The haptic cuing of visual spatial attention: Evidence of a spotlight effect

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ABSTRACT

This article provides an overview of an ongoing program of research designed to investigate the effectiveness of haptic cuing to redirect a user's visual spatial attention under various conditions using a visual change detection paradigm. Participants visually inspected displays consisting of rectangular horizontal and vertical elements in order to try and detect an orientation change in one of the elements. Prior to performing the visual task on each trial, the participants were tapped on the back from one of four locations by a vibrotactile stimulator. The validity of the haptic cues (i.e., the probability that the tactor location coincided with the quadrant where the visual target occurred) was varied. Response time was recorded and eye-position monitored with an eyetracker. Under conditions where the validity of the haptic cue was high (i.e., when the cue predicted the likely target quadrant), initial saccades predominantly went to the cued quadrant and response times were significantly faster as compared to the baseline condition where no haptic cuing was provided. When the cue validity was low (i.e., when the cue provided no information with regard to the quadrant in which the visual target might occur), however, the participants were able to ignore haptic cuing as instructed. Furthermore, a spotlight effect was observed in that the response time increased as the visual target moved away from the center of the cued quadrant. These results have implications for the designers of multimodal (or multisensory) interfaces where a user can benefit from haptic attentional cues in order to detect and/or process the information from a small region within a large and complex visual display.

Keywords: haptic cuing, visual spatial attention, eye-gaze, cue validity, spotlight of attention

1. INTRODUCTION

The research described here pertains to the following scenario: Imagine standing in front of a large visual display that requires multiple glances in order for you to inspect all parts of the display. To what extent can the designer of the display influence how your eyes move across the scene? Take, for example, an air traffic controller center where the need might arise for an operator's attention to be directed toward an area that requires immediate action; Alternatively, imagine an electronic art exhibition in which the designer wants to narrate a story by guiding the viewer's gaze through a pre-determined spatial trajectory. The studies reported here have shown that haptic cues presented to a viewer's back can be used to effectively direct the viewer's visual spatial attention, thus providing an effective means of manipulating a viewer's gaze by the crossmodal cuing of their spatial attention (i.e., by relying on the crossmodal links in spatial attention between vision, touch, and audition that have been documented by recent research).

In our daily lives, we are all familiar with the use of touch to gain a person's attention. A tap on the shoulder provides an effective means of getting someone's attention at a noisy cocktail party, say. The question then arises as to whether the same approach can be utilized, for example, in order to redirect a driver's visual attention in order to avoid an impending collision? In the studies reported here, we used a 2-by-2 tactor array placed on a viewer's back. We measured the times required by our participants in order to find a visual change occurring in one of the four quadrants of a computer monitor. The validity of the haptic cues (i.e., the probability that the tactor location coincided with the quadrant where the visual target occurred) was varied in different studies. We investigated the effect of haptic cues on

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visual target search time during valid and invalid cuing trials under conditions of varying cue validity. In our more recent studies, we have used an eye-tracker in order to measure a viewer's (overt) spatial attention more directly (i.e., when compared to the indirect measure provided by reaction time, RT, data). We were interested in measuring this use of overt responding by shifting gaze in practical situations, as opposed to the covert orienting of a person's attention in the absence of any head/eye movements that has been the focus of many previous laboratory-based studies. Finally, we also examined how cuing effects subsided as the spatial separation between the cue and target increased (i.e., spotlight effect[1 2 3]).

1.1 Background

The amount of information available to operators in modern complex systems continues to increase. However, it is important to note that interface operators have only a limited capacity (or ability) to attend to the information available in a complex multimodal (or multisensory) environment such as is represented by the cockpit of an aircraft. That is, attentional resources are strictly limited. The phenomenon that perhaps best illustrates the importance of attention is "change blindness"[4] which has an analog in both audition[5] and touch[6]. Specifically, easily perceptible changes in visual, auditory, or haptic displays often go unnoticed by people, and change detection improves when the user's attention is directed toward the change (e.g., by means of crossmodal, or intramodal, attentional cuing). It is therefore important to provide cues to critical information in a user's work environment when the user can be temporarily distracted (i.e., when the transients marking the change may be somehow masked). Crossmodal, non-visual (i.e., auditory or tactile) channels are attractive candidates for the design of warnings and cues, because they do not place any additional demands on an operator's frequently-overloaded visual system[7]. However, the choice of cue modality, and the optimal cue format within each sensory modality is currently unknown.

