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RESEARCH ARTICLE

Directing visual attention with spatially informative and spatially noninformative tactile cues

Chanon M. Jones · Rob Gray · Charles Spence · Hong Z. Tan

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Abstract We investigated the tactile cuing of visual spatial attention using spatially-informative (75% valid) and spatially-noninformative (25% valid) tactile cues. The participants performed a visual change detection task following the presentation of a tactile spatial cue on their back whose location corresponded to one of the four visual quadrants on a computer monitor. The participants were explicitly instructed to use the spatially-informative tactile cues but to ignore the spatially-noninformative cues. In addition to reaction time data, participants' eye-gaze was monitored as a measure of overt visual attention. The results showed that the spatially-informative tactile cues resulted in initial saccades toward the cued visual quadrants, and significantly reduced the visual change detection latencies. When spatially-noninformative tactile cues were used, the participants were largely successful at ignoring them as indicated by a saccade distribution that was independent of the quadrant that was cued, as well as the lack of a significant change in search time as compared to the baseline measure of no tactile cuing. The eye-gaze data revealed that the participants could not always completely ignore the spatially-noninformative tactile cues. Our results suggest that the tactile cuing of visual attention is natural but not automatic when the tactile cue and visual target are not collocated spatially, and that it takes effort to ignore the cues even when they are known to provide no useful information. In addition, our results confirm previous findings that spatially-informative tactile cues are especially effective at directing overt visual attention to locations that are not typically monitored visually, such as the bottom of a computer screen or the rearview mirror in an automobile.

Keywords Tactile cuing · Eye gaze · Visual attention · Spatial cuing · Crossmodal · Overt orienting · Cue validity

Introduction

The amount of information available to operators in modern complex systems continues to increase. Yet, people have only a limited capacity to attend to the information available in a complex multisensory environment, such as the scene in front of a driver. The importance of attention is illustrated by the phenomenon of "change blindness" (e.g., Rensink 2000; Simons and Ambinder 2005; Simons and Rensink 2005): easily perceptible changes in visual (Simons and Levin 1998), auditory (Eramudugolla et al. 2005; Vitevitch 2003) and tactile stimuli (Gallace et al. 2006) often go unnoticed by people, and change detection improves when the user's attention is directed toward the change (e.g., by cross-modal attentional cuing; see Auvray et al. 2007). Thus, it is important to provide cues to critical information in the operator's working environment. Cross-modal, nonvisual channels are attractive candidates for the design of warning signals and cues, because they do not place additional demands on the operator's often-overloaded visual system (Proctor and Vu 2004; Fitch et al. 2007; Sivak 1996; Spence and Driver 1997b).

C. M. Jones · H. Z. Tan (✉)
Haptic Interface Research Laboratory, Purdue University,
Electrical Engineering Building, 465 Northwestern Avenue,
West Lafayette, IN 47907-2035, USA
e-mail: hongtan@purdue.edu

R. Gray
Perception and Action Laboratory, Arizona State University East,
7001 E Williams Field Road, Mesa, AZ 85212, USA

C. Spence
Crossmodal Research Laboratory, University of Oxford,
South Parks Road, Oxford OX1 3UD, UK

Cuing studies typically use RTs and error rates as performance measures (e.g., Spence et al. 2000). The difference between performance on valid and invalid trials (i.e., when the cue and target occur on the same side vs. difference sides, respectively) has been taken as a measure of the extent to which stimuli in one sensory modality can direct, or capture, spatial attention in another modality (e.g., Spence 2001). Auditory, visual, and tactile stimuli have been examined in spatial cuing experiments (e.g., Spence and Driver 1997b; see Spence et al. 2004, for a review). The speeded detection (and discrimination) of a visual target is faster and often more accurate following the presentation of a spatially-noninformative peripheral auditory cue on the same side as the visual target rather than on the opposite side (e.g., Bolognini et al. 2005; Spence and Driver 1997a; Spence et al. 1998). Speeded discrimination responses for auditory targets are affected by the prior presentation of spatially non-informative visual cues under certain conditions, but not others (see McDonald et al. 2001; Ward et al. 2000; Spence et al. 2004, for a review). For the cross-modal pairing of visual and tactile stimuli, the evidence now clearly demonstrates that visual target judgments can be significantly affected by spatially non-predictive tactile cues, and vice versa (Gray and Tan 2002; Kennett et al. 2001; Kennett et al. 2002; Spence et al. 1998; Tan et al. 2003). Spatially non-predictive tactile cues have also been shown to lead to significant cross-modal spatial-cuing effects upon auditory target judgments, and vice versa (Spence et al. 1998).

An important issue in studies of crossmodal attentional cuing, which constitutes the focus of the present study, is the effect of cue validity on crossmodal attentional cuing (Chica et al. 2007). We found that when tactile cues were spatially informative, detection times decreased significantly with valid tactile cues and increased significantly with invalid cues. When tactile cue validity was low (i.e., when the tactile cues were spatially non-informative with regard to the likely target location), the RTs of some participants were affected by tactile cues while those of others were not (Young et al. 2003). The results from spatially non-informative cues were particularly interesting because they could potentially shed some light on the question of whether the attentional link between a tactile cue and a visual target is automatic (in which case it would be difficult to ignore the cues) or a learned strategic shift in attention (in which case the cues can be ignored). A lack of change in the RT does not necessarily mean that tactile cues were completely ignored. There were at least two possible scenarios. In the first case, participants performed visual search regardless of the presence (vs. absence) of the tactile cues and they were indeed successful at ignoring spatially non-informative cues. In the second case, the participants executed an initial saccade to cued location then quickly moved their eye-gaze elsewhere. The resulting average RTs might have remained statistically indistinguishable from those in the no-cuing condition even though the participants were unable to suppress the initial saccade due to the tactile cuing.

