auditory cues on auditory and visual targets. The target intensities were selected on the basis of our previous work (Reuter-Lorenz et al. 1996) and have been shown to generate the maximal amount of IOR in each modality, at least with visual precues. These target intensities also produced approximately equivalent detection latencies in this earlier work. It should be noted that previously we found IOR to be a reliable, albeit small effect with auditory targets and visual precues (i.e., approximately 13 ms; Reuter-Lorenz et al. 1996).

Experiment 3

Method

Participants. Eleven undergraduates, participating for Introductory Psychology course credit, had normal or corrected-to-normal vision and no hearing abnormalities according to their self-report.

Apparatus. See General methods.

Procedure. The procedure followed is described in General methods except that the target modality, which could be either visual or auditory, varied randomly within blocks. Each participant completed six experimental blocks.

Results and discussion

An ANOVA with target modality (visual/auditory), SOA (1000/1300 ms) and target type (cued/uncued) as within-subjects factors indicated that only the effect of SOA was reliable [$F(1,10)=10.117$; $P<0.01$]. Responses were faster at the longer SOA (287 ms vs 300 ms). The lack of any cueing effects for either target modality [$F(1,10)=0.022$; $P>.50$] indicates that the absence of IOR with auditory cues cannot be attributed to the modality of the target

(Fig. 3). Under nearly identical experimental conditions with visual precues, Reuter-Lorenz et al. (1996, experiment 1) found clear evidence of IOR with visual (approximately 30 ms of IOR) and with auditory targets (approximately 13 ms of IOR). Together with the results of experiments 1–3, it appears that the modality of the cue, rather than the modality of the target, accounts for the presence or absence of IOR, at least under the present experimental conditions.

How can we understand this result? Consider the hypothesis that the function of IOR is to prevent the system from orienting to the same location repeatedly. Perhaps one way to describe the problem posed by our data, then, is that auditory cues are unable to engage the requisite components of the orienting system in order to initiate IOR. What might those components be? As noted in the Introduction, the oculomotor system seems to play an important role in IOR, as evidenced by a number of lines of evidence (e.g., Posner et al. 1985; Abrams and Dobkin 1994), including the observation that endogenous cues do not evoke IOR unless the saccade system is involved (Rafal et al. 1989).

According to the present results then, auditory cues appear to be similar to central or endogenous cues in their inability to generate IOR. This outcome is surprising in that, unlike central cues, auditory cues occur in the periphery and evoke an automatic covert orienting response, as indicated by the results of experiment 2. Nevertheless, it is conceivable that auditory cues do not engage the oculomotor system in a manner that is sufficient (or necessary) to generate IOR. The next experiment evaluated this possibility by requiring the observers to saccade to the location of an auditory cue and then return their eyes back to the fixation LED prior to detecting the peripheral visual target. The idea here is that if auditory cues, like central cues, do not engage the oculomotor system sufficiently, then IOR should result when the saccade system is explicitly engaged by the generation of saccades to the auditory cues.

Experiment 4

Method

Participants. Eight volunteers, between the ages of 18 and 25 years, were paid for their participation. All participants had normal or corrected-to-normal vision and no hearing abnormalities according to their self-report.

Apparatus. See General methods. Eye movements were monitored using the Applied Sciences Model 210 scleral reflection device, which has a resolution of approximately 0.25° . The eye-position signal was digitized at a rate of 500 Hz.

Procedure. The procedure was the same as that described in General methods with the following exceptions. Observers participated in two different types of trial blocks. In saccade-to-cue blocks, they were instructed to move their eyes to the location of the auditory cue and then to return their gaze rapidly to the central LED. The interval between the onset of the cue and the flash of the fixation LED was increased to 700 ms. The fixation LED flashed for

