Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision

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Three experiments investigated cross-modal links between touch, audition, and vision in the control of covert exogenous orienting. In the first two experiments, participants made speeded discrimination responses (continuous vs. pulsed) for tactile targets presented randomly to the index finger of either hand. Targets were preceded at a variable stimulus onset asynchrony (150, 200, or 300 msec) by a spatially uninformative cue that was either auditory (Experiment 1) or visual (Experiment 2) on the same or opposite side as the tactile target. Tactile discriminations were more rapid and accurate when cue and target occurred on the same side, revealing cross-modal covert orienting. In Experiment 3, spatially uninformative tactile cues were presented prior to randomly intermingled auditory and visual targets requiring an elevation discrimination response (up vs. down). Responses were significantly faster for targets in both modalities when presented ipsilateral to the tactile cue. These findings demonstrate that the peripheral presentation of spatially uninformative auditory and visual cues produces cross-modal orienting that affects touch, and that tactile cues can also produce cross-modal covert orienting that affects audition and vision.

Our senses are constantly bombarded by information arriving at the various sensory epithelia. Mechanisms of attention allow us to process selectively just those stimuli that may be of particular interest to us. Numerous studies have shown that people can focus their visual attention covertly (i.e., without head or eye movements, etc.) on a particular location, and so enhance the processing of stimuli occurring there (see Posner, 1978, for a classic description of such findings; see also Klein, Kingstone, & Pontefract, 1992, and LaBerge, 1995, for more recent reviews). Although the majority of such studies of spatial attention have focused on unimodal selection, within just visual scenes, there has been a resurgence of interest recently in the possible effects of covert spatial orienting within the other sensory modalities—particularly, audition (e.g., Buchtel, Butter, & Ayvasik, 1996; Mondor & Zatorre, 1995; Schröger & Eimer, 1997; Spence & Driver, 1994)

and touch (e.g., Bradshaw, Howard, Pierson, Phillips, & Bradshaw, 1992; Driver & Grossenbacher, 1996; Kilgard & Merzenich, 1995; Sathian & Burton, 1991; Whang, Burton, & Shulman, 1991).

These studies have revealed that responses to both auditory and tactile targets can be facilitated by the presentation of spatially informative cues (which predict their likely location) in a manner similar to that reported for visual stimuli (e.g., Mondor & Zatorre, 1995; Schröger, Wolff, Tschakert, & Schubö, in press; Spence & Driver, 1994). The finding that similar mechanisms of covert spatial orienting may exist in different sensory modalities has prompted researchers to look for possible cross-modal links in covert orienting, which might facilitate the coordination of attention to the multimodal objects and events that fill our environments. Two of the seminal studies in this area tested for any audiovisual links (Buchtel & Butter, 1988) and visuotactile links (Butter, Buchtel, & Santucci, 1989) in spatial attention, using a variant of the visual cuing paradigm popularized by Posner (1978; see also Posner, Nissen, & Ogden, 1978). Participants were required to make a simple speeded detection response to the onset of auditory, visual, or tactile targets presented from either the left or the right of fixation. Every target was preceded by a peripheral cue in the same or a different modality, presented at stimulus onset asynchronies (SOAs) in the range of 50–1,000 msec. The cue was presented from the same position as the subsequent

This research was supported by grants from the Australian Research Council, from St. John's College, Cambridge, from the Medical Research Council (U.K.), and from the Wellcome Trust (U.K.). The authors thank Ray Klein, Jan Theeuwes, and two anonymous reviewers for their helpful comments on an earlier draft of this article. Correspondence should be addressed to C. Spence, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, England (e-mail: charles.spence@psy.ox.ac.uk), or to J. Driver, Institute of Cognitive Neuroscience, Department of Psychology, University College London, Gower Street, London, WC1E 6BT, England (e-mail: j.driver@ucl.ac.uk).

target on the majority (80%) of unilateral-cue trials and was thus spatially informative. Performance on these "valid" trials was compared with that on "invalid" trials (20% of unilateral-cue trials), where cue and target were presented contralaterally, and also compared with performance on "neutral" trials, where peripheral cues were presented on both sides of fixation simultaneously.

Detection latencies for suprathreshold visual and tactile targets were faster following valid cues in either vision or touch than following neutral and invalid cues, across all SOAs tested (Butter et al., 1989). In addition, visual detection latencies were also significantly facilitated by valid auditory cuing (Buchtel & Butter, 1988). These results were interpreted as showing the existence of some cross-modal links in covert attention, such that the presentation of a peripheral cue in one modality can lead to cross-modal shifts of visual and/or tactile attention in the direction of the cue. By contrast, no validity effects were reported for auditory targets following the ipsilateral presentation of either auditory or visual cues.

Several potential methodological problems with Buchtel and Butter's pioneering studies (Buchtel & Butter, 1988; Butter et al., 1989) have since been raised (e.g., Driver & Spence, 1994; Spence & Driver, 1996), which render the interpretation of both their positive cross-modal findings for visual and tactile targets and their null effects for auditory stimuli somewhat problematic. First, while the simple detection of auditory targets is often uninfluenced by spatial cuing (e.g., Hugdahl & Nordby, 1994; Posner, 1978; Scharf, Quigley, Aoki, Peachey, & Reeves, 1987; Spence & Driver, 1994; though see Buchtel et al., 1996), several subsequent researchers have argued that this may be simply because detection latencies provide a relatively insensitive measure of the spatial distribution of attention for the particular case of hearing (see Rhodes, 1987; Spence & Driver, 1994), since detection in audition may be based on early nonspatial levels of the system. As such, Buchtel and Butter's (1988) failure to demonstrate any effect of visual cuing on auditory detection latencies may merely reflect the use of a relatively insensitive measure for the distribution of auditory attention, rather than having any general implications for cross-modal links in attention. Second, it is uncertain whether the cross-modal facilitatory effects reported for visual and tactile targets reflect an increased sensitivity to stimuli at the cued location, caused by a cross-modal shift of attention to the cued side, or merely a criterion shift caused by participants' lowering their criterion for responding to events occurring at the expected target location (see Duncan, 1980; Shaw, 1984).

Perhaps the most serious problem in interpreting Butter et al.'s (1989; Buchtel & Butter, 1988) studies unambiguously stems from their use of spatially informative cues. It is possible that participants may simply have used the cue as an instruction to shift their attention strategically to the probable target side, *within just the expected target modality*. If so, identical unimodal shifts of attention might have been elicited, for example, by a

central arrow cue pointing to one side or by a purely verbal instruction to focus attention on a particular location. Consequently, the actual modality and position of the cues used in Buchtel and Butter's (1988; Butter et al., 1989) studies may have been irrelevant to the cuing effects observed, and, as such, they may have no direct implications for the existence of cross-modal links in covert orienting (see Driver & Spence, 1994; Spence & Driver, 1996, for further discussion of this point).

The use of spatially informative cues in Buchtel and Butter's pioneering studies can also be questioned in the light of a common distinction between two putatively different forms of covert spatial orienting, which has been drawn by several unimodal studies of attention within audition and vision. *Exogenous* orienting is elicited automatically by the presentation of spatially uninformative peripheral cues, which need not predict the likely target location but occur directly at it. This form of involuntary orienting has been contrasted with the *endogenous* orienting elicited by informative cues, which indirectly predict the likely target location, such as the central arrows commonly used in spatial cuing experiments. Several qualitative behavioral differences have now been found between these two putative forms of covert orienting (e.g., Briand & Klein, 1986; Jonides, 1981; Klein, 1994; Schröger et al., in press; Spence & Driver, 1994), and neurological evidence also suggests that they may have different neural substrates (e.g., Butter, 1987; Ladavas, 1993; Rafal, Henik, & Smith, 1991; see also Robinson & Kertzman, 1995).

The use of *informative* and *peripheral* cues in Buchtel and Butter's (1988; Butter et al., 1989) experiments means that both exogenous orienting (to the location of the peripheral cuing event) and endogenous orienting (to the same location, but only because the subsequent target was more likely to appear there) may have been induced by the cues. It therefore remains uncertain whether any of the effects on tactile and visual target detection, if taken at face value, should be attributed to exogenous orienting, endogenous orienting, or some unknown combination of the two.¹ Given that numerous differences have been reported between these two types of orienting in purely unimodal situations, it seems important to consider potential cross-modal links separately for the cases of endogenous versus exogenous orienting (see Spence & Driver, 1996, 1997, on this point). Accordingly, in the present paper, we focus solely on purely exogenous orienting situations (i.e., where the peripheral cues are always spatially uninformative with regard to the likely target location).

Existing research suggests there may be some cross-modal links in the control of exogenous covert orienting between audition and vision. For example, studies of both normals (e.g., Klein, Brennan, & Gilani, 1987; Reuter-Lorenz & Rosenquist, 1996) and parietal patients (e.g., Farah, Wong, Monheit, & Morrow, 1989) have revealed that the speeded detection of visual targets is faster following a spatially uninformative peripheral auditory cue on the same side rather than on the opposite side. Spence

and Driver (in press, Experiment 1) recently found an audiovisual spatial cuing effect when participants were required to make a speeded elevation discrimination (up vs. down) for visual targets presented from one of two positions on either side of fixation while maintaining central fixation. All targets were preceded by a spatially uninformative lateralized auditory cue at a variable SOA (100, 200, or 700 msec) on the ipsilateral or contralateral side to the subsequent target. Participants responded significantly faster on ipsilateral trials at the 100-msec SOA, and this reaction time (RT) effect was accompanied by a trend for fewer errors, showing that participants had not simply lowered their criterion for responding to targets on the same side as the cue. Further experiments with this method have revealed that the advantage for visual judgments immediately following an ipsilateral auditory cue dissipates as the spatial separation between the cue and the target increases, even when both stimuli are presented within the same hemifield (Driver & Spence, in press). Thus, the cross-modal covert orienting effect has some spatial specificity, and it does not simply apply to one entire hemifield versus the other.