Studies on cuing effects typically use RT and error rates as performance measures. In a typical visuotactile experiment using the orthogonal cuing paradigm[8], a participant receives vibrotactile stimulation to their left or right hand (the cue), followed shortly thereafter by the illumination of one of two LEDs (the target) held by the left or right hand. The participant makes a speeded response in order to indicate whether an upper or lower LED is illuminated by lifting the toes or heel of a foot placed on two pedals (one under the toes and the other under the heel). Cuing effects are measured in terms of the difference in RT between valid (when the cue and target occur on the same side) and invalid (when the cue and target occur on different sides) trials. This difference between performance in the valid and invalid trials has been taken to provide a measure of the extent to which the presentation of stimuli in one sensory modality can direct, or capture, a person's spatial attention in another sensory modality[9].

Auditory, visual, and haptic stimuli have been examined in spatial cuing experiments. Researchers have shown that the speeded detection of a visual target is faster (and tends to be more accurate) following the presentation of a spatially-nonpredictive peripheral auditory cue presented on the same side as the visual target rather than on the opposite side[10 11 12]. By contrast, while speeded discrimination responses for auditory targets are affected by the prior presentation of spatially-nonpredictive visual cues under certain situations (e.g., when the task is spatial, and the cue and target come from the same spatial location), they are not in others[13 14]. For the crossmodal pairing of visual and tactile stimuli, the evidence suggests that visual target judgments are significantly affected by spatially non-predictive tactile cues, and vice versa[15 16 17 18 19]. Finally, spatially non-predictive haptic cues can also lead to significant crossmodal cuing effects upon auditory target judgments, and vice versa[18].

The issue of spatial-colocation is an important one in studies of crossmodal spatial attention. In general, performance is enhanced if information coming from more than one sensory modality is presented from approximately the same spatial location. Even when auditory and visual tasks are entirely unrelated, actively performing them together can be more efficient when the visual and auditory stimuli are presented from a common spatial location (or direction), than from different locations[20 21]. Gray and Tan[15] provided evidence for the existence of dynamic and predictive spatial links in attention between touch and vision. In particular, the participants in their study had to discriminate the spatial locations of visual targets (left or right) presented randomly at one of five locations on the forearm pointing toward a computer monitor placed in front of them. Tactile pulses simulating motion along the forearm preceded the visual targets. Discrimination was more rapid when the final tactile pulse and visual target were presented from the same location at short tactile-visual interstimulus intervals. Gray and Tan also demonstrated an exception to the cue-target spatial colocation rule in a study in which their participants received vibrotactile cues from one of the four corners of their backs prior to searching for a visual change on a computer monitor[19]. Visual detection latencies decreased significantly when the haptic cue was located in the same quadrant as the visual change, and increased significantly when the haptic cue and the visual target occurred in different quadrants. Another study confirmed that cross-modal attentional cuing effects can be elicited when the (haptic) cue and the (visual) target are presented from very different locations (so long as the direction in which the stimuli are presented was matched)[22]. In a driving simulator, participants felt a vibrotactile stimulus presented on the front or back around their waist (i.e., from a belt with two tactors, one near the naval and the other near the spine), and were required to brake, accelerate, or else to maintain a constant speed by checking the front or the rear-view mirror for a potential collision (i.e., the rapid approach of a vehicle from either the front or rear). Participants responded more rapidly following valid vibrotactile cues (i.e., front vibration for the sudden breaking of the vehicle in the front, or back vibration for the sudden acceleration of the vehicle in the rear) 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, the participants were able to look at the rear-view mirror (actually situated in front of them) in order to check the traffic condition behind their vehicle. Therefore, it appears that the cue-target colocation rule can be relaxed when a haptic cue is involved, and when the spatial mapping between the cue and target is in some sense overlearned (such as in driving when looking in the rearview mirror to determine what is going on behind). This is a useful result that should be explored when thinking about the design of multimodal (or multisensory) systems. Whereas it is generally desirable to match the cue and target stimuli locations in order to maximize any spatial cuing effects, haptic cues may be effectively deployed even when it is not feasible to place warning signals at exactly the same location as that of dangerous events (i.e., when the haptic/tactile cues must be presented to a driver's body in order to warn them about a potentially dangerous driving event occurring outside the driven vehicle).

Numerous studies have demonstrated that spatially non-informative haptic cues can effectively elicit an automatic shift of attention that will facilitate subsequent responses to visual, auditory, and haptic stimuli[16 17 18 23 24]. Therefore, touch is an extremely effective sensory modality for alerting purposes. Spatially-informative tactile stimuli can potentially speed-up visual responses to pending hazardous situations. Given the effectiveness of exogenous spatial cuing to elicit automatic shifts of spatial attention, there seems to be no need for extensive user training for a multimodal (or multisensory) warning system to be highly effective, since exogenous spatial cuing effects are thought to be stimulus-driven and automatic.