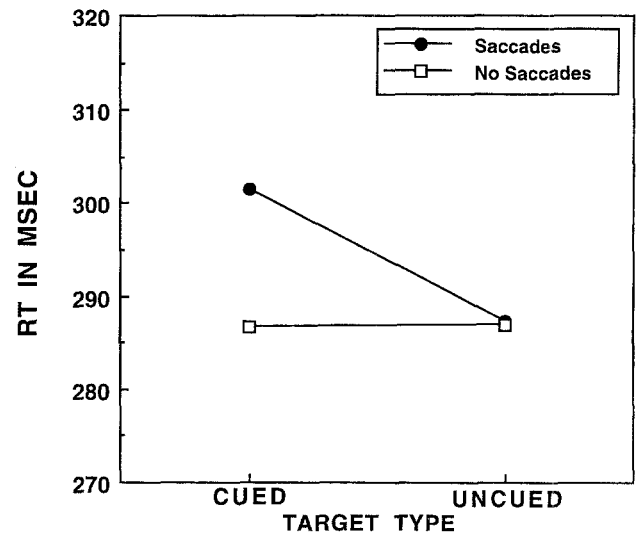


Fig. 4 Effects of auditory cues on visual detection latencies when observers saccade to the cue or remain fixated

300 ms and was then followed approximately 200 or 500 ms later by the onset of one of the peripheral LEDs. The observer made a manual key-press to the onset of the peripheral target LED. The events in the no-saccade blocks were identical except that observers maintained their gaze on fixation throughout the trial. The order of saccade and no-saccade blocks was counterbalanced between subjects.

In both types of trial blocks, eye position was monitored. Each block began with a brief calibration procedure which required observers to fixate on the fixation LED and each of the lateral cue/target locations in turn while eye position was sampled and saved for subsequent analyses. Eye records were monitored by the experimenter, on line, to insure that subjects complied with the instructions and feedback was given when necessary. Only trials with saccades that were 9° or more in the same direction as the cue were included in subsequent RT analyses. Trials in which the observers did not return their eyes to fixation by at least 300 ms prior to target onset were also excluded from subsequent analyses. Altogether approximately 4% of the trials were excluded for these reasons. Eye movements were very rare (less than 1% of the trials) in the no-saccade blocks, but trials on which they occurred were eliminated.

Results and discussion

A three-way ANOVA with block type (saccade-to-cue/no-saccade), SOA (1200/1500 ms) and target type (cued/uncued) as within-subject factors revealed a main effect for SOA [$F(1,7)=13.51$; $P<0.008$], with responses being faster at the longer SOA (279 ms vs 302 ms). The main effect for target type was also reliable [$F(1,7)=8.79$; $P<0.02$], with uncued targets yielding faster responses than cued targets (287 ms vs 294 ms). Of importance, however, was the significant interaction between block type and target type [$F(1,7)=6.89$; $P<0.03$]. As Fig. 4 reveals, IOR was only evident when observers made saccades to the cue. When the eyes remained fixated, there was no IOR. Note that this latter condition once again replicates the absence of IOR from auditory cues using a longer SOA and monitoring eye position.

General discussion

In each of four experiments we found no evidence for IOR following auditory cues in the absence of explicit oculomotor activation. The targets themselves were vulnerable to the effects of IOR, and the experimental parameters were effective at eliciting it as evidenced by the IOR produced by visual cues in experiment 1. Moreover, the auditory cues were clearly localized and effective at summoning attention automatically as evidenced by attentional costs-plus-benefits produced by the cues at short SOAs in experiment 2. Nevertheless, these auditory cues did not produce IOR unless the observer generated a saccade to the source of the sound and back to center. This result indicates that automatic covert orienting alone is not sufficient to generate IOR to auditory cues.

So, if automatic orienting is not a causal antecedent to IOR, what is? The results of the last experiment suggest that the explicit activation of the saccadic system is sufficient to evoke IOR. Indeed, oculomotor processes have figured prominently in accounts of IOR. According to the view advanced by Rafal et al. (1989), IOR is activated by priming the oculomotor system (see also Klein and Taylor 1994). The instruction to prepare a saccade, or the automatic preparation induced by an eccentric visual cue, is sufficient to generate IOR at the location that is targeted by the saccadic system.