What about the reverse influence, from vision on hearing? Klein et al. (1987, Experiment 6) reported that spatially uninformative visual cues have no effect on simple auditory detection latencies. This null cross-modal influence has since been replicated in a series of studies by Spence and Driver (1997, Experiments 3, 4, and 6) using their elevation discrimination task (which is particularly sensitive to the spatial distribution of auditory attention; see Spence & Driver, 1994) for sound targets following lateral visual cues. On the basis of these results, Spence and Driver suggested that asymmetrical links between audition and vision may govern exogenous covert orienting, since the presentation of uninformative peripheral auditory cues reliably results in the cross-modal orienting of covert visual attention, whereas the spatial distribution of auditory attention is apparently unaffected by uninformative visual cues when eye movements are prevented (though see Givotti & Peri, 1963; Maruyama, 1961; Ward, 1994; and Ward, McDonald, & Golestani, in press, for differing results when eye movements were not excluded).

Tassinari and Campara (1996) conducted the only published study (to our knowledge) of cross-modal links in purely exogenous orienting between vision and touch. Participants were presented either with a spatially uninformative tactile cue (a tap on the shoulder) prior to a visual target (the illumination of a square on a screen) or with a visual cue prior to a tactile target (the same stimuli but in the reverse order). They reported no advantage for visual detection latencies on the ipsilateral side of an uninformative tactile cue at a 200-msec cue–target SOA, although significant cross-modal inhibitory effects were observed at longer intervals on this side (i.e., at SOAs in the range of 600–4,000 msec), suggesting the existence of cross-modal links in inhibition of return (IOR²; though see Spence & Driver, 1998a, 1998b, for further discussion of these data). In addition, ipsilateral visual cues were

reported to inhibit tactile detection at an SOA of 200 msec, although there was little evidence for such cross-modal IOR at the longer intervals.

The absence of any early advantage on the cued side in Tassinari and Campara's (1996) study should not be taken as conclusive evidence against cross-modal links in early facilitatory components of exogenous orienting for the case of vision and touch, because the cue and target stimuli were presented from very different spatial locations, even when on a common side. This means that any cross-modal facilitatory effects that were present at the cued location itself may simply have dissipated at the large ipsilateral cue–target separations that were examined, as found by Driver and Spence (in press) in their audiovisual cuing study. We attempted to examine all possible links in exogenous covert spatial orienting between touch and the other modalities (audition and vision) in the present series of experiments, while ensuring that ipsilateral cues and targets were always presented from common external positions, across the modalities, to minimize the chance that we might miss any early advantage for targets on the cued side.

All our experiments had the following critical features: (1) The peripheral cues were always spatially uninformative, so that only exogenous mechanisms should be involved. (2) All our tasks involved speeded discrimination of lateralized targets, so that accuracy as well as speed could be measured, and, hence, criterion-shifting accounts could be assessed for any cuing effects. (3) The eye movements of a subset of participants were measured in every experiment to rule out the possibility of overt orienting accounting for any cuing effects observed, since it has been demonstrated that merely fixating the appropriate target location can significantly facilitate speeded responses to imperative stimuli, even for tactile targets in complete darkness (Driver & Grossenbacher, 1996; Honoré, 1982; Honoré, Bourdeaud'hui, & Sparrow, 1989; Larmande & Cambier, 1981). (4) We concentrated on a range of short cue–target SOAs, to maximize our chances of observing any early advantages on the cued side due to exogenous covert spatial orienting.

EXPERIMENT 1

In Experiment 1, we investigated whether the presentation of a spatially uninformative auditory cue on one side or the other would lead to a covert exogenous shift in tactile attention to the cued side. Participants were required to make a speeded discrimination (continuous vs. pulsed) for tactile targets presented to either the left or the right index finger. Every target was preceded at a variable SOA by an auditory cue on the same side as the subsequent target (50% of the trials) or on the opposite side (50% of the trials). Auditory cues were presented from one of two loudspeaker cones situated directly in front of either index finger (i.e., from the same external position as ipsilateral tactile targets). Advantages for targets on the cued side are typically short-lived in exogenous covert orienting

Figure 1. Schematic bird's-eye view of the fixation light, cue loudspeakers, tactile stimulators, and body position (head, shoulders, and arms cartooned) in Experiment 1.

studies, lasting for only 200–300 msec after cue onset within hearing and vision (see Spence & Driver, 1994, 1997). We therefore used a range of short SOAs in the present study to maximize the possibility of detecting any such early cross-modal cuing effects. The potential influence of cross-modal links on the phenomenon of IOR, which can dominate at longer interstimulus intervals, has recently been documented elsewhere (e.g., Spence & Driver, 1998a, 1998b) and so was not examined here.

Method

Participants. Sixteen unpaid first-year psychology students at the University of Melbourne were recruited through advertisement to participate in this experiment for course credit. All of the participants (5 men and 11 women) were right-handed. Their mean age was 20 years, with a range of 17–38 years. The participants in this and subsequent experiments were naive as to the purpose of the studies. All reported normal hearing and touch, and normal or corrected-to-normal vision. The experimental session lasted approximately 55 min.

Apparatus and Materials. The participants were seated at a table in a darkened room, with their arms resting on the tabletop, facing straight ahead. Head movements were precluded by an adjustable chinrest and nose brace. A green LED was used as a fixation point, placed directly in front of the participant. Auditory cues were presented from one of two loudspeaker cones (12.7 cm in diameter) situated at an eccentricity of 41° from fixation on either side. The fixation light and loudspeakers were located on a virtual circle (with a radius of 50 cm) centered on the participant's head at eye level. Highly localizable auditory cues were used, each consisting of three 15-msec bursts of white noise presented at 30-msec intervals, at an intensity of 90 dB(A) as measured from the participant's ear position.

The participants rested the left index finger over a circular aperture in a tactile stimulator placed directly behind the left loudspeaker cone, and the right index finger on a stimulator placed behind the right loudspeaker (see Figure 1 for a schematic bird's-eye view of the experimental setup). Tactile targets consisted of the presentation of a circular rod (0.7 mm in diameter) to the underside of either index finger. This rod was raised through the aperture in the tactile stimulator to produce target events (travel time for the rod

was 5 msec; the rod was capable of vertically displacing a weight of 5 g). This led to a clear perception that the finger had been lightly tapped. On half of the trials, the rod was raised and kept in constant contact with either index finger for 120 msec (a continuous target). On the remainder of the trials, the rod was raised (for 10 msec) and then lowered (for 20 msec) four times consecutively (a pulsed target). The participants were unable to see either their hands or the tactile stimulators (which were placed behind a black cloth), to prevent any possibility that visual motion induced by the presentation of tactile targets could influence performance serendipitously. Velcro straps were used to ensure that the index finger of one hand remained over each aperture throughout each block of trials. White noise was presented continuously at 70 dB(A) (i.e., at a much lower amplitude than the auditory cues) from a loudspeaker cone situated centrally under the table, in order to mask any slight noises caused by making a response or by the operation of the tactile stimulators. Preliminary testing revealed that the participants were completely unable to detect the sound of these stimulators under such conditions.

The participants were required to depress two foot pedals situated under their right foot throughout each block of trials: one positioned under the toes, and the other under the heel. They had to raise the heel briefly in response to continuous tactile targets, and they had to raise the toes briefly in response to pulsed tactile targets, as rapidly as possible. RTs were measured in milliseconds from target onset using an 82C54 interval-timer chip on a digital input-output card (DCM-16, Blue Chip Technology) that interfaced to the loudspeaker cones, tactile stimulators, and foot pedals. The horizontal position of the left eye of each participant was monitored (see Procedure section for details) by means of an Eye-Trac 200 monitor (Applied Science Laboratories), which relies on the infrared scleral reflectance method. This monitor was connected to the microcomputer controlling the experiment via an analog-to-digital interface board (ADC-42, Blue Chip Technology). Timing of the stimuli and responses was controlled by an IBM 386 compatible microcomputer, using a program written in Turbo Pascal.

Design. There were two blocks of 30 practice trials (which were not analyzed), usually followed by five experimental blocks of 144 trials (though 3 of the participants had time to complete only four experimental blocks within their testing sessions). There were 12 equiprobable conditions produced by crossing the three within-participant factors of target side (left or right), SOA (150, 200, and 300 msec), and cuing (cue ipsilateral vs. contralateral to the subsequent target). The various conditions appeared in a random order, and equal numbers of continuous and pulsed targets were presented from the left and the right side within each experimental block.

Procedure. The fixation light was continuously illuminated during the experimental session, and the participants were instructed prior to the experiment, and periodically throughout, to maintain fixation on it during each trial. At the beginning of every trial, an auditory cue was presented from either the left or the right loudspeaker cone for 75 msec. After a further delay (unpredictably 75, 125, or 225 msec depending on SOA), the tactile target was presented from the stimulator situated on the ipsilateral side (50% of the trials) or the contralateral side (the remaining 50% of the trials) as the cue. The participants were instructed to discriminate the tactile target as rapidly and accurately as possible with a foot-pedal response, and the trial was terminated if no response was made within 1,000 msec of target onset (1,500 msec in the first practice block). If no response was made, or if the response was incorrect, then the feedback signal was presented. This consisted of the pulsed presentation of white noise from both cue loudspeaker cones, together with tactile stimulation from both tactile stimulators, all for six 10-msec bursts separated by 30-msec intervals. There was a 2,000-msec interval between the onset of the target in one trial and the onset of the auditory cue on the next trial. The participants were instructed to ignore the auditory cues as much as possible, because they were spatially uninformative with regard to the likely location for tactile targets.