A practical consideration in motivating our study of the low-validity cuing condition concerns the use of multisensory attentional cuing in a collision warning system. Should a false alarm occur due to sensor errors, a driver may choose to ignore a high-validity cue that is *perceived* to be of low validity (Enriquez and MacLean 2004). The question then becomes one of whether the driver can completely suppress the crossmodal attentional cues, which will render the collision warning system ineffective (see also Spence and Ho 2008).

The present study tracked participants' eye-gaze in order to gain a more direct measure of their overt visual attention in an attempt to differentiate between the aforementioned two scenarios with spatially non-informative cues. Previous studies have shown that saccadic movements can influence visual (Kowler et al. 1995), auditory (Rorden and Driver 1999), and tactile (Rorden et al. 2002) performance. For example, Kowler et al. observed a direct relationship between participants' ocular movements and their attentional shifts during endogenous spatial attentional cuing. We would therefore expect to observe a saccadic movement toward a cued visual location and a reduction in RTs following spatially informative tactile cuing. With spatially non-informative tactile cues, we were interested in determining whether participants would be able to suppress any initial saccade toward the cued quadrant. Although other studies have shown that a shift in attention can occur independently of ocular movements in a task of endogenous cuing (Klein 1980; Remington 1980; Stelmach et al. 1997), we note that those results were obtained by instructing the participants to make or withhold a saccade toward a particular direction regardless of target location, hence not applicable to our study where participants simply looked around on a computer monitor to detect the change in a visual scene. Therefore, the eye-gaze data were used as a direct measure of a participant's overt visual attention in the present study. They were recorded and analyzed, in addition to RTs, in order to investigate the extent to which the tactile priming of visual spatial attention is an automatic or learned behavior.

Methods

Participants

Ten participants (4 men and 6 women; 21–26 years old with an average age of 23 years old) took part in the experiment as paid volunteers. All of the participants had normal or corrected-to-normal vision and reported no known abnormalities with tactile perception on their backs. Prior to the experiments, the participants gave their written informed consent to the protocol approved by the Institute Review Board at Purdue University.

Apparatus and stimuli

The visual stimuli used in these experiments utilized the flicker paradigm developed for studies of change blindness (Rensink 2000). The visual scenes were composed of 12 white rectangular elements (3 per quadrant) oriented either horizontally or vertically on a black background (see Fig. 1a). The elements in the display were randomly placed in each quadrant with the constraint that they did not overlap. Two alternating scenes, differing only in the orientation of one of the rectangular elements, were presented to the participant. A black screen was presented between successive scenes. The sequence was repeated until the user indicated with a mouse click that the changing element had been identified. The duration of the alternating scenes, the "on time," was held constant at 80 ms for all conditions. The duration of the blank scene, the "off time," was held constant at 200 ms (sufficient to eliminate visual motion cues).

The tactile cues were provided by a tactor array display consisting of the 2 × 2 corner tactors of a 3 × 3 tactor array draped over the back of an office chair (see Fig. 1b). The tactors lay on the corners of a 20 cm (W) × 15 cm (H) rectangle. Each tactor (VBW32, Audiological Engineering Corp., Somerville, MA, USA) was driven by a 60-ms 290-Hz sinusoidal pulse using custom-designed circuitry capable of controlling up to nine tactors independently (Haptic Interface Research Laboratory, West Lafayette, IN, USA). The intensity of the stimulus was around 27 dB SL (sensation level; decibels above human detection threshold; see Verrillo and Gescheider 1992). The vibratory pulses could be felt clearly through whatever clothing the participant happened to be wearing.

At the beginning of each trial, a red fixation cross was displayed in the center of the computer screen for 500 ms. The participants were instructed to look at the fixation cross that preceded the tactile cue. As illustrated in Fig. 2, the tactile cue came on at the offset of the visual fixation cross, and the visual scenes (see Fig. 1a) started 140 ms after the offset of the tactile cue.

An infrared-based eye tracker (RK-726PCI Pupil/Corneal Reflection Tracking System, ISCAN, Inc., Burlington, MA, USA) was used to collect eye-gaze data at a sampling rate of 60 Hz. A nine-point calibration procedure was performed for each participant before each session. The quality of the calibration was confirmed by asking the participant to follow a moving dot on the computer screen that drew a closed rectangle, and simultaneously overlaying the eye-gaze data on top of the target rectangle. A chin rest with a forehead stabilizer (Table Mounted Head Restraint, Applied Science Group, Inc., Bedford, MA, USA) was used to restrict the movement of the participant's head. On each