The auditory channel also provides an important candidate for alerts and warnings. Although most current auditory alarms do not provide information about the location of the critical event that they refer to, recent technological advances have made auditory spatial cuing in complex systems a distinct possibility. Auditory spatial cues are similar to haptic cues in that they can be detected regardless of where the person is currently facing. However, haptic cues must stimulate the tactile receptors directly, meaning that spatial information regarding externalized visual events must somehow be mapped onto the haptic cue. Audio spatial stimuli can be perceived at a distance from the operator, meaning that an auditory cue can be positioned at (or at least appear to emanate from) the exact target location, thus creating a stimulus to which people will tend to orient automatically[25]. Moreover, auditory spatial acuity is superior to visual acuity in the periphery[26], thus leading some researchers to suggest that a primary function of auditory spatial processing is to direct visual orienting[27]. For example, people saccade more rapidly to audiovisual targets than to unimodal visual or auditory targets[28], and the available evidence suggests that the orientation of spatial attention to auditory and visual stimuli involves some of the same brain mechanisms[29].

In summary, both haptic and audio cues provide attractive channels for alerting and cuing operators to the locations of critical events in complex systems. Both sensory modalities can provide an effective means of reducing search times when an interface operator has to detect specific visual events. However, experiments on haptic cuing have focused on detecting a change in the stimulus array (e.g., as in the change blindness paradigm), whereas experiments on audio cuing have focused on searching for a known visual target over large search fields. Both tasks are relevant to human performance in complex systems: Change detection is analogous to the task of monitoring several information sources for critical deviations. Target localization and identification is analogous to searching (e.g., out the window) for objects and determining whether or not a response is required. In this article, we focus our discussion on the use of haptic cues in aiding visual search (as measured by visual change detection performance).

1.2 Definition of haptics terms

Before we proceed, we briefly lay out the definition of terms related to haptics research. The word *haptics* refers to sensing and manipulation through the sense of touch. The term *cutaneous* or *tactile* refers to an awareness of stimulation of the outer surface of the body mediated by the mechanoreceptors situated in the skin[30]. The term *kinesthesis* or *proprioception* denotes the awareness of joint-angle positions and muscle tension mediated by receptors embedded in the muscles and joints[31]. Haptics includes both tactile and kinesthetic sensing, as well as motor outputs. In this article, we use the term *tactor* to refer to tactile stimulators, or vibrators. We use the term *vibrotactile stimulation* in order to denote tactile stimulation mediated by vibrations. Although the cues used in our studies are vibrotactile in nature, we also refer to them as haptic cues, as the term haptic includes tactile perception. Note that the above definition is functional and useful when characterizing patterns of stimulation from laboratory studies. In performing daily tasks such as estimating the weight of an object with one's hand, however, tactile and kinesthetic stimulation cannot be so easily separated. Modern haptics research is concerned with the science, technology, and applications associated with information acquisition and object manipulation via the sense of touch, including all aspects of manual exploration and manipulation by humans, machines, and interactions between the two, performed in real, virtual, teleoperated, or networked environments. For an overview of the current opportunities and challenges facing haptics research, see the recent article concerning The Technical Committee on Haptics[32].

The rest of this article is organized as follows. Section 2 provides an overview of the Methods used in our studies, while Section 3 presents the results from a series of our experiments. The article finishes with some concluding remarks in Section 4.

2. METHODOLOGY

This section provides an overview of the methods used in the experiments reported in this article. We focus on the elements that are common to most of the experiments. Details that are specific to a single experiment are described later in Section 3 when the results from the corresponding experiments are presented.

2.1 Visual stimuli

As stated above, our latest research has been concerned with the effect of haptic cues on redirecting a viewer's visual attention. This required a visual task in which a performance metric (in this case RT) has been shown to depend on where a person's visual spatial attention happens to be focused. The flicker paradigm developed originally to study change blindness in vision fits our requirement here[4]. In our studies, the visual scenes consisted of rectangular elements of equal sizes, but presented in either a horizontal or vertical orientation (see Fig. 1). Two scenes, differing only in the orientation of one of the elements, were presented in an alternating sequence until the participant responded. A blank scene was inserted between the two scenes in order to mask any motion cues associated with the change[4]). The participants in our studies had to try and locate the visual element that changed its orientation from scene to scene. Since the changing visual element could not be detected unless the participant paid attention to it, we expected RTs to decrease if haptic cues successfully directed the participant's eye-gaze toward the quadrant where the visual change occurred. Likewise, we expected RTs to increase if the haptic cues directed visual attention away from the quadrant where the visual change occurred.