Table 1
Mean of Median Reaction Times (in Milliseconds)
and Their Standard Errors, Percentages of Errors,
and Mean Cuing Effects (in Milliseconds) for
Tactile Targets in Experiment 1 as a Function
of the Position of the Auditory Cue and the
Stimulus Onset Asynchrony (SOA; in Milliseconds)

SOA	Cue Position						Mean Cuing Effect
	Ipsilateral			Contralateral			
	RT	SE	% Errors	RT	SE	% Errors	
150	605	20	4.8	615	19	5.0	10*
200	594	21	5.2	603	20	6.2	9
300	583	19	5.2	592	20	4.1	9*

* $p < .05$, t -test pairwise comparison.

The eye-movement monitor was calibrated to provide a signal to the computer whenever an eye movement of 3° or more was detected in the period between the onset of the cue and the initiation of a manual choice response. This was the smallest signal that we could reliably detect across participants with the apparatus; however, note that, in any case, the peripheral auditory cues and tactile targets were located very far from central fixation (at 41°). The monitor was recalibrated to confirm true "straight-ahead" at the beginning of every block and also during a block if fixation ever appeared to drift from the calibrated center point. Trials on which potential eye movements were detected (note that blinks sometimes resulted in signals that were indistinguishable from actual eye-movement signals) were automatically excluded from the analyzed data.

Results

All participants performed the tactile discrimination task at over 85% correct. Trials on which an incorrect response occurred were discarded from the RT analysis. Trials on which a response was made prior to target onset, or where no response was made within 1,000 msec of target onset (when the trial was terminated) were also discarded, leading to the removal of 4.5% of the trials. Due to excessive eye movements, 2.4% of trials were also removed. The interparticipant mean of participants' median RTs (after these exclusions), together with the corresponding error rates for all trials, are shown in Table 1.³

The data were analyzed using a within-participant analysis of variance (ANOVA), with three factors [target side (2) $\times$ cuing (2) $\times$ SOA (3)]. In the RT analysis, there was a main effect of SOA [$F(2,30) = 17.5$, $p < .0001$], with the participants responding more rapidly to targets presented at the longer SOAs (the conventional "alerting" effect; see Niemi & Näätänen, 1981; Spence & Driver, 1994). There was also a main effect of cuing [$F(1,15) = 9.0$, $p < .01$], caused by the participants' responding more rapidly overall on ipsilateral trials ($M = 594$ msec) than on contralateral trials ($M = 603$ msec). There was no interaction between SOA and cuing [$F(2,30) < 1$, n.s.], suggesting that the facilitation of performance on ipsilateral trials was consistent at all three SOAs tested (though the results of t -test pairwise comparisons at each SOA are shown for completeness in Table 1). None of the other effects or interactions was significant. An analogous ANOVA on the error data revealed no significant effects

or interactions. The participants made as many errors on ipsilateral trials as on contralateral trials overall ($M = 5.1\%$ for both conditions).

Discussion

The presentation of a spatially uninformative auditory peripheral cue in Experiment 1 led to an advantage in the discrimination (continuous vs. pulsed) of tactile targets presented from the same position, relative to targets presented contralateral to the cue. The participants also made fewer errors on ipsilateral trials than on contralateral trials at the 150-msec SOA, allowing us to rule out a simple criterion-shifting account of the cuing effect in RT at this interval. Nor can overt orienting toward the cue explain the present RT effects, because all trials on which an eye movement might have occurred were removed from the analysis of the data. Therefore, these data unambiguously demonstrate that the peripheral presentation of an auditory cue can result in the cross-modal orienting of covert tactile attention toward the cued side. Because the cue was spatially uninformative with regard to the likely target location, purely exogenous orienting mechanisms are presumably involved.⁴ This result therefore extends previous findings, which have shown that auditory cues lead to the covert cross-modal exogenous orienting of visual attention, as well as to intramodal auditory orienting (Spence & Driver, 1994, 1997). The results of Experiment 1 show, for the first time, that auditory events can also attract covert tactile attention. In Experiment 2, we examined whether spatially uninformative visual peripheral cues could similarly lead to the cross-modal exogenous orienting of tactile attention.

EXPERIMENT 2

Method

Participants. Seventeen (11 men and 6 women) naive participants were recruited through advertisement at the University of Cambridge to take part in this experiment. Their mean age was 23 years, with a range of 18–35 years. All but 1 of them were right-handed. Eight of the participants had their eye movements monitored to ensure that overt orienting toward the cue could not account for any cuing effects observed. All participants were paid £4 (approximately \$7 U.S.) for their participation.

Apparatus, Materials, Design, and Procedure. A yellow LED (luminance of 41.4 cd/m^2) was used as the fixation point, placed 48 cm from the participant's eyes, at an angle of 33° below eye level.⁵ Visual cues consisted of the illumination of a single red LED (luminance of 64.3 cd/m^2) for 90 msec on one or the other side. These cues were placed at the same elevation as the fixation light, and at an eccentricity of 15° (12.9 cm) to either the left or the right of fixation (see Figure 2 for a schematic bird's-eye view of the experimental setup). The participants rested their forearms and hands, palms downward, on a board placed directly in front of them. They were required to press the tip of the left index finger over the upper end of a small hole situated directly behind (from the participants' viewpoint) the left target LED and to press the right index finger over an aperture situated directly behind the right target light. Tactile targets were presented using 12-V solenoids (with a rise time of approximately 25 msec), one placed directly below the aperture on either side. A plastic rod with a blunt conical tip (2 mm in diame-

Figure 2. Schematic bird's-eye view of the fixation light, cue lights, tactile stimulators, and body position in Experiment 2.

ter at the extremity) was attached to the end of the plunger located in each solenoid. The plunger was raised so that the tip of this rod came up through the hole and into contact with the participant's finger, with a pressure of about 10 g. Rubber bungs were used to dampen the sound made by the action of the solenoids. The participant's arms were placed under a black cloth, and velcro straps were again used to ensure that the index fingers remained over the apertures of the tactile stimulators throughout each block of trials. Continuous tactile targets consisted of the rod being raised against one of the participant's fingers for a duration of 210 msec, and pulsed targets consisted of the rod being raised three times for 30 msec at 90-msec intervals. The participants were presented with white noise over headphones at 92 dB(A) throughout every experimental block, to mask any sound made by the operation of the solenoids or the foot pedals. All noises were attenuated further by approximately 26 dB via the additional use of plastic earplugs. Preliminary testing again revealed that the participants were completely unable to detect the sound of the tactile stimulators operating under these conditions. An Eye-Trac 210 was used to monitor eye position in this experiment. The fixation light was illuminated at the beginning of every trial and was extinguished as soon as a response was made or, if no response had been made, within 1,500 msec of target onset, at which time the trial was terminated. In all other respects, the apparatus, materials, design, and procedure were as described for Experiment 1.

Results

All participants performed the tactile discrimination task at over 75% correct. Due to potential excessive eye movement for the participants whose eye position was monitored, 6% of the trials were removed. Less than 2% of the trials were removed from the analysis because the participants failed to make a response within 1,500 msec of target onset. The interparticipant mean of the participants' median RTs (after these exclusions), together with the corresponding error rates for all trials, are shown in Table 2, pooled across the between-participant factors of eye-movement monitoring, and the within-participant factor of target side, since these had no important influences in the analyses described below.

The data were analyzed using a mixed ANOVA, with the between-participant factor of eye monitoring and with three within-participant factors [target side (2) $\times$ cuing (2) $\times$ SOA (3)]. In the RT analysis, there was a near-significant main effect of SOA [$F(2,30) = 3.2$, $p = .05$], with the participants responding more rapidly at the 300-msec SOA ($M = 593$ msec) than at the 150-msec interval ($M = 601$ msec), presumably reflecting the usual alerting effect as before. There was also a main effect of cuing [$F(1,15) = 23.2$, $p = .0002$], caused by the participants' responding more rapidly on ipsilateral trials ($M = 592$ msec) than on contralateral trials ($M = 601$ msec) overall. However, this spatial cuing effect reached significance only at the two longer SOAs (see Table 2), resulting in an interaction between cuing and SOA [$F(2,30) = 5.2$, $p = .01$]. It should be noted that a criterion-shifting account for these RT effects can only be ruled out at the 200-msec SOA, where the participants were both faster and more accurate for targets on the cued side (at the 300-msec SOA, the RT effect was offset by a reverse trend in the error data). The participants also responded more rapidly to tactile targets presented to the right index finger ($M = 593$ msec) than to the left finger ($M = 601$ msec), resulting in a main effect of target side [$F(1,15) = 5.7$, $p = .03$]. This RT effect was also offset by a reverse trend in the error data, making a criterion-shifting account plausible. None of the other terms in the RT analysis reached significance [e.g., for target side $\times$ cuing, $F(1,15) = 0.0$, n.s.; for target side $\times$ SOA, $F(2,30) = 1.5$, $p = .23$; for target side $\times$ cuing $\times$ SOA, $F(2,30) = 1.1$, n.s.], so target side did not influence the spatial cuing effect. An analogous ANOVA on the error data revealed no main effects or interactions.