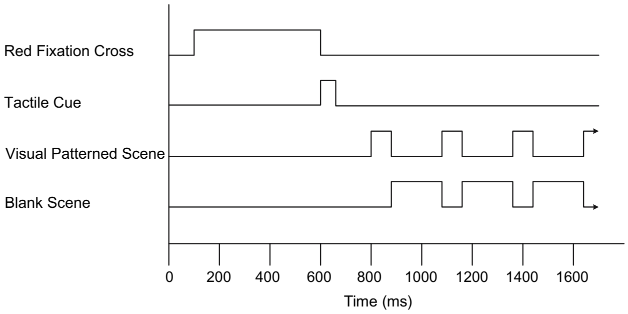

Fig. 2 Timing diagram for visual and tactile stimuli on each trial

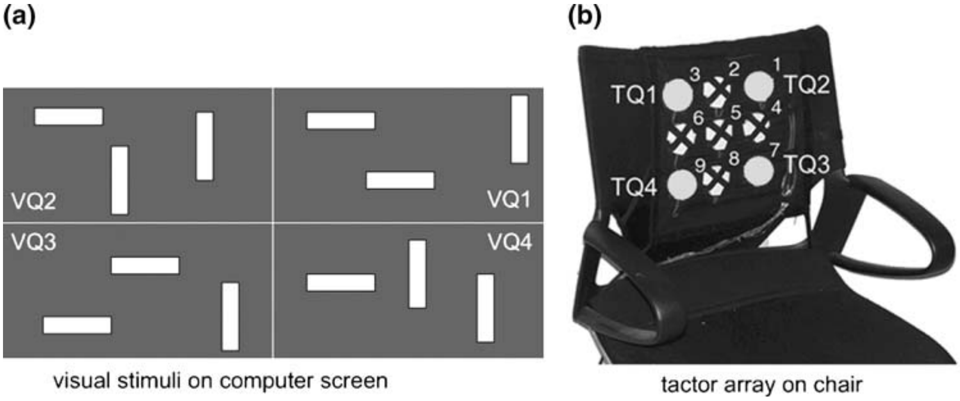

Fig. 1 Illustration of the layout of **a** visual stimuli on a computer monitor, **b** tactor array on an office chair, and the corresponding visual and tactile quadrants (VQ and TQ, respectively). Only the four corner tactors (#1, #3, #7, #9) of the tactor array were used in the experiments. The four tactor locations (TQ1–TQ4) and the four visual quadrants (VQ1–VQ4) of the computer screen are numbered accordingly so that tactile cuing near the right shoulder (TQ1) corresponded to the upper-right quadrant VQ1, from the point of view of a participant sitting in the chair facing the monitor. The numbering of the four quadrants follows the convention used in trigonometry

trial, a "record" signal was sent to the eye tracker prior to the onset of the tactile cue, and a "stop" signal was sent after the participant had identified the changing visual element.

Procedure

In order to ensure that the tactile cues could be easily perceived, each participant performed an absolute identification task on the location of the tactile stimuli before the main experiment. The participants sat with their backs against the tactor array shown in Fig. 1b. One randomly selected tactor was turned on for 60 ms. The participants had to click on one of four large boxes in the four quadrants of the computer screen in order to indicate where the vibration was felt on their back. A perfect score on a 60-trial run was required before the participant could proceed to the main experiment. All participants were able to identify the tactor location perfectly within one or two runs. The pretesting therefore helped the participants establish the correspondence between the quadrants on their backs and those on the visual monitor.

The main experiment used a randomized block design. Each participant served in two 11-run blocks of trials where each run consisted of 60 trials. One block of runs contained 25% valid (spatially non-informative) tactile cues, meaning that the tactile-cue location coincided with the visual-change quadrant on 25% of trials (chance level). The other block of runs contained 75% valid (spatially informative) tactile cues. Half of the participants completed the 25% valid block first while the other half were assigned to the 75% valid block first. In both blocks there were three 60-trial visual-only (no tactile cue) control runs. The tactors-off condition provided a baseline measure against which to compare the data from the 25 or 75% valid conditions. In the remaining eight 60-trial runs, tactile cues were presented with 25% validity in one of the blocks and with 75% validity in the other block. More runs were conducted for the tactor-on conditions than for the tactor-off condition so that enough data were available from both valid and invalid tactile cuing trials. The order of the eleven runs within each block was randomized for each participant. Before each session, the participant completed a practice run of 60 trials with 50% valid tactile cues. The results of the practice run were not analyzed.

During the main experiment, the participants were told that their task was to locate a change in a visual scene. More specifically, they were instructed to *locate* and *identify* as rapidly as possible the rectangular element that was changing in orientation. The participants were informed that the validity of the tactile cues was either 75% (spatially informative) or 25% (spatially noninformative). For the 75% valid condition, the participants were encouraged to look first in the visual quadrant that corresponded to the tactile cue location. For the 25% valid condition, the participants were instructed to *ignore* the tactile cues to the best of their ability or to start their visual search away from the cued quadrant. The exact instructions were as follows: "*Before each experiment, you will be told what the percent validity of the tactile cues will be* or if there are not going to be any tactile cues. For runs with 25% valid tactile cues, you are encouraged to *ignore the cue* and search elsewhere. For runs with 75% valid tactile cues, you are encouraged to *use the cue*." (The bold face text also appeared on the instruction sheet provided to the participants.) The latter strategy was mentioned because in an earlier study (see Young et al. 2003), one of the participants had reported that he looked away from the visual quadrant cued by the vibrotactile signal in the low-validity condition. We wanted to examine whether this could indeed happen, because of the potential impact on the design of real-world warning systems. For the tactor-off condition, the participants were told to use whatever visual search strategy they felt comfortable with. No feedback was provided during the main experiment.

On each trial, the participant felt a 60-ms vibration from one of the four corners of their back for the tactor-on conditions. The visual search then commenced. The participants were instructed to click the left mouse button as soon as they found the changing element *without moving the mouse*. The image on the computer screen froze upon the first mouse click. The reaction time from the onset of the first visual scene to the first mouse click was then recorded. The participants had to move the cursor over the changing element and click the left mouse button a second time to *identify* the element. Data from any error trials where the location of the second mouse click did not match that of the changing element were discarded.

Data analyses

The dependent variables were the mean reaction times (*mRT*), their standard errors, and eye-gaze data. The tactor-off data served as a baseline measure of performance. The data for the trials with valid cues (where the tactile-cue quadrant coincided with the visual-change quadrant) and invalid cues (where the tactile-cue quadrant was different from the visual-change quadrant) were processed separately. Cuing effects were determined by subtracting the baseline (no tactile cue) *mRT* from the *mRT* obtained from tactile cuing conditions. The baseline *mRT* values were found to differ significantly for visual targets occurring in the four quadrants. For instance, *mRT* was much lower for the upper-left quadrant (VQ2) for most participants presumably because they started their visual search in that quadrant. Therefore, four baseline *mRT* values were calculated by pooling all trials with the changing elements in the same quadrant on the computer screen. Cuing effects were then calculated as follows. Suppose that the baseline *mRT* for the upper-left quadrant VQ2 was 1,300 ms, and that the *mRT* for visual changes in VQ2 given tactile cues in the upper-right quadrant TQ1 was 1,376 ms. Then the cuing effect of 76 ms was found by subtracting the baseline measure of 1,300 ms from the 1,376 ms obtained under tactile cuing conditions. A negative *difference mRT* corresponded to a decrease in *mRT* whereas a positive value corresponded to an increase in *mRT*. From the four possible tactile-cue locations on the participant's back and the four possible visual-change quadrants on the computer screen, there were a total of 16 tactile-cue/visual-change quadrant pairs. Of the 16 pairs, 4 corresponded to trials with valid tactile cues and 12 with invalid tactile cues. Data from each participant were processed separately.