An alternative account proposed by Tassinari, Berlucchi and their colleagues (e.g., Berlucchi et al. 1989; Tassinari et al. 1989; cf. Umiltá et al. 1991) attributes IOR to the response inhibition that must accompany the natural tendency to look towards an eccentric cue when that tendency is suppressed by the instruction to maintain central fixation. On the face of it then, instructing observers to look towards the cue, as we did in experiment 4, would seem to obviate the need for response inhibition: if IOR was due to response inhibition, then IOR would not be expected when observers are permitted to move their eyes toward the cue. In contrast to this expectation, experiment 4 revealed evidence of IOR only when saccades were permitted but not when they were presumably suppressed. However, Tassinari, Berlucchi and their colleagues (Chelazzi et al. 1995; see also Tassinari and Berlucchi 1995) have recently pointed out an important feature of the saccade task used in the present paradigm, and used previously by Rafal et al. (1989). While observers were instructed to look at the cued location, they were also instructed to return their gaze to the central fixation point. Therefore this task, like the one used by Rafal et al. (1989), required a saccade *away* from the cued location following the initial cue-directed saccade. Chelazzi et al. (1995) outline a more general framework in which they posit that orienting is accompanied by two opposing lateral response tendencies: an excitatory tendency toward and an inhibitory tendency away from the targeted location (cf. Kinsbourne 1973). According to this view, the requirement to saccade back to the fixation stimulus suppresses lateral orienting tendencies toward the cued location and the IOR we observed in the sac-

cade-to-cue condition of experiment 4 resulted from this suppression.

So, the account proposed by Rafal et al. (1989) would attribute the occurrence of IOR in the saccade-to-cue condition of experiment 4 to the preparation of the cue-directed saccade (Rafal et al. 1989), whereas Tassinari and Berlucchi would attribute it to the generation of a saccade away from the cued location in order to return gaze to the fixation stimulus. In either case, oculomotor processes are pivotal to the occurrence of IOR.

It would follow, then, from either of these accounts that the lack of IOR to auditory cues in the absence of saccades would be due to insufficient oculomotor activation. If the auditory cues were insufficient to prime the oculomotor system, then there would be no response tendency to suppress. Both accounts invite us to consider the possibility that the auditory cues used in the present study did not automatically prime the oculomotor system, whereas the visual cues did. Is there any evidence to support this conjecture?

Modality effects and the superior colliculus

There is little in the way of direct evidence about the neural basis for IOR because there have been few, if any, neurophysiological investigations using the IOR paradigm in animals. Yet, behavioral and neurological evidence in adults and developmental data from humans implicates the superior colliculus (SC) as the locus of this effect (Posner et al. 1985; Rafal et al. 1989; Clohessy et al. 1991). Therefore, the differential effectiveness of auditory and visual stimuli in evoking IOR may be related to modality differences at the level of the SC.

The elegant work by Jay and Sparks (1987, 1990) and by Stein and Meredith (1993) reveals that visual and auditory inputs converge on common units in the intermediate and deep layers of the SC. Neurophysiological recordings from the SC in awake animals indicate that visual and auditory signals utilize a final common pathway for the generation of saccades. Furthermore, behavioral evidence from humans (Miller 1986; Hughes et al. 1994; Nozawa et al. 1994; Frens et al. 1995) demonstrates that auditory and visual inputs combine to control movements of the eyes.

While intersensory integration appears to be a prominent feature of the functional architecture of the SC, there are notable differences between eye movements elicited by visual and auditory targets (Zahn et al. 1978; Zamberieri et al. 1981; Jay and Sparks 1990). Compared with visually elicited saccades, saccades to auditory targets have lower peak velocities, are less accurate, and are associated more frequently with multiple or corrective saccades. In addition, Jay and Sparks (1990) found that the latency of saccades to visual targets increases with increasing target eccentricity, whereas for auditory saccades the opposite is true. By varying the initial position of the eyes and holding the target position constant in relation to the head, Jay and Sparks demonstrated that the larger the eye movement the shorter the latency of the auditory re-

sponse. Taken together, such modality differences suggest that, sensory convergence notwithstanding, the modality of sensory input plays an important role in the dynamics of orienting control and processing at the level of the SC.

There is at least one prominent and potentially critical difference between visual and auditory input to the SC: the superficial layers of the SC receive direct visual input from the retina via the retinotectal pathway whereas auditory signals arrive at the SC via a multisynaptic pathway that includes the inferior colliculus (e.g., Stein and Meredith 1993). If SC mechanisms play a role in IOR, then the magnitude of IOR might vary as a function of the circuitry by which a sensory signal reaches the SC. Indeed, within the visual modality there is evidence that this circuitry affects the magnitude of IOR. Rafal and his colleagues (1989) compared the magnitude of IOR produced by nasal versus temporal hemiretinal stimulation. The direct projection to the SC is stronger from the nasal hemiretina than from the temporal hemiretina, and Rafal et al. (1989) showed that IOR is greater in response to nasal hemiretinal stimulation. The directness of the input appears to influence some properties of the signal reaching the SC, which may in turn influence the processes that are critical to IOR.