Discussion

The participants responded significantly faster to tactile targets presented from the same position as the spatially uninformative visual cue than when cue and target were presented contralaterally. Overt orienting cannot account for this result, since the eye movements of a subset of the participants were monitored, and yet no influence of this eye-monitoring factor was observed. The eye-monitored group actually showed a mean cuing benefit that was

Table 2
Mean of Median Reaction Times (in Milliseconds)
and Their Standard Errors, Percentages of Errors,
and Mean Cuing Effects (in Milliseconds) for
Tactile Targets in Experiment 2 as a Function
of the Position of the Visual Cue and the
Stimulus Onset Asynchrony (SOA; in Milliseconds)

SOA	Cue Position						Mean Cuing Effect
	Ipsilateral			Contralateral			
	RT	SE	% Errors	RT	SE	% Errors	
150	602	15	9.6	597	14	10.6	-5
200	585	14	9.3	603	14	9.5	18†
300	586	14	9.4	597	16	7.9	11*

* $p < .05$, t -test pairwise comparison. † $p < .01$, t -test pairwise comparison.

Figure 3. Schematic view of the position of the fixation light, tactile cue stimulators, target loudspeaker cones, and target lights, as seen from behind the participant's head, in Experiment 3.

numerically slightly greater than that for the unmonitored group (mean contralateral–ipsilateral difference of 10 msec overall for the monitored group, relative to 7 msec for the unmonitored group). Given that the RT effect at the 200-msec SOA was matched by a tendency for the participants to respond more accurately on ipsilateral trials than on contralateral trials, a simple criterion-shifting account for these results is also untenable. Hence, this experiment provides the first unequivocal evidence that visual events can exogenously summon covert tactile attention, thus extending the cross-modal influence from audition on touch that was documented in Experiment 1.

It is unclear which of the many differences in experimental design between this study and that reported by Tassinari and Campara (1996) are responsible for the fact that an advantage following ipsilateral cues was reported at the 200-msec SOA in the present study, whereas a disadvantage (i.e., participants actually responding more rapidly on contralateral trials than on ipsilateral trials) was reported by Tassinari and Campara at the same interval in their own visual-to-tactile spatial cuing study with a detection measure (see the General Discussion section for a detailed analysis of this point). The important point to note for present purposes is that the continuous/pulsed discrimination task used here evidently provides a reliable means of measuring the spatial distribution of facilitatory exogenous tactile attention following both auditory cues (Experiment 1) and visual cues (Experiment 2).

Nevertheless, it should be noted that the size of the cuing effects reported in Experiments 1 and 2 using the continuous/pulsed tactile discrimination task were somewhat smaller than those typically seen when the targets are in audition or vision (e.g., Spence & Driver, 1994, 1997). It may be that the effects of exogenous orienting are simply smaller for touch than for the other modalities. Alternatively, however, these differences may re-

flect differences in the particular discrimination tasks used. Spence and Driver (1994) reported that, within audition at least, exogenous cuing effects were much larger when a spatial discrimination task was used than when participants were required to make a frequency discrimination response. It remains a question for further investigation whether a similar increase in cuing effects for tactile targets could also be achieved simply by introducing a spatial discrimination response. For the moment, the two experiments reported so far have demonstrated that the peripheral presentation of both auditory and visual cues results in the exogenous covert orienting of tactile attention in the cued direction. In Experiment 3, we examined the converse influences: that is, whether spatially uninformative tactile cues lead to the cross-modal exogenous orienting of both auditory and visual attention.

EXPERIMENT 3

Uninformative tactile peripheral cues were now presented prior to randomly intermingled auditory and visual targets. We used an adaptation of the orthogonal-cuing paradigm developed by Spence and Driver (1994, 1996, 1997), in which participants are required to judge the elevation (up vs. down) of randomly intermingled auditory and visual targets presented from one of two positions (at the same azimuth, but at different elevations) on either side of fixation. In contrast to the simple detection measure used by Buchtel and Butter (1988; Butter et al., 1989) and to the speeded discrimination of non-spatial dimensions, such as frequency or intensity (e.g., Posner, 1978; Spence & Driver, 1994), this spatial discrimination of elevation has now been repeatedly shown to provide a sensitive measure of the distribution of both auditory and visual attention (e.g., Spence & Driver, 1997). Spatially uninformative tactile cues were presented to participants via one of two tactile stimulators placed at the same eccentricity as possible targets on one side and midway between them in terms of elevation (see Figure 3 for a schematic view of the experimental apparatus, as seen from behind the participant's cartooned head). If there are mutual cross-modal links between touch and the other modalities in the control of exogenous covert orienting, then participants should respond more rapidly and/or accurately on those trials where the cue and target are presented from the same side than when they occur contralaterally. Although ipsilateral cue and target stimuli were not actually presented from identical spatial positions in this experiment (they differed in elevation; see Figure 3), the distance between cues and ipsilateral target stimuli was much smaller than in Tassinari and Campara's (1996) study, and their eccentricity was equivalent.

Method

Participants. Twenty-one unpaid (5 men and 16 women) right-handed students from the University of Melbourne were recruited to participate in this experiment. Their mean age was 21 years, with a range of 17–36 years. Twelve of the participants had their eye movements monitored, using the Eye-Trac 200 infrared monitor.

Table 3
Mean of Median Reaction Times (in Milliseconds)
and Their Standard Errors, Percentages of Errors,
and Mean Cuing Effects (in Milliseconds) for Auditory
and Visual Targets in Experiment 3 as a Function
of the Position of the Tactile Cue and the
Stimulus Onset Asynchrony (SOA; in Milliseconds)

SOA	Cue Position						Mean Cuing Effect
	Ipsilateral			Contralateral			
	RT	SE	% Errors	RT	SE	% Errors	
Auditory Targets							
150	534	9	3.6	550	9	4.3	16†
200	524	9	5.6	539	7	6.2	15†
300	524	8	5.5	534	9	7.0	10†
Visual Targets							
150	489	8	3.4	493	8	3.5	4
200	466	7	3.8	488	8	5.4	22†
300	454	8	4.8	484	8	5.6	30†

† $p < .01$, t -test pairwise comparison.

Apparatus, Materials, Design, and Procedure. The auditory targets were presented from any one of four loudspeaker cones (identical in design to those used in Experiment 1) placed 50 cm from the participant at a horizontal eccentricity of 41°. There was a pair of these loudspeaker cones on both the left and the right of the participant, each loudspeaker placed 23.5 cm above or below ear level. A red LED with a luminance of 64.3 cd/m² was placed next to the center of each of these loudspeaker cones to provide a possible visible target. Auditory targets consisted of a 100-msec burst of white noise presented at 85 dB(A); white noise was chosen because it provides an auditory event that is relatively easy to localize vertically (see Spence & Driver, 1994). Visual targets comprised the illumination of one of the four possible target LEDs for the same duration. The up-down decision for the targets required an elevation discrimination of 33°.

Equal numbers of auditory and visual targets were presented from each of the four possible target positions within each block of trials in a random order, and every target was preceded by a spatially uninformative tactile cue on the same or opposite side. The tactile stimulators used for targets in Experiment 1 were now used to present the cues, which consisted of the rod in one stimulator being raised for 15 msec on three successive occasions, each separated by 15-msec intervals. The stimulators were situated at an intermediate elevation to the possible target locations on either side. The participants were required to raise the toes briefly in response to auditory or visual targets coming from one of the two upper positions and to raise the heel in response to lower targets. Erroneous responses now elicited simultaneous feedback in the auditory, visual, and tactile modalities. In all other regards, the apparatus, materials, design, and procedure followed that of Experiment 1. Three of the participants had enough time to complete only four rather than five experimental blocks within their testing sessions.

Results

All participants performed the elevation task at over 85% correct. Less than 6% of the trials were removed due to potential excessive eye movement for those participants whose eyes were monitored (remember that blinks sometimes resulted in eye-movement signals that were indistinguishable from actual saccades). Less than 4% of the trials were removed because the participants failed to make a choice response within 1,000 msec of target

onset. The interparticipant mean of the participants' median RTs (after these exclusions), together with the corresponding error rates for all trials, are shown in Table 3, pooled across the between-participant factors of eye-movement monitoring and target side, which did not affect the major results.

The data were analyzed using a mixed ANOVA, with the between-participant factor of eye monitoring and with four within-participant factors [target modality (2) × target side (2) × cuing (2) × SOA (3)]. In the RT analysis, there was a main effect of cuing [$F(1,19) = 58.1$, $p < .0001$], caused by the participants' responding more rapidly overall on ipsilateral trials ($M = 500$ msec) than on contralateral trials ($M = 518$ msec). There was a near-significant interaction between cuing and SOA [$F(2,38) = 3.2$, $p = .05$], reflecting the fact that cuing effects increased at the longer SOAs (mean contralateral–ipsilateral difference of 12 msec at the 150-msec SOA, 19 msec at 200-msec SOA, and 23 msec at the 300-msec SOA). The interaction between modality, cue position, and SOA was also significant [$F(2,38) = 4.7$, $p = .01$]. Pairwise comparisons (t tests) revealed that cuing effects were significant for auditory targets at all three SOAs and for visual targets at the two longer intervals (all p s $< .01$; see Table 3).