The eye-tracking data provided a basis for determining the extent to which the participants utilized the tactile cues in each condition. Data from all trials were separated into four groups corresponding to the four possible cue locations on the back. The eye-gaze trajectories for the trials in each group were then analyzed by determining the quadrant on the computer screen where the participants looked immediately following the presentation of the tactile cue (i.e., the initial saccades).

Results

Mean reaction time

The mean reaction times for the baseline condition of no tactile cuing, averaged over all 10 participants and all trials with visual targets in the same quadrant, are shown in Table 1. On average, less than 7% of the trials were removed from analysis because the participants failed to correctly identify the visual target. RTs were lowest for visual targets in the upper-left quadrant (VQ2), indicating a tendency for the participants to start their visual search from the upper-left quadrant of the monitor in the absence of any cuing information. An analysis of variance (ANOVA) performed on the *mRT* data with the factors of participant and visual quadrant revealed a significant main effect of both factors [participant: $F(9,27) = 22.04$, $P < 0.0001$; visual quadrant: $F(3,27) = 6.30$, $P = 0.0022$]. A Tukey test indicated two *mRT* groups: VQ1 and VQ2 (mean = 1.52, 1.30 s, respectively), and VQ1, VQ3 and VQ4 (mean = 1.52, 1.60, 1.68 s, respectively). Pair-wise comparisons indicated that the *mRT* in VQ2 was indeed significantly lower than that in any of the other three quadrants [$F(3,27) = 6.30$, $P = 0.0022$].

Table 1 The reaction times for the baseline condition of no tactile cuing, averaged over all ten participants and all trials with the visual targets in the same quadrant

Visual change quadrant	VQ1	VQ2	VQ3	VQ4
mRT (ms)	1,520	1,300	1,601	1,676
Standard error (ms)	145	101	195	194

The overall effect of tactile cuing and cue validity is summarized in Table 2. When the tactile cues were spatially informative (75% valid), valid cues resulted in a significant decrease in *mRT* whereas invalid cues resulted in a significant increase in *mRT*. This result shows that the participants were able to utilize the tactile cues when performing the visual search task. When the tactile cues were spatially non-informative (25% valid), the same trends were observed but the changes in *mRT* were not significant. It thus appears that the participants were able to ignore the tactile cues in this case.

A more detailed analysis of the effect of spatially-informative (75% valid) tactile cues on *mRT* is shown in Fig. 3 for all participants and all of the 16 tactile-cue/visual-target quadrant pairs. Each bar shows the difference between the *mRT* obtained under tactile cuing conditions and the baseline *mRT* for visual targets in the same quadrant. Each panel shows the *difference mRT* data as a function of the visual-change quadrant for a particular tactile-cue quadrant. In general, valid tactile cues led to a negative change (decrease) in *mRT* and invalid tactile cues led to a positive change (increase) in *mRT*. The former is demonstrated by the four negative values in the four panels associated with the four cue-change pairs of (TQ1, VQ1), (TQ2, VQ2), (TQ3, VQ3) and (TQ4, VQ4), respectively. The latter is demonstrated by the rest of the (positive) bars in Fig. 3. An ANOVA performed on the *mRT* data with the factors participant, tactile-cue quadrant, and visual-change quadrant indicates that participant was a significant factor [$F(9,81) = 2.72$, $P = 0.0080$], but not tactile-cue quadrant [$F(3,81) = 0.41$, $P = 0.7495$] or visual-change quadrant [$F(3,81) = 1.48$, $P= 0.2265$]. As expected, the interaction between tactile-cue quadrant and visual-change quadrant

Table 2 Overall effect of valid and invalid tactile cuing on the visual search time, shown separately for spatially-informative and spatially-noninformative cues

Tactile cue validity	75%		25%	
	Valid cue	Invalid cue	Valid cue	Invalid cue
Difference *mRT* (ms)	−445*	242*	−76	44
Standard error (ms)	116	144	69	87

* Value is significantly different from 0 ms; i.e., the change in *mRT* is significant