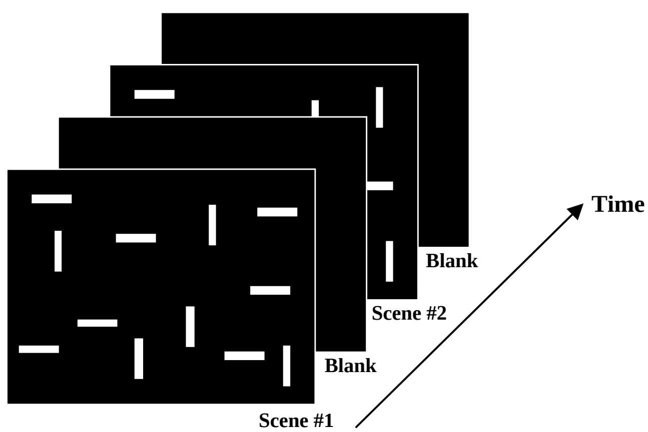
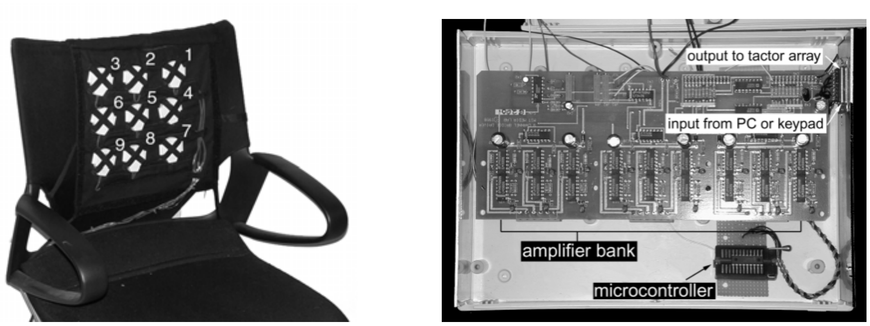


Fig. 1. Visual displays used in the flicker paradigm (modified from Fig. 2 in Rensink's study[4]). In this example, the rectangular bar in the upper-right corner changes its orientation between the two visual scenes. The sequence shown is repeated until a mouse button has been pressed indicating that a visual change has been spotted.

2.2 Haptic cues

A haptic back display was developed at the Haptic Interface Research Laboratory at Purdue University (see Fig. 2a). The hardware for the haptic back display consisted of nine tactors and the associated driver circuit. The tactors formed a 3-by-3 array with an inter-tactor spacing of 8 cm. Each tactor was fastened to a piece of supporting fabric by elastic bands. The supporting fabric was then draped over the backrest of a standard office chair. Each tactor was modified from a 40-mm diameter flat magnetic speaker (FDK Corp., Tokyo, Japan) with an additional mass to lower its resonant frequency and increase the gain at the resonant frequency (David Franklin, President of Audiological Engineering Corp., personal communication, 1996). In our studies, only the four corner tactors were used: tactors 1, 3, 7 and 9 corresponded to the upper-left, upper-right, lower-left, and lower-right visual quadrants, respectively. A custom-made control box supplied amplified oscillating signals to the tactors in the haptic back display (see Fig. 2b). Audio power amplifiers based on LM383 (National Semiconductor Corp.) were used to drive the modified speakers at around 250-300 Hz, a frequency range over which humans are most sensitive to vibrations[33]. The pulse duration and interpulse interval were controlled by a PIC16C84 (Microchip Inc., Arizona) microcontroller. The intensity of the tactors was adjusted so that the vibrations could be clearly felt through whatever clothing the participants happened to be wearing when they took part in the study.



(a) (b)

Fig. 2. (a) The haptic back display developed at the Haptic Interface Research Laboratory at Purdue University, and (b) the control box[19].

On a typical trial, a red fixation cross was displayed in the center of the computer monitor for 500 ms. The participants were instructed to look at the fixation cross. The haptic cue was presented at the offset of the visual fixation cross. It consisted of a 60-ms 290-Hz sinusoidal pulse delivered to one of the corner tactors. Following a 140ms pause after the offset of the haptic cue, the visual stimuli shown in Fig. 1 were displayed. The haptic cues were delivered once at the beginning of a trial, and then the participants performed a visual change detection task without further haptic input.