There was also a main effect of SOA [$F(2,38) = 12.1$, $p = .0001$], with the participants responding more rapidly to targets when presented at the longer SOAs, reflecting the usual alerting effect. The participants also responded more rapidly to visual targets ($M = 481$ msec) than to auditory targets ($M = 537$ msec), leading to a main effect of target modality [$F(1,19) = 184.8$, $p < .0001$]. The effect of eye monitoring was just significant [$F(1,19) = 4.7$, $p = .04$], revealing that eye-monitored participants responded more rapidly ($M = 495$ msec) than those in the unmonitored group ($M = 524$ msec). Although there is no obvious explanation for this result, the important point to note is that eye monitoring did not interact with any of the other factors; of particular importance, there was no interaction with cuing [$F(1,19) = 0.0$, n.s.]. Furthermore, the mean cuing effects were the same (mean contralateral–ipsilateral difference of 18 msec overall) for both the monitored and the unmonitored participant groups. None of the other effects or interactions in this RT analysis was significant.

An analogous ANOVA on the error data revealed a main effect of SOA [$F(2,38) = 13.6$, $p < .0001$], with the participants making fewer errors at the 150-msec interval ($M = 3.7\%$) than at either of the longer SOAs ($M = 5.3\%$ at 200 msec; $M = 5.8\%$ at 300 msec). There was also a main effect of cuing [$F(1,19) = 9.6$, $p < .01$], caused by fewer errors on ipsilateral trials ($M = 4.5\%$) than on contralateral trials ($M = 5.3\%$), in support of the spatial cuing effects in the RT data. None of the other effects or interactions in the analysis of the error data was significant.

Discussion

Elevation judgments for both auditory and visual targets were faster and more accurate for targets appearing shortly after the presentation of a spatially uninformative

tactile cue, on the same side rather than opposite side of fixation as the target. These cuing effects were present at all three SOAs for auditory targets and at the 200- and 300-msec SOAs for visual targets (the trend for a similar cuing effect at the 150-msec SOA for visual targets failed to reach significance). These results suggest that the presentation of a peripheral tactile cue can lead to the cross-modal exogenous orienting of both auditory and visual attention in the cued direction. The fact that no differences were observed between the spatial cuing effects for the two eye-movement groups suggests that overt orienting cannot explain these cuing effects and, thus, that cross-modal covert orienting was responsible instead.

The cuing effect failed to reach significance for visual targets at the shortest SOA (i.e., at 150-msec) in Experiment 3. This time course is somewhat surprising, given that intramodal cuing studies normally show exogenous cuing effects peaking at much shorter cue–target intervals (e.g., Spence & Driver, 1994, 1997). However, it should be noted that there are various difficulties associated with comparing the relative size and time course of cross-modal cuing effects across different pairs of sensory modalities. First, the physical SOAs reported here may not correspond to the psychological SOAs when cue and target stimuli are presented in different modalities. Simple RT studies have revealed that simple response latencies to visual stimuli are usually longer than to either tactile or auditory stimuli (e.g., Dinnerstein & Zlotogura, 1968; Elliott, 1968; Rutschmann & Link, 1964). Consequently, the most effective SOA between cues and targets in different modalities may vary as a function of the particular stimulus pairs under investigation (see Spence & Driver, 1997, for a fuller discussion of this point). Second, the magnitude of exogenous cuing effects depends on the intensity of the particular cuing stimuli used (e.g., Lambert & Hockey, 1991). No attempt was made in the present experiments to match the intensity of the auditory, visual, and tactile cues, and, in fact, it is unclear whether such a matching procedure can be sensibly done for the present purposes. Given these difficulties, drawing any firm conclusions from the time course of the various cuing effects for different pairs of sensory modalities in the present experiments might be somewhat premature.

GENERAL DISCUSSION

Our results demonstrate that there are extensive cross-modal links between touch, vision, and audition in the control of exogenous covert orienting. In Experiments 1 and 2, it was found that the speeded discrimination (continuous vs. pulsed) of tactile targets was affected by the prior presentation of a spatially uninformative auditory peripheral cue (Experiment 1) or visual peripheral cue (Experiment 2) on the same versus opposite side as the subsequent tactile target. In Experiment 3, elevation discriminations (up vs. down) for auditory and visual targets were similarly influenced by the ipsilateral versus contralateral presentation of a tactile cue, with better performance on the side of the cue shortly after it. Note that these experiments

present a similar pattern of cross-modal results overall to those reported by Bachtel and Butter (1988; Butter et al., 1989). However, in contrast to their studies and to the other previous studies of cross-modal orienting (e.g., Farah et al., 1989; Ward, 1994), we were able to rule out various nonattentional explanations for our spatial cuing effects on RT. For instance, any contributions from overt orienting were ruled out (by monitoring the eye position for a majority of the participants), as were criterion shifts (by measuring accuracy as well as latency in speeded discrimination tasks) and response priming (by having the side of the cue be entirely irrelevant to the required choice response, unlike several previous lateral cuing studies, where participants made left/right responses to targets following a cue on the left versus right; see Bernstein & Edelstein, 1971; Simon & Craft, 1970; Ward, 1994). Moreover, since our cues were always spatially uninformative, endogenous mechanisms should not be involved, and our experiments should have isolated purely exogenous covert orienting mechanisms (see note 4).

Since such alternative explanations can be ruled out for our data, the various cuing effects reported here presumably all reflect cross-modal exogenous covert orienting, triggered by the peripheral presentation of salient auditory, visual, or tactile events. As such, the present findings extend the previous cross-modal cuing results of Spence and Driver (1994, 1997), who found with similar methodologies that peripheral auditory cues can result in both the intramodal orienting of auditory attention and the cross-modal orienting of visual attention. The results of the present experiments extend those findings dramatically, to reveal additional links between touch, vision, and hearing. To summarize all these data, unambiguous cross-modal links in exogenous covert orienting have now been found between all pairings of touch, audition, and vision, with the sole exception that uninformative visual cues apparently do not influence the spatial distribution of auditory exogenous attention when eye movements are prevented (see Spence & Driver, 1997), a point to which we return later. These cross-modal links in covert exogenous orienting are summarized schematically in Figure 4.

Our findings on tactile–visual links contrast somewhat with those previously observed by Tassinari and

Figure 4. Schematic view of the cross-modal links in exogenous covert orienting, which have been unambiguously demonstrated to date. Note that we have not indicated an effect of vision on hearing (see Spence & Driver, 1997).

Campara (1996). We found (in Experiment 3) an advantage for visual targets ipsilateral to tactile cues and (in Experiment 2) an advantage for tactile targets ipsilateral to visual cues at short cue–target SOAs in discrimination tasks. By contrast, in their detection experiments, Tassinari and Campara found that tactile cues had no reliable effect on visual performance at a 200-msec SOA, and that tactile detection latencies were significantly inhibited by the ipsilateral presentation of a visual cue at the same interval, overlapping the SOAs at which we found an ipsilateral advantage.

It could be argued that Tassinari and Campara's (1996) failure to demonstrate any facilitatory effects might have been due to their use of a simple detection measure (which may be fairly insensitive to the distribution of facilitatory tactile attention; see Posner, Davidson, & Nissen, 1976, cited in Posner, 1978), rather than a discrimination task like those in the present experiments, and to the consequent possible involvement of IOR effects (see note 2). Tassinari, Aglioti, Chelazzi, Peru, and Berlucchi (1994) found no early facilitatory effects from a spatially uninformative visual cue on detection latency even for subsequently presented visual targets; instead, they found only significant IOR effects at the majority of SOAs. They argued that the absence of intramodal facilitatory cuing on the ipsilateral side to the cue was not caused by a failure of the peripheral visual cue to elicit any exogenous visual orienting toward it, but rather by such facilitatory influences being opposed by rapidly emerging IOR effects, which may have occurred contemporaneously. A similar explanation might also account for the absence of an early advantage on the cued side in Tassinari and Campara's cross-modal study of visual–tactile interactions; that is, cross-modal exogenous orienting effects may have been present at their 200-msec SOA (as found here), but they might simply have been obscured by any opposing IOR effects that would also apply ipsilaterally to the cue if they arose (and which may be more apparent in detection tasks).

Previous research has demonstrated that IOR can affect performance in certain discrimination tasks (e.g., Cheal, Chastain, & Lyon, *in press*; Pratt, 1995) but not in others (e.g., Pontefract & Klein, 1988, cited in Klein & Taylor, 1994; Spence & Driver, 1994, 1997; Terry, Valdes, & Neill, 1994). Of particular relevance is the finding that speeded elevation discriminations within the orthogonal-cuing procedure, as used in Experiment 3, showed no trace of any IOR effect in Spence and Driver's previous studies, at SOAs in the range of 100–1,000 msec. As a consequence, response latencies in the present experiment, which utilized similar discrimination tasks, may have been influenced solely by the spatial distribution of facilitatory exogenous attention, producing the observed advantages for ipsilateral trials while being unaffected by any opposing IOR effects.

Cue and target stimuli were also presented from very different positions even on ipsilateral trials in Tassinari

and Campara's (1996) study (i.e., tactile stimuli were presented to the participant's shoulder, and visual targets from a screen placed directly in front of them), whereas we made ipsilateral locations across modalities as similar as possible in the present experiments. Driver and Spence (*in press*) have shown that facilitatory cross-modal cuing effects at short cue–target SOAs dissipate rapidly as cue–target separation increases; however, effects such as IOR can affect responses to all stimuli presented in a cued hemifield (see Berlucchi, Tassinari, Marzi, & Di Stefano, 1989; Tassinari, Aglioti, Chelazzi, Marzi, & Berlucchi, 1987; Tassinari *et al.*, 1994; though also see Maylor & Hockey, 1985, Experiment 2; and O'Donnell & Pratt, 1996). Therefore, differences between the cue–target spatial separation used in Tassinari and Campara's experiments versus those reported here may also help to explain the discrepancy between the cuing effects reported in the two studies.