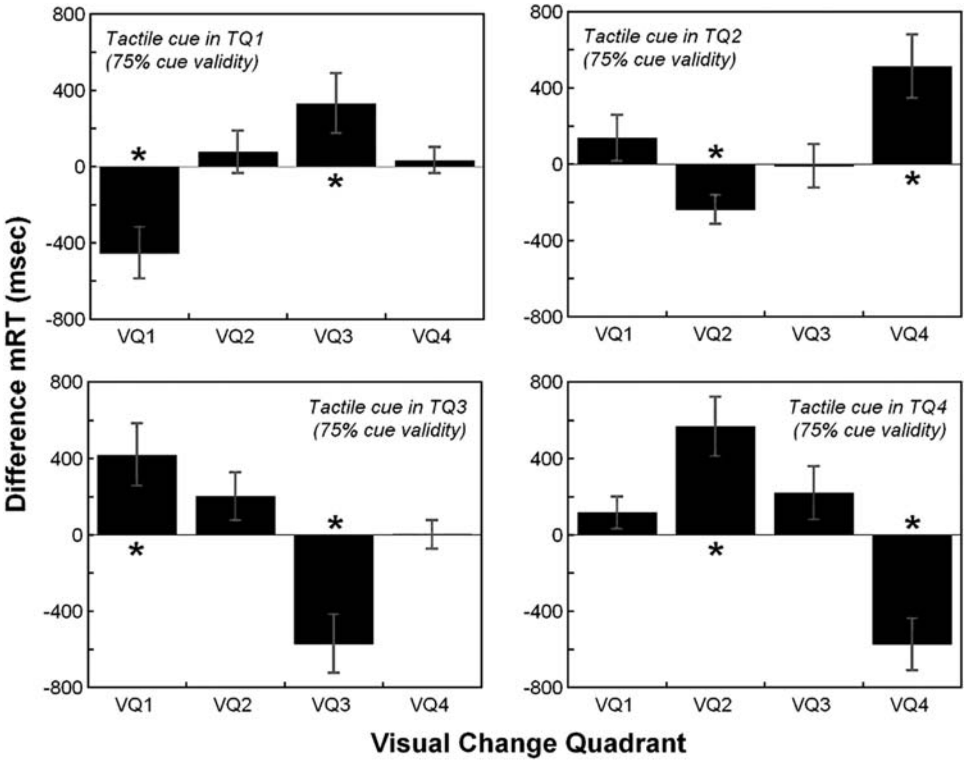

Fig. 3 Change in *mRT* for spatially-informative (75% valid) tactile cues, with standard errors. Each *panel* shows the *difference mRT* as a function of the quadrant where visual change occurred. The four panels correspond to the four tactilely cued quadrants. An *asterisk* indicates that the value is significantly different from 0 ms

was highly significant [$F(9,81) = 10.61$, $P = 0.0001$]. This interaction can be observed by the significant decrease in *mRT* when the cue and change quadrants coincided, and the varying amount of increase in *mRT* when the cue and change quadrants were not matched. Furthermore, it appears that the effect of tactile cuing was smaller for visual targets in the upper-left quadrant VQ2 than for those in the other three quadrants, as confirmed by a pairwise *t* test ($t = -2.58$, $P = 0.0142$). Presumably, the participants tended to look in the upper-left quadrant VQ2 first and therefore did not benefit as much from valid tactile cues in the upper-left corner TQ2. It can also be seen that significant increases in *mRT* occurred when the invalid tactile cues drew the participants' attention to the quadrant that was diagonal from the visual-change quadrant. These were the cue-change pairs corresponding to the most positive value in each of the four panels of Fig. 3, respectively: (TQ1, VQ3), (TQ2, VQ4), (TQ3, VQ1), and (TQ4, VQ2). The *mRT* changes for other cue-change pairs were not significant (i.e., no asterisk above or below the bars in Fig. 3). This result suggests that when the participants failed to find a visual target in the tactilely cued quadrant, they tended to redirect their visual attention horizontally or vertically, but not diagonally.

When the tactile cues were spatially non-informative (25% valid), cuing effect was significantly reduced. None of the *mRT* averaged across all participants for all of the 16 tactile-cue/visual-target quadrant pairs was significantly different from 0 ms, suggesting that the participants successfully disregarded the tactile cues. An ANOVA performed on the *mRT* data with the three factors of participant, tactile cue quadrant, and visual change quadrant indicated that participant had a significant effect on the difference *mRT* values [$F(9,81) = 11.73$, $P < 0.001$], and so did visual change quadrant [$F(3,81) = 3.05$, $P = 0.0331$). The interactions between tactile cue and visual change quadrants [$F(9,81) = 3.30$, $P = 0.0018$] and between participant and visual change quadrant [$F(9,81) = 2.21$, $P = 0.0034$] were also significant.

Eye-gaze data

The eye-gaze data provided a direct measure of participants' overt visual spatial attention. In the present study, the initial saccades in each visual quadrant were estimated from the eye-gaze data. The initial saccades were defined as the first eye-gaze data outside of ±0.3° of visual angle (0.91×0.91 cm) from the fixation point at the center of the visual display. If the initial eye-gaze movement ended to the right and above the fixation point, then we counted one saccade in the upper-right quadrant VQ1, and so forth. Figure 4 shows the number of initial saccades averaged across all participants from the baseline condition of no tactile cuing. It is evident that the upper-left quadrant VQ2 received the most initial saccades (137), which was roughly twice the number of initial saccades received by either the upright-right quadrant VQ1 (68) or the lower-left quadrant VQ3 (65), which in turn were more than twice the number

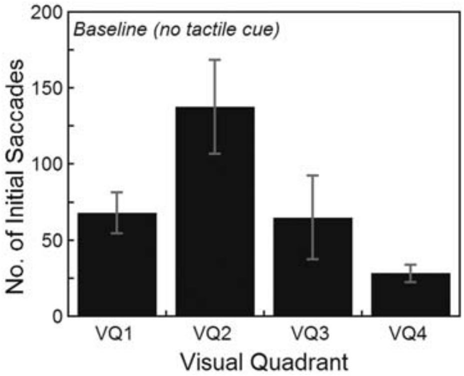

Fig. 4 Number of initial saccades averaged over all participants for the baseline condition of no tactile cuing, as a function of the visual quadrants. Also shown are the standard errors

received by the lower-right quadrant VQ4 (28). An ANOVA performed on the number of initial saccades with the factors of participant and visual quadrant showed that participant was not a significant main factor [$F(9,27) = 0.29$, $P = 0.9711$], but visual quadrant was [$F(3,27) = 3.55$, $P = 0.0277$]. A Tukey test revealed two groups of visual quadrants: (VQ1, VQ2, VQ3) and (VQ1, VQ3, VQ4). The findings that the participants tended to look in the upper-left quadrant VQ2 first and the groupings of the visual quadrants were consistent with the results from the baseline *mRT* data shown in Table 1.