2.3 Procedures

Before an experiment began, the participants were informed of the nature of the task. Specifically, they were told to find the rectangular element on the computer monitor that was changing its orientation from horizontal to vertical or vice versa between the alternating scenes. Their task was to (1) detect and (2) locate this element as quickly as possible. They indicated detection of the visual change by clicking the left mouse button without moving the cursor (in order not to confound RT with movement time). The image on the monitor then froze and all of the rectangular elements turned pink. The participants were instructed to move the cursor to the element that they had detected changing and to click the left mouse button for the second time. The location of the cursor was recorded and compared against the location of the changing element.

To ensure that the participants could feel the haptic cues on their back clearly, a tactor-location identification experiment was performed once for each participant at the beginning of the first session. On each trial, one of the corner tactors was turned on briefly. The participants had to click one of four large boxes located in each of the four quadrants of the monitor. For example, if the haptic cue was delivered to the vicinity of the right shoulder, the correct response would be to click the box in the upper right quadrant of the monitor. Each participant had to complete one perfect run of 60 trials before proceeding to the main experiments. All of the participants achieved 100% correct tactor-location identification with no difficulty.

The independent variables included the state of the tactors (“on” vs. “off”), the amount of time each visual scene was on (the “on time”), and the validity of the haptic cues. Practice was allowed at the beginning of each run. Throughout the experiments, the participants were instructed to sit upright with their back pressed against the tactor array. They were instructed not to move their body relative to the chair, or to move the chair relative to the monitor. Headphones were used to block out any audible noise from the tactor array and the environment. During the experiments where an eye-tracker was used, a chin-rest was used to stabilize the participant’s head position.

2.4 Data analyses

The dependent variables were mean RT and their standard errors, and (in some experiments) eye-gaze data. Data from the tactor-off condition served as a baseline measure of performance. The data for the trials with valid cues (where the haptic-cue quadrant coincided with the quadrant of the visual-change) and invalid cues (where the haptic-cue quadrant was different from the quadrant of the visual-change) were processed separately. Error trials, where the participant failed to locate the changing element with the second mouse click, were discarded (<7% of total trials). Cuing effects were determined by comparing the baseline (no haptic cue) RTs with those obtained from haptic cuing conditions. Combining the four possible haptic-cue locations on the participant’s back with the four possible visual-change quadrants on the computer monitor gave rise to a total of 16 haptic-cue / visual-change quadrant pairs. Of the 16 pairs, 4 corresponded to trials with valid haptic cues (haptic-cue quadrant = visual-change quadrant) and the remaining 12 corresponded to trials with invalid haptic 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 haptic cues in each condition. Data from all trials were separated into four groups according to the haptically cued quadrants on the back. The eye-gaze trajectories for the trials in each group were then analyzed by determining the quadrant on the computer monitor where the participants looked immediately following the presentation of the haptic cue (i.e., the initial saccades).

3. RESULTS

3.1 Valid haptic cues reduce response time and invalid haptic cues increase response time

Results from several studies have shown that valid haptic cues reduce RTs[19 34 35 36]. In one of the earliest studies, haptic cue validity was set to 50%[19]. During half of the trials, the haptically-cued quadrant matched the visual change quadrant. During the remaining trials, the haptic cue corresponded to one of the three quadrants with no visual change. Therefore, the haptic cues were informative with regard to the location of the visual change since it was above the chance level of 25%. Figure 3 shows the mean RT for ten participants as a function of “on-time”, the amount of time each visual scene was displayed. The off time, the amount of time the blank screen was shown, was kept at 120 ms (see Fig. 1). On average, RT decreased by 41% (1630 ms) with valid haptic cues and increased by 19% (781 ms) with invalid haptic cues. Cue validity had a significant effect on mean RT for all three “on-time” values.

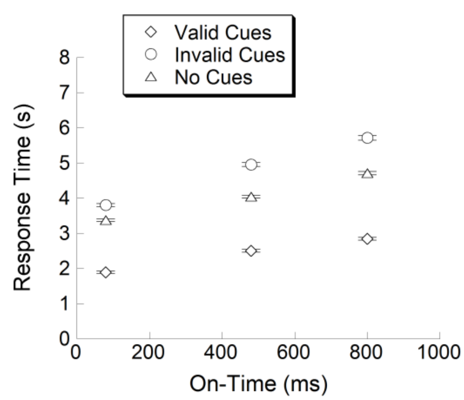


Fig. 3. Results from 10 participants (Modified from Fig. 4 of an early study[19]). Shown are the baseline response times (triangles), and response times with valid (diamonds) and invalid (circles) haptic cues, and their standard errors.