For present purposes, the most important point to note is that, whatever the correct explanation for the absence of ipsilateral advantages in Tassinari and Campara's (1996) study, the present continuous/pulsed discrimination task as used in Experiments 1 and 2 and the up/down elevation discrimination as used in Experiment 3 (and in Spence & Driver, 1994, 1997) evidently provide a reliable measure of the advantages that can accrue as a function of exogenous covert orienting of attention in the cued direction. As such, these tasks might be profitably used in further studies concerned with the exact nature of the extensive cross-modal links that we have uncovered for the first time here.

Recent studies that have focused on the effects of spatially uninformative cues upon speeded target detection at long intervals following an uninformative peripheral cue have revealed that the phenomenon of IOR can also occur cross-modally (e.g., Reuter-Lorenz, Jha, & Rosenquist, 1995; Reuter-Lorenz & Rosenquist, 1996; Spence & Driver, 1998a, 1998b, 1998c; Tassinari & Campara, 1996), as we found here for the early facilitatory influences of attention. For instance, Spence and Driver (1998c) used a target–target procedure in which the location of a target on one trial acted as the spatially uninformative cue for the target on the next trial.⁶ They reported that the speeded detection of targets in all three modalities was inhibited (at interstimulus intervals of 950–1,250 msec) by the prior presentation of an auditory, visual, or tactile target from the same location, relative to performance on trials where successive stimuli were presented contralaterally. These results suggest that there are intramodal and cross-modal links in IOR between all possible combinations of successive auditory, visual, and tactile stimuli. When taken together with the facilitatory results from the present experiments, plus the audiovisual experiments of Spence and Driver (1997), it becomes clear that very extensive cross-modal links between audition, vision, and touch affect the processing of stimuli appearing in the various modalities.

These cross-modal links in information processing imply that some degree of spatial integration must arise between the modalities prior to participants making a response, such that common locations are treated as such across the different senses. How such cross-modal coordination of spatial representation arises is a nontrivial problem, given that information is initially coded in very different coordinates in the various senses. For instance, auditory stimuli are initially coded tonotopically, visual stimuli retinotopically, and tactile stimuli somatotopically, so that there is little in common between a shared location across the modalities at input. However, neurophysiological studies in a number of species have demonstrated that, by the time this sensory information reaches the deeper layers of the superior colliculus (SC), it has been transformed into spatiotopically arrayed "maps" of auditory, visual, and somatosensory space (for reviews see Groh & Sparks, 1996; King, 1993; B.E. Stein & Meredith, 1993). Moreover, these maps are in approximate spatiotopic register with each other and with the motor maps found in the deepest layers, which are associated with overt orienting of the eyes, head, and body (e.g., Groh & Sparks, 1996; Sparks, 1988; B. E. Stein, 1984). Neurophysiological and neuropsychological studies have implicated SC involvement in the subcortical control of both overt and covert exogenous orienting both in animals (e.g., Dean, Redgrave, Sahibzada, & Tsuji, 1986; Grantyn & Grantyn, 1982; Knudsen, Knudsen, & Masino, 1993; Kustov & Robinson, 1996; Peck, 1987; Robinson & Kertzman, 1995) and in humans (e.g., Butter, 1987; Ladavas, 1993; Rafal et al., 1991).

The majority of cells in the deeper layers of the SC are multimodal (e.g., B. E. Stein, Wallace, & Meredith, 1995), thus providing one possible neural substrate for cross-modal cuing effects, such as those reported here. Spence and Driver (1997) suggested that intramodal visual exogenous orienting might arise purely in the superficial layers of the SC, where cells only respond to visual stimuli and so would not influence auditory judgments (which could account for the null effect of visual cues on auditory spatial attention). However, if this account were correct, then, by the same argument, visual cues might also be expected to have no effect on the distribution of tactile attention. This tentative prediction is falsified by the results of the present Experiment 2, which provided clear evidence for tactile exogenous covert orienting in response to uninformative visual cues and in the absence of eye movements. However, it should be noted that, although neuroscience interest in recent years has tended to focus on multimodal integration and its implications for spatial orienting within just the SC, there are actually many other neural centers, such as the posterior parietal cortex, the putamen, and the premotor cortex, that also show multimodal spatial integration and may also be involved in the modulation of attention (e.g., Graziano & Gross, 1993, 1995; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981; J. F. Stein, 1989).

The pattern of cross-modal findings summarized in Figure 4 may make sense from a more ecological perspective. It could clearly be useful for tactile attention to be directed toward sudden visual events, in order to facilitate manual responses to the seen objects in the environment. By contrast, it is not immediately clear what behavioral advantage would occur from directing auditory attention to the location of a visual cue. Indeed, many researchers have argued that one of the primary purposes of auditory localization is the reverse influence: to direct attention toward interesting visual events that may be outside the current field or focus of view (e.g., Aitkin, 1986; Harrison & Irving, 1966; Heffner & Heffner, 1992a, 1992b; Perrott, Saberi, Brown, & Strybel, 1990; Pumphrey, 1950). According to this account, there might be no adaptive advantage in directing auditory attention to a sudden visual event, given that any such event in the field of view will automatically result in an exogenous shift of visual attention in its direction.

It remains for future research to examine whether the cross-modal cuing effects demonstrated here would apply for stimuli presented anywhere on the side ipsilateral to the cue, or whether the cross-modal influences are more spatially specific, such that they only affect stimuli in close proximity to the cue, as recently found for the audio-visual case by Driver and Spence (in press). A further question is how the visuo-tactile and auditory-tactile cuing effects would be affected by changes in body posture. For example, a question currently under examination in our laboratory is how visuotactile links in exogenous orienting operate when participants are required to cross their hands (i.e., so that the left hand now receives the tactile event from the right side of space, and vice versa for the other hand). It may be that a tactile cue to one side of the body always results in cross-modal visual orienting to the same visual hemifield, irrespective of current body position. According to such an account, a tactile cue presented to the left hand might always result in the cross-modal orienting of attention to the left visual field, regardless of whether the hands are crossed or uncrossed. Alternatively, it may be that visual attention is exogenously oriented to the allocentric position of a tactile cue (i.e., irrespective of which part of the tactile epithelium was actually stimulated). According to this view, a tactile cue presented to the left hand should result in the cross-modal orienting of visual attention to the right visual field when the hands are crossed. The latter finding might seem more behaviorally adaptive (and is consistent both with recent neurophysiological data from the receptive fields of bimodal visual-tactile neurons in the putamen in macaque monkeys [Graziano & Gross, 1993] and with behavioral research showing that spatial-compatibility effects, such as the Simon effect, are coded in environmental coordinates [e.g., Riggio, Gawryszewski, & Umiltà, 1986]). However, note that it would imply some remapping of somatosensory to retinotopic coordinates (cf. Groh & Sparks, 1996), perhaps implicating

a role for yet another modality in the cross-modal integration that evidently controls exogenous covert orienting—namely, an influence of proprioception, which could indicate the current disposition of the hands. The various cross-modal cuing effects identified here, and the tasks used to reveal them, can hopefully be exploited further to investigate exactly how sensory information in the different modalities is integrated to allow coordination of our attention across the senses, in a manner that is adapted to the complex multimodal environment in which we live.