With spatially informative (75% valid) tactile cues, the maximum number of initial saccades always occurred in the visual quadrant correlated with the tactilely cued quadrant. Figure 5 shows the number of initial saccades averaged over all participants. Each panel shows the average number of initial saccades in the four visual quadrants given tactile cues in a particular quadrant. It is apparent that the majority of initial saccades went to the visual quadrant cued by the tactile signal. The four bars corresponding to valid tactile cuing conditions (TQ1, VQ1), (TQ2, VQ2), (TQ3, VQ3) and (TQ4, VQ4) coincided with the four bars with negative values (indicating a reduction in *mRT*) in Fig. 3. From Figs. 3 and 5, we conclude that when overt visual attention was directed toward one of the visual quadrants (high saccade count in Fig. 5), RTs for detecting a visual change in the corresponding quadrant decreased (negative *difference mRT* in Fig. 3). An ANOVA performed on the number of initial saccades with the factors participant, tactile-cue quadrant, and visual quadrant revealed that there was a significant main effect of participant [$F(9,81) = 2.46$, $P = 0.0156$], and as expected, the interaction between tactile-cue quadrant and visual quadrant was also significant [$F(9,81) = 19.17$, $P < 0.0001$]. Subsequent t tests confirmed that, when the upper-right quadrant TQ1 was cued, the average number of saccades in VQ1 was significantly higher than those in the other three visual quadrants ($t = -5.56$, $P < 0.0001$). The same was true for tactile cues in the other three quadrants (TQ2: $t = -5.76$; TQ3: $t = -7.39$; TQ4: $t = -6.56$, all $P < 0.0001$).

Following the presentation of spatially-noninformative (25% valid) tactile cues, most of the initial saccades occurred in the upper-left quadrant VQ2 and the least number of initial saccades occurred in the lower-right quadrant VQ4, regardless of the location of the tactile cues (Fig. 6). An ANOVA with the factors participant, tactile cue quadrant and visual quadrant showed that all three were highly significant [participant: $F(9,81) = 12.30$, $P < 0.0001$; tactile cue quadrant: $F(3,81) = 214.42$, $P < 0.0001$; visual quadrant: $F(3,81) = 9.05$, $P < 0.0001$]. The interaction between participant and tactile cue quadrant was also significant [$F(27,81) = 56.67$, $P < 0.0001$], as was the interaction between tactile cue quadrant and visual quadrant [$F(9,81) = 5.16$, $P < 0.0001$], but not the interaction between participant and visual quadrant [$F(27,81) = 0.38$, $P = 0.9967$]. Subsequent Tukey and t-tests confirmed three groupings of initial saccade counts: VQ2 (mean = 47.3; $t = -3.58$, $P = 0.0013$), VQ1 and VQ3 (mean = 22.7; $t = -0.14$, $P = 0.8915$; and mean = 24.8, $t = -0.28$, $P = 0.7782$; respectively), and VQ4 (mean = 8.925; $t = 1.88$, $P = 0.0713$).

Discussion

The present study investigated the tactile cuing of visual attention using tactile cues that were either spatially informative (75% cue validity condition) or non-informative (25% cue validity condition). The results from the spatially informative tactile cuing condition were as expected: That is, participants were able to utilize the tactile cues to reduce reaction time in a visual search task when the cues were valid, and the RT increased when the cues were invalid. These results are consistent with the findings of other studies on crossmodal attentional cuing (e.g., see Fujawa and Strybel 1997; Perrott et al. 1996, for similar results on auditory cuing of visual attention; also see Spence et al. 2004, for a recent review). The eye-gaze data corroborated the reaction time data in that most of the initial saccades went to the visual quadrant corresponding to the tactilely cued quadrant when the cue validity was high and when the participants were explicitly instructed to use the high-validity cues in the visual change-detection task.

The main findings of the present study concern the use of spatially non-informative tactile cues in directing overt visual attention. Numerous studies have indicated that performance on a visual task can be significantly affected by spatially non-predictive tactile cues (see Spence and Driver 2004). However, the participants in the present study were explicitly instructed to ignore the spatially non-informative

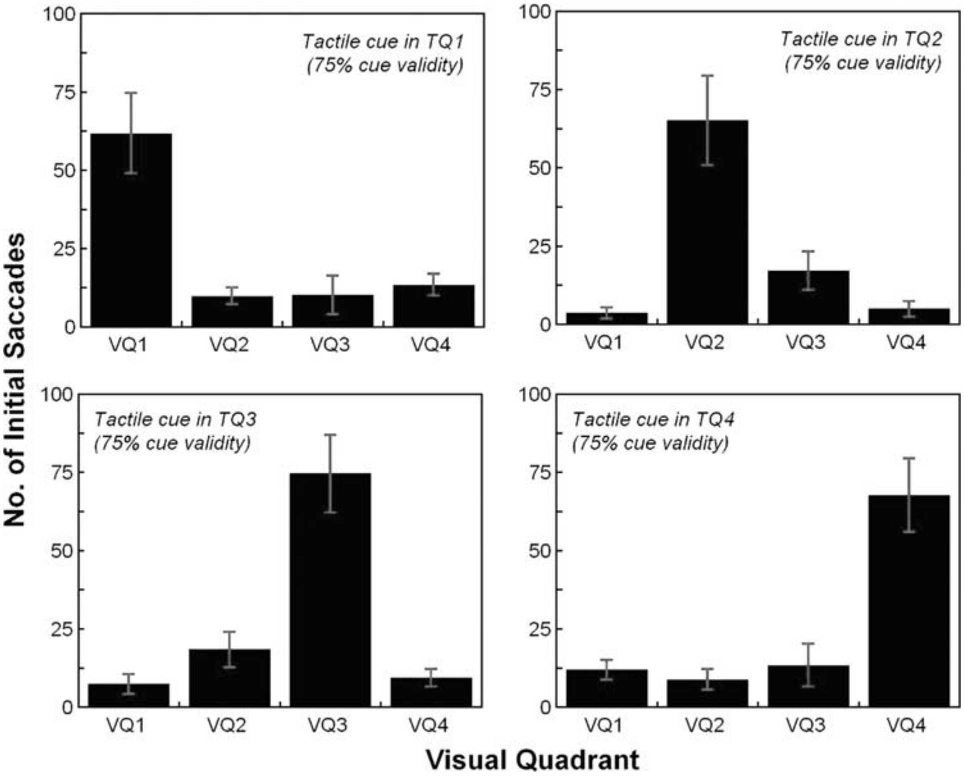

Fig. 5 Average number of initial saccades for spatially-informative (75% valid) tactile cues, with standard errors. Each *panel* shows the saccade count as a function of the four visual quadrants where the initial saccade occurred. The four panels correspond to the four tactilely-cued quadrants