3.2 Effect of cue validity

Having established the effectiveness of haptic cues in terms of their ability to direct a person's visual spatial attention as demonstrated by the speeding up and slowing down of the visual change-detection task following valid and invalid haptic cues, we asked the question of whether the haptic-visual attentional link was automatic (i.e., exogenous) or voluntary (i.e., endogenous). We reasoned that if the haptic cues were equally effective when the cue validity was high or low (and the participants were informed so), then the crossmodal attentional link between touch and vision was likely automatic and involuntary. If, however, the participants were able to use haptic cues when the cue validity was high but managed to ignore the haptic cues when the cue validity was low, then we would have gathered evidence that the haptic cuing effect we have observed so far was due to a voluntary strategic shift in visual attention. In a follow-up study[35], cue validity was either high (80%) or low (20%) and the participants were informed of the validity of the haptic cues before each run. Ten participants were randomly assigned to the two cue-validity conditions. Our results indicated, as expected, that for the participants in the 80% cue validity group, response times decreased significantly with valid haptic cues, and increased significantly with invalid haptic cues. For the participants in the 20% validity group, however, the results were less consistent. Some of the participants benefited from haptic cues, while others managed to ignore the (mostly invalid) haptic cues. These results were interpreted as evidence that the use of haptic cues to reorient a person's visual spatial attention was natural and intuitive when the validity of the haptic cues was high. It was also concluded that the observed cross-modal attentional links between haptics and vision may involve a voluntary shift in attention as supposed to a purely involuntary mechanism.

A later study using an eye-tracker (RK-726PCI pupil/corneal reflection tracking system, ISAN, Inc., Burlington, MA, USA) sought to gain a more direct measure of participants' visual spatial attention by monitoring the initial saccades immediately following the haptic cues[36]. The experimental set-up is shown in Fig. 4. The validity of the haptic cues was either 25% (chance level – i.e., spatially-nonpredictive) or 75% (spatially-informative). The participants were encouraged to use the haptic cues when the cue validity was high (75%). They were instructed to ignore the cue and start their search elsewhere in the low cue-validity (25%) condition. The results from the no-cue baseline condition showed a clear correlation between initial saccade count and mean RT. Fig. 5 shows the number of initial saccades that went to each of the four visual quadrants when no haptic cues were used. Note that we numbered the four visual quadrants (VQ) according to the convention in trigonometry (VQ1=upper-right, VQ2=upper-left, VQ3=lower-left, VQ4=lower-right). Fig. 5 also shows the mean RT to find a visual change in each of the four quadrants (in ms). It can be seen that most initial saccades went to VQ2 (upper-left) which resulted in the lowest mean response time. The initial saccade count to VQ4 (lower-right) was the lowest and the mean response time for that quadrant was consequently the highest. Therefore, the eye-tracker data were consistent with the recorded response times in that the more frequently the initial saccade went to a visual quadrant, the more quickly the participants detected a visual change in that quadrant.

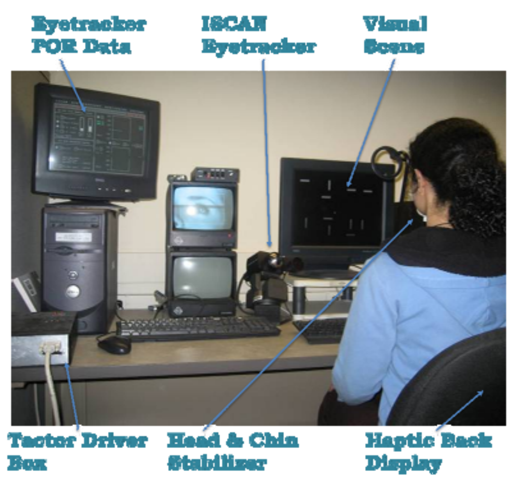


Fig. 4. Experimental setup using an ISCAN eye-tracker. During the experiment, the point-of-regard (POR) data monitor and the eye image monitors were turned off.