REFERENCES

- AITKIN, L. (1986). *The auditory midbrain*. Clifton, NJ: Humana.
- BERLUCCHI, G., TASSINARI, G., MARZI, C. A., & DI STEFANO, M. (1989). Spatial distribution of the inhibitory effect of peripheral non-informative cues on simple reaction time to non-fixated visual targets. *Neuropsychologia*, **27**, 201-221.
- BERNSTEIN, I. H., & EDELSTEIN, B. A. (1971). Effects of some variations in auditory input upon visual choice reaction time. *Journal of Experimental Psychology*, **87**, 241-247.
- BRADSHAW, J. L., HOWARD, M. J., PIERSON, J. M., PHILLIPS, J., & BRADSHAW, J. A. (1992). Effects of expectancy and attention in vibrotactile choice reaction time tasks. *Quarterly Journal of Experimental Psychology*, **44A**, 509-528.
- BRIAND, K. A., & KLEIN, R. M. (1986). Is Posner's "beam" the same as Treisman's "glue"? On the relation between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception & Performance*, **13**, 228-241.
- BUCHTEL, H. A., & BUTTER, C. M. (1988). Spatial attention shifts: Implications for the role of polysensory mechanisms. *Neuropsychologia*, **26**, 499-509.
- BUCHTEL, H. A., BUTTER, C. M., & AYVASIK, B. (1996). Effects of stimulus source and intensity on covert orientation to auditory stimuli. *Neuropsychologia*, **34**, 979-985.
- BUTTER, C. M. (1987). Varieties of attention and disturbances of attention: A neuropsychological analysis. In M. Jeannerod (Ed.), *Neurophysiological and neuropsychological aspects of spatial neglect* (pp. 1-23). Amsterdam: Elsevier: North-Holland.
- BUTTER, C. M., BUCHTEL, H. A., & SANTUCCI, R. (1989). Spatial attentional shifts: Further evidence for the role of polysensory mechanisms using visual and tactile stimuli. *Neuropsychologia*, **27**, 1231-1240.
- CHEAL, M., & LYON, D. R. (1991). Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology*, **43A**, 859-880.
- CHEAL, M., CHASTAIN, G., & LYON, D. R. (in press). Inhibition of return in visual identification tasks. *Visual Cognition*.
- DEAN, P., REDGRAVE, P., SAHIBZADA, N., & TSUJI, K. (1986). Head and body movements produced by electrical stimulation of superior colliculus in rats: Effects of interruption of crossed tectoreticulospinal pathway. *Neuroscience*, **19**, 367-380.
- DE JONG, R., LIANG, C.-C., LAUBER, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 731-750.
- DINNERSTEIN, A. J., & ZLOTOGURA, P. (1968). Intermodal perception of temporal order and motor skills: Effects of age. *Perceptual & Motor Skills*, **26**, 987-1000.
- DRIVER, J., & GROSSENACHER, P. G. (1996). Multimodal spatial constraints on tactile selective attention. In T. Inui & J. L. McClelland (Eds.), *Attention and performance XVI* (pp. 209-235). Cambridge, MA: MIT Press.
- DRIVER, J., & SPENCE, C. J. (1994). Spatial synergies between auditory and visual attention. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 311-331). Cambridge, MA: MIT Press.
- DRIVER, J., & SPENCE, C. J. (in press). Crossmodal links in spatial attention. *Proceedings of the Royal Society of London: Series B*.
- DUNCAN, J. (1980). The demonstration of capacity limitation. *Cognitive Psychology*, **12**, 75-96.
- ELLIOTT, R. (1968). Simple visual and simple auditory reaction time: A comparison. *Psychonomic Science*, **10**, 335-336.
- FARAH, M. J., WONG, A. B., MONHEIT, M. A., & MORROW, L. A. (1989). Parietal lobe mechanisms of spatial attention: Modality-specific or supramodal? *Neuropsychologia*, **27**, 461-470.
- GIVOTTI, G., & PERI, G. (1963). Selective effects of monoauricular stimulation upon extrafoveal visual acuity. *Archivio di Psicologia, Neurologia e Psichiatria*, **24**, 246-288.
- GRANTYN, A., & GRANTYN, R. (1982). Axonal patterns and sites of termination of cat superior colliculus neurons projecting in the tecto-bulbo-spinal tract. *Experimental Brain Research*, **46**, 243-265.
- GRAZIANO, M. S. A., & GROSS, C. G. (1993). A bimodal map of space: Somatosensory receptive fields in the macaque putamen with corresponding visual receptive fields. *Experimental Brain Research*, **97**, 96-109.
- GRAZIANO, M. S. A., & GROSS, C. G. (1995). The representation of extrapersonal space: A possible role for bimodal, visual-tactile neurons. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1021-1034). Cambridge, MA: MIT Press.
- GROH, J. M., & SPARKS, D. L. (1996). Saccades to somatosensory targets: 2. Motor convergence in primate superior colliculus. *Journal of Neurophysiology*, **75**, 428-438.
- HARRISON, J. M., & IRVING, R. (1966). Visual and nonvisual auditory systems in mammals. *Science*, **154**, 738-743.
- HARVEY, N. (1980). Non-informative effects of stimuli functioning as cues. *Quarterly Journal of Experimental Psychology*, **32**, 413-425.
- HEFFNER, R. S., & HEFFNER, H. E. (1992a). Evolution of sound localization in mammals. In D. B. Webster, R. R. Fay, & A. N. Popper (Eds.), *The evolutionary biology of hearing* (pp. 691-715). New York: Springer-Verlag.
- HEFFNER, R. S., & HEFFNER, H. E. (1992b). Visual factors in sound localization in mammals. *Journal of Comparative Neurology*, **317**, 219-232.
- HONORÉ, J. (1982). Posture oculaire et attention selective à des stimuli cutanés [Eye position and selective attention to cutaneous stimuli]. *Neuropsychologia*, **20**, 727-730.
- HONORÉ, J., BOURDEAUD'HUI, M., & SPARROW, L. (1989). Reduction of cutaneous reaction time by directing eyes towards the source of stimulation. *Neuropsychologia*, **27**, 367-371.
- HUGDAHL, K., & NORDBY, H. (1994). Electrophysiological correlates to cued attentional shifts in the visual and auditory modalities. *Behavioral & Neural Biology*, **62**, 21-32.
- JONIDES, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.
- KILGARD, M. P., & MERZENICH, M. M. (1995). Anticipated stimuli across skin. *Nature*, **373**, 663.
- KING, A. J. (1993). A map of auditory space in the mammalian brain: Neural computation and development. *Experimental Physiology*, **78**, 559-590.
- KLEIN, R. M. (1994). Perceptual-motor expectancies interact with covert visual orienting under conditions of endogenous but not exogenous control. *Canadian Journal of Experimental Psychology*, **48**, 167-181.
- KLEIN, R. M., BRENNAN, M., & GILANI, A. (1987, November). *Covert cross-modality orienting of attention in space*. Paper presented at the annual meeting of the Psychonomic Society, Seattle.
- KLEIN, R. M., KINGSTONE, A., & PONTEFRAC, A. (1992). Orienting of visual attention. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 46-65). New York: Springer-Verlag.
- KLEIN, R. M., & TAYLOR, T. L. (1994). Categories of cognitive inhibition with reference to attention. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 113-150). New York: Academic Press.
- KNUDSEN, E. I., KNUDSEN, P. F., & MASINO, T. (1993). Parallel pathways mediating both sound localization and gaze control in the fore-

- brain and midbrain of the barn owl *Journal of Neuroscience*, **13**, 2837-2852.
- KUSTOV, A. A., & ROBINSON, D. L. (1996). Shared neural control of attentional shifts and eye movements. *Nature*, **384**, 74-77.
- LABERGE, D. (1995). *Attentional processing: The brain's art of mindfulness*. Cambridge, MA: Harvard University Press.
- LADAVAS, E. (1993). Shifts of attention in patients with visual neglect. In I. H. Robertson & J. C. Marshall (Eds.), *Unilateral neglect: Clinical and experimental studies* (pp. 193-209). Hillsdale, NJ: Erlbaum.
- LAMBERT, A., & HOCKEY, R. (1991). Peripheral visual changes and spatial attention. *Acta Psychologica*, **76**, 149-163.
- LARMANDE, P., & CAMBIER, J. (1981). Influence de l'état d'activation hémisphérique sur le phénomène d'extinction sensitive chez 10 patients atteints de lésions hémisphériques droites [Effects of the state of activation of the cerebral hemisphere on sensory excitation: A study of 10 patients with right hemisphere lesions]. *Revue Neurologique*, **137**, 285-290.
- MARUYAMA, K. (1961). "Contralateral relationship" between the ears and the halves of the visual field in the sensory interaction. *Tohoku Psychologica Folia*, **19**, 81-92.
- MAYLOR, E. A., & HOCKEY, R. (1985). Inhibitory components of externally controlled covert orienting in visual space. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 777-787.
- MILLER, J. O. (1988). A warning about median reaction time. *Journal of Experimental Psychology: Human Perception & Performance*, **14**, 539-543.
- MONDOR, T. A., & ZATORRE, R. J. (1995). Shifting and focussing auditory spatial attention. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 387-409.
- NIEMI, P., & NÄÄTÄNEN, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin*, **89**, 133-162.
- O'DONNELL, C., & PRATT, J. (1996). Inhibition of return along the path of attention. *Canadian Journal of Experimental Psychology*, **50**, 386-392.
- PECK, C. K. (1987). Visual-auditory interactions in cat superior colliculus: Their role in control of gaze. *Brain Research*, **420**, 162-166.
- PERROTT, D. R., SABERI, K., BROWN, K., & STRYBEL, T. Z. (1990). Auditory psychomotor coordination and visual search performance. *Perception & Psychophysics*, **48**, 214-226.
- PONTEFRAC, A., & KLEIN, R. M. (1988). *Assessing inhibition of return with simple and choice reaction time*. Unpublished manuscript.
- POSNER, M. I. (1978). *Chronometric explorations of mind*. Hillsdale, NJ: Erlbaum.
- POSNER, M. I., & COHEN, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 531-556). Hillsdale, NJ: Erlbaum.
- POSNER, M. I., DAVIDSON, B. J., & NISSEN, M. J. (1976, November). *The process of stimulus detection*. Paper presented at the annual meeting of the Psychonomic Society, St. Louis.
- POSNER, M. I., NISSEN, M. J., & OGDEN, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. I. Pick & I. J. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137-157). Hillsdale, NJ: Erlbaum.
- PRATT, J. (1995). Inhibition of return in a discrimination task. *Psychonomic Bulletin & Review*, **2**, 117-120.
- PUMPHREY, R. J. (1950). Hearing. *Symposium of the Society for Experimental Biology: Physiological Mechanisms in Animal Behavior*, **4**, 3-18.
- RAFAL, R., HENIK, A., & SMITH, J. (1991). Extrageniculate contributions to reflex visual orienting in normal humans: A temporal hemifield advantage. *Journal of Cognitive Neuroscience*, **3**, 322-328.
- REUTER-LORENZ, P. A., JHA, A. P., & ROSENQUIST, J. N. (1995). What is inhibited in inhibition of return? *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 367-378.
- REUTER-LORENZ, P. A., & ROSENQUIST, J. N. (1996). Auditory cues and inhibition of return: The importance of oculomotor activation. *Experimental Brain Research*, **112**, 119-126.
- RHODES, G. (1987). Auditory attention and the representation of spatial information. *Perception & Psychophysics*, **42**, 1-14.
- RIGGIO, L., GAWRYSZEWSKI, L. D. G., & UMITÀ, C. (1986). What is crossed in crossed-hand effect? *Acta Psychologica*, **62**, 89-100.
- RIZZOLATTI, G. C., SCANDOLARA, M., MATELLI, M., & GENTILUCCI, M. (1981). Afferent properties of periaruate neurons in macaque monkeys: II. Visual responses. *Behavioural Brain Research*, **2**, 147-163.
- ROBINSON, D. L., & KERTZMAN, C. (1995). Covert orienting of attention in macaques. III. Contributions of the superior colliculus. *Journal of Neurophysiology*, **74**, 713-721.
- RUTSCHMANN, J., & LINK, R. (1964). Perception of temporal order of stimuli differing in sense mode and simple reaction time. *Perceptual & Motor Skills*, **18**, 345-352.
- SATHIAN, K., & BURTON, H. (1991). The role of spatially selective attention in the tactile perception of texture. *Perception & Psychophysics*, **50**, 237-248.
- SCHARF, B., QUIGLEY, S., AOKI, C., PEACHEY, N., & REEVES, A. (1987). Focused auditory attention and frequency selectivity. *Perception & Psychophysics*, **42**, 215-223.
- SCHMIDT, W. C. (1996). "Inhibition of return" without visual input. *Neuropsychologia*, **34**, 943-952.
- SCHRÖGER, E., & EIMER, M. (1997). Endogenous covert spatial orienting in audition: "Cost-benefit" analyses of reaction times and event-related potentials. *Quarterly Journal of Experimental Psychology*, **50A**, 457-474.
- SCHRÖGER, E., WOLFF, C., TSCHAKERT, R., & SCHUBO, A. (in press). Involuntary attentional capture versus voluntary attentional orienting in audition. In H.-J. Heinze, T. F. Münte, & G. R. Mangun (Eds.), *Mapping cognition in time and space*.
- SHAW, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 277-296). Hillsdale, NJ: Erlbaum.
- SIMON, J. R., & CRAFT, J. L. (1970). Effects of an irrelevant auditory stimulus on visual choice reaction time. *Journal of Experimental Psychology*, **86**, 272-274.
- SPARKS, D. L. (1988). Neural cartography: Sensory and motor maps in the superior colliculus. *Brain, Behavior, & Evolution*, **31**, 49-56.
- SPENCE, C. J., & DRIVER, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms facilitate sound localization. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 555-574.
- SPENCE, C. J., & DRIVER, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 1005-1030.
- SPENCE, C. J., & DRIVER, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics*, **59**, 1-22.
- SPENCE, C. J., & DRIVER, J. (1998a). Auditory and audiovisual inhibition of return. *Perception & Psychophysics*, **60**, 125-139.
- SPENCE, C. J., & DRIVER, J. (1998b). Inhibition of return following an auditory cue: The role of central reorienting events. *Experimental Brain Research*, **118**, 352-360.
- SPENCE, C. J., & DRIVER, J. (1998c). *Cross-modal inhibition of return between auditory, visual, and tactile stimuli*. Manuscript submitted for publication.
- STEIN, B. E. (1984). Multimodal representation in the superior colliculus and optic tectum. In H. Vanegas (Ed.), *Comparative neurology of the optic tectum* (pp. 819-841). New York: Plenum.
- STEIN, B. E., & MEREDITH, M. A. (1993). *The merging of the senses*. Cambridge, MA: MIT Press.
- STEIN, B. E., WALLACE, M. T., & MEREDITH, M. A. (1995). Neural mechanisms mediating attention and orientation to multisensory cues. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 683-702). Cambridge, MA: MIT Press.
- STEIN, J. F. (1989). Representation of egocentric space in the posterior parietal cortex. *Quarterly Journal of Experimental Physiology*, **74**, 583-606.
- TASSINARI, G., AGLIOTI, S., CHELAZZI, L., MARZI, C. A., & BERLUCCHI, G. (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., AGLIOTI, S., CHELAZZI, L., PERU, A., & BERLUCCHI, G. (1994). Do peripheral non-informative cues induce early facilitation of target detection? *Vision Research*, **34**, 179-189.
- TASSINARI, G., & BERLUCCHI, G. (1995). Covert orienting to non-