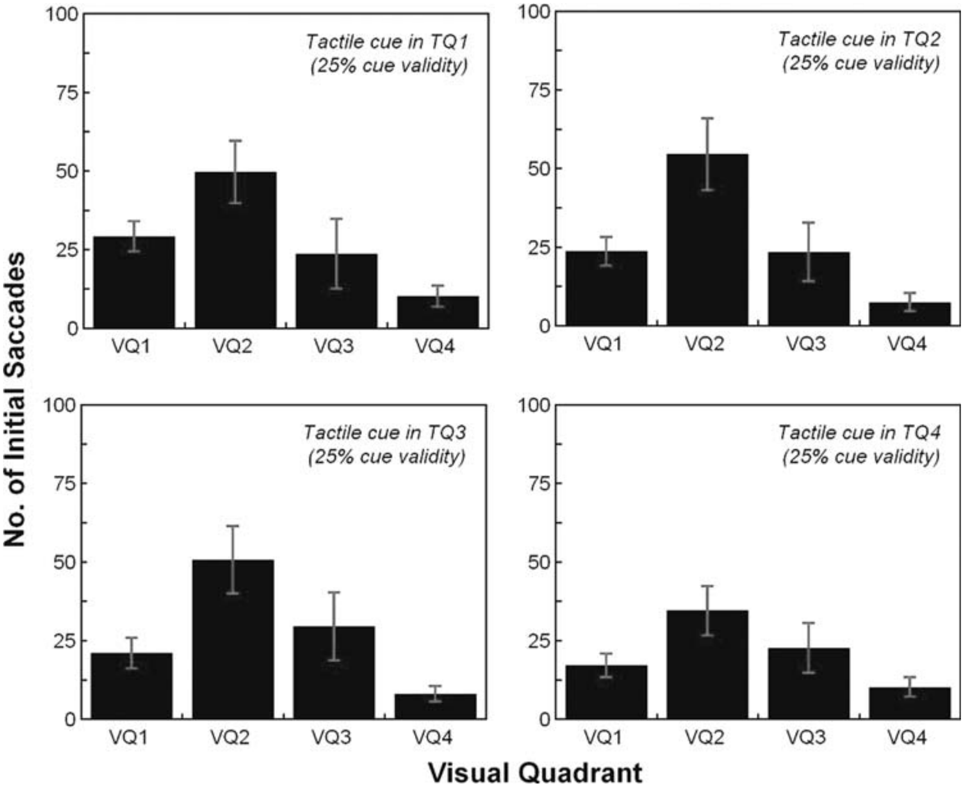

Fig. 6 Average number of initial saccades for spatially-noninformative (25% valid) tactile cues, with standard errors. Each *panel* shows the saccade count as a function of the four visual quadrants where the initial saccade occurred. The four panels correspond to the four tactilely-cued quadrants

cues. We were interested in investigating the extent to which the participants were able to do so. The results showed that the participants in the present study were able to suppress the spatially non-informative cues because the overall changes in RT were not significant. Furthermore, we found that most of the initial saccadic movements went to the upper-left visual quadrant where the participants tended to start their visual search in the absence of any tactile cues (cf. Figs. 4, 6). The results also showed that the participants did not use the spatially non-informative tactile cues to alter their natural visual search pattern in that the distributions of initial saccades across the four visual quadrants as shown in the four panels of Fig. 6 were remarkably similar to that shown in Fig. 4.

Our eye-gaze data indicated that without any cuing signals, the participants' natural tendency was to search in the upper-left visual quadrant (VQ2) first, then the upper-right (VQ1) and lower-left quadrants (VQ3), followed by the lower-right quadrant (VQ4). This raises the interesting issue of visual search strategy. To what extent is this raster-scan pattern followed by most people? It may appear that this is a natural search pattern for anyone who reads texts from left to right and from top to bottom. However, it has been shown that saccadic eye movements are highly idiosyncratic under different viewing conditions (e.g., Andrews and Coppola 1999). An examination of the initial saccade counts for individual participants reveals that of the ten participants tested in the present study, six showed the left–right and top–down raster scan pattern as described above, one always looked in the lower-left corner (VQ3) first, and the remaining three did not show a strong preference for examining a particular visual quadrant first. All of the participants in the present study read English on a daily basis and none has a native language (when English is not their first language) that is arranged in a spatial format that is different from English. Furthermore, an analysis of individual participant's eye-gaze data in the 25% validity condition showed that the initial saccade counts were similar to each individual's saccade counts in the baseline condition of no tactile cuing, indicating that the participants did not use the spatially non-informative tactile cues to alter their natural visual search pattern.