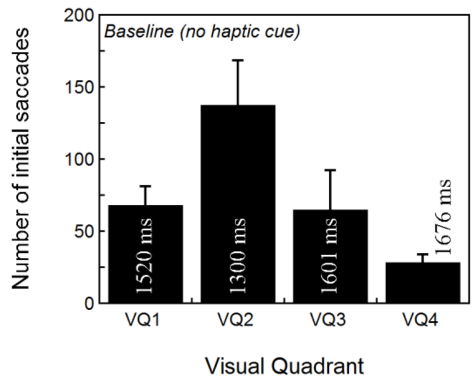


Fig. 5. Number of initial saccades averaged over ten participants for the baseline condition of no haptic cuing, as a function of the visual quadrants, and the standard errors. Modified from Fig. 4 in Jones et al.'s study[36]. The numbers indicate the mean response times (in ms) for the corresponding visual quadrant.

For the high cue-validity condition, the eye-tracker data confirmed that the decrease in RTs with valid haptic cues was accompanied by an increase in the number of initial saccades to the visual quadrant cued by the haptic stimuli. This is shown in Fig. 6 where each panel shows the number of initial saccades to each of the four visual quadrants given a haptic cue in one quadrant, when the validity of haptic cues was high (75%). It is apparent that the majority of participants' initial saccades went to the visual quadrant cued by the haptic stimuli. Mean RTs showed an overall statistically significant decrease of 445 ms with valid haptic cues, and a statistically significant increase by 242 ms with invalid haptic cues compared to the no-cue baseline RTs. It was therefore concluded that when eye-gaze was directed toward (or away from) one of the visual quadrants, mean response times for detecting a visual change in the corresponding quadrant decreased (or increased).

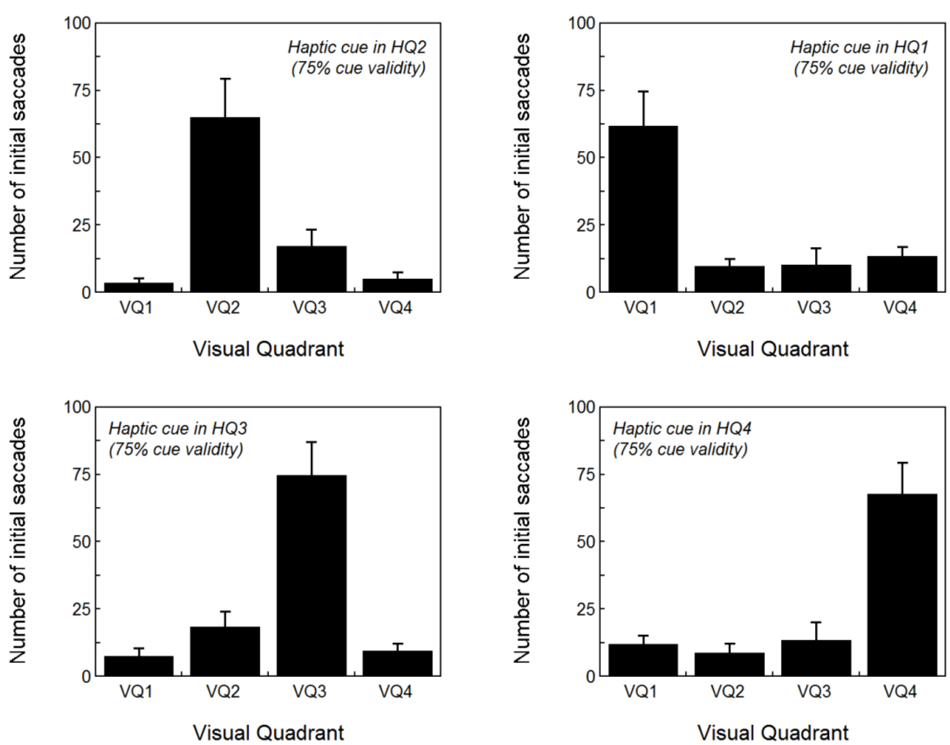


Fig. 6. Number of initial saccades averaged over ten participants for the high validity condition, and the standard errors. Data are organized according to the cued quadrant. Slightly modified from Fig. 5 in Jones et al.'s study[36].

Finally, when cue validity was low (25%), the distribution of initial saccades remained similar to that shown in Fig. 5 regardless of where the haptic cue was applied. In addition, mean response time did not change significantly for any of the cue-target quadrant combinations, regardless of whether the haptic cues were valid or invalid.