- informative cues: Reaction time studies. *Behavioural Brain Research*, **71**, 101-112.
- TASSINARI, G., & CAMPARA, D. (1996). Consequences of covert orienting to non-informative stimuli of different modalities: A unitary mechanism? *Neuropsychologia*, **34**, 235-245.
- TERRY, K. M., VALDES, L. A., & NEILL, W. T. (1994). Does "inhibition of return" occur in discrimination tasks? *Perception & Psychophysics*, **55**, 279-286.
- WARD, L. M. (1994). Supramodal and modality-specific mechanisms for stimulus-driven shifts of auditory and visual attention. *Canadian Journal of Experimental Psychology*, **48**, 242-259.
- WARD, L. M., McDONALD, J. A., & GOLESTANI, N. (in press). Cross-modal control of attention shifts. In R. Wright (Ed.), *Visual attention*. New York: Oxford University Press.
- WHANG, K. C., BURTON, H., & SHULMAN, G. L. (1991). Selective attention in vibrotactile tasks: Detecting the presence and absence of amplitude change. *Perception & Psychophysics*, **50**, 157-165.

NOTES

1. It might be argued that endogenous orienting alone cannot account for the validity effects reported at the shortest SOA (50 msec) in Buchtel and Butter's (1988; Butter et al., 1989) studies, since this interval may seem too short to execute a voluntary shift of attention. However, it should be noted, first, that the time available for an effective shift of attention may include the target duration plus any delay before response and, second, that several unimodal studies of visual attention have now revealed that purely endogenous shifts of attention can be effective at very short cue-target SOAs (e.g., Cheal & Lyon, 1991).

2. The usual advantage for ipsilateral trials over contralateral trials at short SOAs often reverses to become a disadvantage at longer SOAs (> 300 msec or so) in spatially uninformative visual cuing studies—the phenomenon of "inhibition of return" (IOR; Posner & Cohen, 1984). This effect typically affects simple detection latencies, but it has also been shown to affect performance on a subset of visual discrimination tasks (e.g., Cheal et al., in press; Pratt, 1995).

3. We used median RTs because researchers have argued that they provide a more accurate measure of average response latency than do mean RTs, being less sensitive to outliers (see Miller, 1988). However, at the request of one reviewer, we repeated all the RT analyses using mean rather than median RTs. The results of these analyses are presented in the Appendix.

4. It should be noted that, although the participants had no rational incentive to use the cue to direct their attention to one side or the other, this does not necessarily mean that they never used it in some idiosyncratic way. One alternative paradigm that has sometimes been proposed to allow one to assert more confidently that any cuing effects observed must have been due to purely exogenous orienting is to present peripheral cues that are predictive of a target appearing on the opposite side of fixation (e.g., see Klein et al., 1987, Experiment 4; Spence & Driver, 1994, Experiment 5). However, it should be noted that even this paradigm is not free from potential problems: As soon as the cue is made informative, there is presumably a good reason for participants to process that cue as quickly as possible, perhaps by initially directing their endogenous attention toward it.

5. The minor changes in the apparatus, materials, and procedure from those used in Experiment 1 were necessitated by the fact that this experiment was conducted several months after Experiments 1 and 3, within a different laboratory.

6. We used a target-target procedure in our IOR study, rather than the cue-target procedure employed by the majority of researchers who have investigated IOR with nonvisual stimuli (e.g., Reuter-Lorenz et al., 1995; Reuter-Lorenz & Rosenquist, 1996; Schmidt, 1996; Tassinari & Berlucchi, 1995; Tassinari & Campara, 1996), because this method avoids possible confound between manual response inhibition (to prevent anticipatory responses to the cue; cf. De Jong, Liang, & Lauber, 1994;

Harvey, 1980) and genuine IOR, since there is no need to withhold manual responding for the preceding target (see Spence & Driver, 1998a, for a more detailed discussion of this point).

APPENDIX

At the request of one reviewer, we conducted subsequent analyses of the mean (rather than median) RT data for all three experiments. The mean RT data for all three experiments are shown in Table A1. Comparison with the preceding tables shows that a similar pattern of cuing effects was revealed by both RT measures. The only major difference is that mean estimates of response latency were always slightly longer than median estimates. ANOVAs were conducted on the mean data from each experiment, and these revealed essentially the same pattern of significant and nonsignificant effects as reported in the text for the median RT data, with the following exceptions: In Experiment 2, the interaction between cuing and SOA was no longer significant [$F(2,30) = 0.3$, n.s.], reflecting the fact that the trend toward a negative cuing effect at the shortest SOA in the median data reversed to become an insignificant trend toward a positive cuing effect in the mean data. In Experiment 3, the side factor just reached significance in the mean RT data analysis [$F(1,19) = 5.5$, $p = .03$], reflecting the fact that response latencies for left targets ($M = 527$ msec) were slower than for right targets ($M = 521$ msec). This did not interact with cuing.

Table A1
Grand Mean (Rather Than Mean of Median)
Reaction Times (in Milliseconds) and Mean
Cuing Effects (in Milliseconds) for
Experiments 1–3 as a Function of the
Position of the Cue and the Stimulus
Onset Asynchrony (SOA; in Milliseconds)

SOA	Cue Position		Mean Cuing Effect
	Ipsilateral	Contralateral	
Experiment 1: Auditory Cue/Tactile Target			
150	614	622	8*
200	601	611	10†
300	594	603	9†
Experiment 2: Visual Cue/Tactile Target			
150	618	623	5
200	612	622	10*
300	610	617	7
Experiment 3: Tactile Cue/Auditory Target			
150	551	567	16†
200	540	555	15†
300	535	548	13†
Experiment 3: Tactile Cue/Visual Target			
150	503	511	8
200	483	504	21†
300	468	498	30†

* $p < .05$, t -test pairwise comparison. † $p < .01$, t -test pairwise comparison.

(Manuscript received February 13, 1997;
revision accepted for publication July 4, 1997.)