Our finding that the participants were able to ignore the spatially-noninformative tactile cues indicated that the attentional link between touch and vision was learned rather than automatic. One possible reason for this finding was the fact that the tactile cues and the visual targets were not colocated. In general, performance is enhanced if information coming from more than one sensory modality is presented from approximately the same external location. It has been suggested that some of the null crossmodal results found in earlier studies (e.g., Tassinari and Campara 1996, using a tap on the shoulder and the illumination of a square on a screen) might have been due to the fact that the cue and target stimuli were presented from very different spatial locations even when they were presented on the same side with respect to the participant's torso (cf. Spence et al. 1998). An exception to the cue-target collocation rule was provided by an earlier study of Tan et al. (2003) in which participants received vibrotactile cues on the four corners of their backs prior to searching for a visual change on a computer monitor, a setup similar to that used in the present study. The participants were informed that the location of the tactile cue predicted the quadrant of the visual change on 50% of the trials, hence the task elicited both endogenous and exogenous spatial attention cuing. Tan et al. (2003) reported that visual detection time decreased significantly when the location of the tactile cue was in the same quadrant as that of the visual change, and that detection time increased significantly when the tactile cue and the visual target occurred in different quadrants.

Another recent study by Ho et al. (2005) confirmed that crossmodal attention cuing effects can be elicited when the (tactile) cue and the (visual) target are presented from very different locations (so long as the direction in which the stimuli are presented was matched). In a simulated driving environment, participants felt a vibrotactile stimulus presented on the front or back around the waist, and were required to brake, accelerate or maintain constant speed by checking the front or the rearview mirror for a potential emergency driving situation (i.e., the rapid approach of a car from either in front or behind). It was found that participants responded significantly more rapidly following valid vibrotactile cues than following invalid cues. A further twist to the spatial set-up of this experiment was that when prompted by a vibrotactile cue to the back, participants were able to look at the rearview mirror in the front in order to check the traffic condition behind the vehicle. There appear to be some differences between auditory and tactile cuing in that whereas directional congruent tactile cues may be sufficient to facilitate performance due to the priming of the appropriate response, spatially-collocated auditory cues may further facilitate attention and perception of the targets (Ho et al. 2006) and that inaccurate auditory stimuli may not be ignored entirely (Rudmann and Strybel 1999; see also Vu et al. 2006). Overall, it suffices to say that the cue-target collocation rule can be relaxed when a tactile cue is involved, and when the spatial mapping between the cue and target is overlearned (such as is the case in driving). This is a useful result that should be explored in designing multisensory warning systems. Whereas it is generally desirable to match the cue and target stimuli locations to maximize spatial cuing effects, tactile cues may be effectively deployed when it is not feasible to place warning signals at exactly the same location as that of dangerous events. It may also explain why the attention link between touch and vision can be easily broken when the tactile cues are known to be noninformative, as was the case in the present study.

One issue that might have impacted the interpretation of the results from the present study has to do with the instructions provided to the participants for the 25% validity condition. The participants were asked to "ignore the cue and search elsewhere." One might argue that the instruction to "search elsewhere" effectively rendered the spatially-noninformative tactile cues as "anti-cues." The motivation behind our mentioning of this strategy in passing to participants was precisely to investigate whether the participants were able to use the anti-cues and subsequently demonstrate eye-gaze patterns that were consistent with such a strategy. From the eyegaze patterns we had analyzed; however, there was no evidence that any participant had used the tactile cues as "anti-cues." Therefore, based on the facts that reaction times did not change significantly in the 25% validity condition as compared to those in the baseline condition and neither did initial saccade count data, we conclude that the participants were able to ignored the spatially non-informative tactile cues. We hasten to point out that from anecdotal reports, it took some effort to intentionally ignore the tactile cues even though they were known to be non-informative. Santangelo et al. have demonstrated an abolishment of the effects of visual, auditory or tactile spatial attentional cues when the participants were engaged in a perceptually demanding rapid serial visual/auditory presentation task (Santangelo et al. 2007; Santangelo and Spence 2007). It is intriguing to speculate on whether the participants in the present study would have found it difficult to ignore the spatially-noninformative tactile cues if a second task was used that consumed the participants' available resources. The assessment of the cognitive load associated with the suppression of tactile cues will be one topic of our future studies.

Our findings have several important implications. First, we have shown that the crossmodal attentional link between touch and vision is a natural and easily established one in that the participants were able to effectively use the spatially-informative tactile cues in the visual change-detection task. Second, the crossmodal attentional link between touch and vision is largely a learned strategic shift in attention because it can be broken when participants are explicitly informed that the cue validity was low and that they should ignore the cues. Third, we found that most participants have an idiosyncratic visual search pattern in the absence of any spatial attention cues. As a consequence, the effect of tactile cuing is the smallest, in terms of the reduction in RT, for visual changes in, say, the upper-left quadrant VQ2 (cf. Fig. 3, upper-right panel) presumably because the participants always looked there first already. A better understanding of the pattern of visual searches will inform the designer of multisensory attentional cuing signals to focus on the situations where visual changes occur in locations where people tend not to monitor visually (such as the rear-view mirror in a car). Finally, our results indicate that for multisensory attentional warning signals to be effective, it is extremely important to minimize or eliminate false alarms so users will always trust these warning signals in dangerous situations. In addition to cue validity, other factors such as the spatial precision of cues can also affect cue effectiveness. For example, Strybel and Bertolotti (2005) showed that audio cue precision can interact with cue informativeness. When false alarms are possible, even small errors produce greater increases in search time, because participants adopt different search strategies when the audio cue is not spatially coincident.

Two directions will be pursued in our future work. First, we intend to use a dual-task paradigm in order to assess the cognitive load associated with the active suppression of crossmodal spatial attentional cues. Even though we expect practical multisensory attentional cuing systems to always utilize high-validity warning signals, it is nevertheless important to understand the possible scenarios under which the effectiveness of such systems may be compromise by, say, a user's mistrust of the warning signals. Second, we will perform further analyses of the vast amount of eyegaze data we have collected in the present study in order to discover and model the visual search strategies employed by the participants. We believe that these efforts will eventually lead to the successful deployment of effective multimodal collision warning systems that will prevent, or lessen the damages of, accidents.

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