3.3 An attentional spotlight effect

One question that remained was whether the effect of haptic cues on RTs depended on the distance between the visual target and the haptically-cued location. In an earlier study where vibrotactile cues were presented on the forearm, we found evidence for the existence of a spotlight effect[37 38]. In the study, the separation between cues and targets were systematically varied. It was found that response time decreased monotonically as a function of the cue-target separation. In a two-dimensional version of this earlier study using again the flicker paradigm and haptic cues presented on the back, the distance between the center of the cued quadrant and the visual changing element was controlled to be at one of six possible values: 0, 90, 180, 350, 450 and 550 pixels (see Fig. 7, assuming that VQ2 was haptically cued). Specifically, the center of the changing element was constrained to lie on the arcs marked in yellow in Fig. 7. It follows that a distance of 0, 90 or 180 corresponded to the valid haptic cuing condition in that the haptic cue and the visual target were in the same quadrant (VQ2 in the example shown in Fig. 7). A distance of 350, 450 or 550 corresponded to the invalid haptic cuing condition because the haptically cued quadrant (VQ2 in Fig. 7) was different from the quadrant where the visual change occurred (VQ1, VQ3 or VQ4 in Fig. 7).

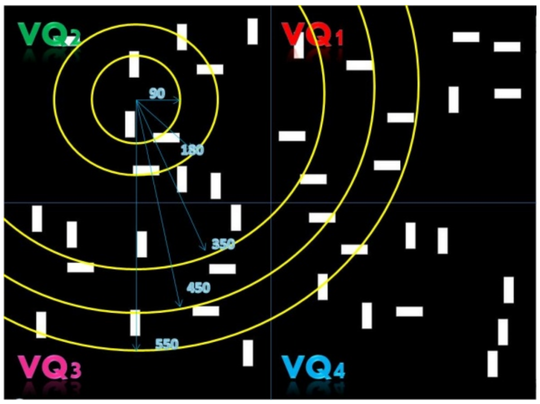


Fig. 7. One of the visual scenes used in the two-dimensional spotlight of attention experiment. During the experiment, the participants saw only the white rectangular elements against a black blackground on the computer monitor.

Results from twelve participants are shown in Fig. 8 in terms of mean response time as a function of the distance between the visual changing element and the center of the haptically-cued visual quadrant. It is evident that mean response time increased monotonically as a function of the separation between cue and target. The RTs for valid haptic cues follow a line (not shown) with a smaller intercept than that of the line followed by the response times for invalid haptic cues. This was expected due to the speeding-up of visual search following valid haptic cues and the slowing-down following invalid haptic cues. We conclude that there existed a spotlight effect for haptic cuing of visual spatial attention and the effect was more noticeable for trials with valid haptic cues than those with invalid haptic cues.

4. CONCLUDING REMARKS

In this article, we have summarized results from a series of studies on the effect of haptic cues on visual spatial attention and visual spotlight effect. Our results clearly demonstrate that valid haptic cues can significantly speed-up visual change detection and invalid haptic cues can significantly slow down visual change detection. This effect was found even though the haptic cues and the visual targets were not collocated spatially. However, the cuing effect did decrease as cue-target separation increased. Data from the eye-gaze study further supported the aforementioned findings. When cue validity was high, initial saccades predominantly went to the cued visual quadrant, thereby providing an explanation for why response time decreased (or increased) with valid (or invalid) haptic cues. When the cue validity was low, however, the participants were able to ignore the haptic cues as demonstrated by initial saccade count as well as response time data.

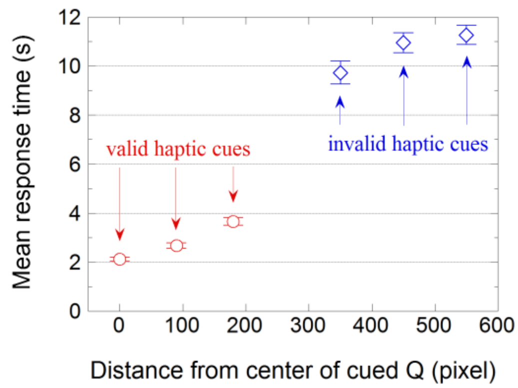


Fig. 8. Mean response time as a function of the distance between the visual changing element and the center of the haptically-cued quadrant.

Future work will proceed in two directions: 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. Anecdotal reports suggest that even though the participants were able to ignore haptic cues when the cue validity was low, they did so with considerable effort[36]. It would therefore, be interesting to investigate if the participants are less able to ignore haptic cues when they are engaged in a cognitively demanding secondary task. Second, we will perform further analyses of the large amount of eye-gaze data we have collected so far in order to discover and model the visual search strategies used by the participants under cuing conditions. Such efforts will lead to a better understanding of how visual spatial attention can be manipulated via crossmodal attention cuing. We imagine that in future galleries, chairs with strategically placed tactors can be an integral part of the exhibition by gently redirecting a viewer's spatial attention across visual art displays.

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