By analogy, then, the relative ineffectiveness of auditory cues in evoking IOR may be related to the relatively indirect circuitry by which auditory signals reach the SC. More specifically, because auditory input to the SC is less direct than visual input, the processes that underlie IOR are not as readily engaged by auditory events. These processes are engaged, however, when the observer is instructed to saccade to the auditory cue and back to center, thus resulting in IOR.

Relation to other studies on auditory IOR

There are at least four other studies that have examined IOR using auditory cues with either visual or auditory targets, two of which appeared during the preparation of this manuscript. A brief overview of this work reveals that IOR is not a reliable consequence of auditory cues. For example, Ward (1994) found that auditory cues produced IOR when the targets were auditory but not when they were visual. All cues and targets were more eccentric than in the present study and subjects were required to indicate the left/right location of the target by generating a left or right hand response. The stimulus-response (S-R) mapping in this choice RT task raises the possibility that processes associated with manual response preparation contributed to the effects Ward observed. S-R compatibility effects could not explain the ineffectiveness of auditory cues given visual targets, however. In contrast, Spence and Driver (1994; experiment 1) found no IOR when auditory targets were preceded by auditory cues. Their experiment also required a localization response but, unlike the Ward study, the response was not spatially compatible with the target.

Tassinari and Berlucchi (1995) report IOR from a preliminary study that used auditory cues and auditory targets in a simple detection task. Once again the eccentric-

ities were greater than in the present study, which could contribute to the different outcomes. Nevertheless, by comparison with the inhibition they report in a visual target/visual cue paradigm, the inhibitory effects from auditory cues were only about half the size.

Finally Schmidt (1996) reports IOR using auditory cues and targets positioned 50 cm to the left and right of midline. However, his subjects were explicitly instructed to prepare an eye movement in response to the cue but to refrain from executing it. To the extent that subjects followed these instructions, it is possible that the oculomotor activation they engendered is critical to the occurrence of IOR. If so, the results of Schmidt are at least consistent with the present results and similarly link IOR to oculomotor activation.

To summarize, then, auditory cues appear to be less reliable than visual cues in their ability to evoke IOR. IOR from auditory cues has been found in at least one study that used simple RT, like the present investigation, but at larger eccentricities (Tassinari and Berlucchi 1995). In other cases where IOR was found from auditory cues response programming and/or response inhibition could have influenced the results, as in the saccade-to-cue condition of the present study (Ward 1994; Schmidt 1996).

Conclusions

The results from the present study support the following conclusions about IOR. First, IOR is a less reliable consequence of eccentric auditory cues than eccentric visual cues. Second, automatic covert orienting to an auditory cue is not sufficient to generate IOR, at least at the eccentricity used in the present investigation. Third, the generation of a saccadic response to an auditory cue and back to the central fixation point is sufficient to evoke IOR when the targets are visual.

On a more speculative note, we suggest that the differential effectiveness of auditory and visual cues may be due to differences in the circuitry by which input from these modalities arrives at the SC. When the observer is instructed in a manner that explicitly engages the oculomotor system, we found that the effectiveness of the auditory cues was enhanced. This suggests the possibility of two routes to IOR. One route, which seems more effective for vision than for audition, is through the detection of a sensory event in the periphery. The other is through the activation of the saccade system to respond towards the event. This route can clearly be accessed via the voluntary control of eye position and, as others have argued, it may be accessed reflexively as well (e.g. Rafal et al. 1989; Klein and Pontefract 1994; Tassinari and Berlucchi 1995). These routes may ultimately operate by means of a common final pathway which may indeed be oculomotor. It is also conceivable that a detection and oculomotor component could each contribute to the magnitude of IOR such that when both are activated, IOR is greater than with either component alone. Future research is needed to evaluate these possibilities.

The present results do not preclude the possibility that auditory cues could evoke IOR reliably in a (nonspatial) discrimination task within the auditory modality (cf. Cheal and Lyon 1995; Pratt 1995; Law et al. 1996) or in a detection task with larger eccentricities. Nevertheless, the present findings suggest that the spatial orienting system may be organized so as to permit, rather than inhibit, reorienting following a peripheral auditory event. To the extent that IOR is a less likely consequence of auditory events, the system may be characterized by a propensity towards *visual verification* whereby visual inspection of auditory sources is enabled.

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