Validity of Haptic Cues and Its Effect on Priming Visual Spatial Attention

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Abstract

This study investigated cross-modal links in attention between haptics and vision. A visual change-detection task was used as a measure of visual attention. Haptic taps on the back was used to prompt the user the visual quadrant within which changes occurred. The location of the haptic cues was consistent with the quadrant of the visual changes on either 80% or 20% of the trials. Ten subjects were randomly assigned to the two test conditions. The subjects were informed of the validity of the haptic cues before the experiments. We measured the effectiveness of haptic cues in terms of the changes in detection times in the visual task. Our results indicated that for the subjects in the 80% validity group, detection times decreased significantly with valid haptic cues, and increased significantly with invalid haptic cues. For the subjects in the 20% validity group, however, the results were less consistent. Some of the subjects benefited from haptic cues, while others managed to ignore the (mostly invalid) haptic cues. These results are interpreted as evidence that the use of haptic cues to reorient a person's visual spatial attention is natural and intuitive when the validity of the haptic cues is high. It is 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.

1. Introduction

The advent of increasingly complex visual displays has imposed rigorous attentional requirements on interface operators. System designers are seeking to alleviate the associated cognitive load through the design of intuitive and ergonomic interfaces. The importance of this objective is well evidenced by the recent growth in multimodal interface research. In everyday life, humans naturally employ multimodal information channels (e.g., speech, gaze and gesture during a conversation). It is well established that multimodal communication can result in increased information transmission, whether multiple modalities convey different information or encode the same information redundantly [1]. However, whether and to what extent this benefit occurs depends on many factors such as spatial proximity of stimuli coming from different modalities (see, for example, [2]).

Our work has focused on the crossmodal attentional links between touch and vision. In an earlier study [3, 4], we found that tactile pulses simulating motion along the forearm facilitated the speed and accuracy with which subjects discriminated visual targets on the same forearm. We also reported that an approaching visual target's time to contact with the forearm influenced the subject's ability to perform tactile discrimination on the forearm. These results demonstrate dynamic links in the spatial mapping between vision and touch. In another study [5, 6], haptic cues presented at one of four quadrants on a user's back were used to redirect spatial attention in a visual change-detection task. On 50% of the trials, the location of the haptic cue coincided with the quadrant of the visual scene where change occurred. We found that detection time decreased significantly with valid haptic cues, and increased with invalid haptic cues. The results demonstrate that haptic attentional cues need not be presented at the same spatial location as visual events in order to be effective. More recently, we used the visual change-detection task to compare the effectiveness of haptic and auditory cues [7]. We found that haptic cues had a much larger effect on detection time than auditory cues.

In the majority of our previous work, we have used a cue validity rate of 50% (i.e., the location of the haptic cue coincided with the visual change on 50% of the trials). Thus, the haptic cues were at least partially informative for the task. In a critique of some of the pioneering research on crossmodal orienting, Spence and Driver [8] argue that the results from crossmodal studies using informative cues are difficult to interpret because it is not

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clear whether cueing effects are due to a strategic shift in attention within a single modality or crossmodal links in attentional orienting. For example, when an informative haptic cue proceeds a visual change, subjects could simply learn to reorient their visual attention to the specified location in a manner similar to what would occur for an visual arrow in the center of the screen pointing to a particular quadrant, or an auditory message "look to the upper left". In this case the subject is treating the cue as a symbolic instruction to reorient their visual attention and the modality of the cue is irrelevant. In order to be certain that cueing effects are due to hard-wired links between visual attention and haptic attention, it is necessary to use uninformative cues.

The present study investigates to what extent the crossmodal attentional link between proximal (haptic) and distal (visual) locations observed in our previous studies is due to a learned strategic shift in attention as opposed to a low-level sensory process. The validity of haptic cues was varied between low and high, and its effect on detection time was examined (i.e., we used both informative and uninformative haptic cues). If attentional reorientation is as robust at low validity rates as at high validity rates, one can conclude that the cueing effect is the result of a natural sensory integration process. Otherwise, high-level processes such as learning might also be involved. Our findings have implications for the design of multimodal user interfaces in, for example, automobiles where a haptic cueing system can be used to redirect a driver's visual attention.

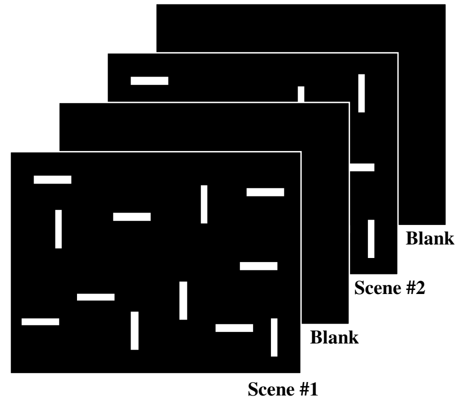

Figure 1. Illustration of the sequence of visual stimuli for the change-detection task displayed on a computer monitor.

Figure 2. The tactor array used for haptic cueing.

2. General Methods

2.1. Stimulus

The visual stimuli used in these experiments were based on the flicker paradigm used for the study of "change blindness" [9]. The visual scenes consisted of 12 rectangular elements of equal sizes (3 per quadrant) oriented horizontally or vertically (Fig. 1). The x-y positions of each element were randomly chosen within each quadrant with the constraint that the elements never overlapped. Two scenes, differing only in the orientation of one of the rectangular elements, were presented in alternating order with a blank scene inserted in between. The sequence repeated until the user responded by pressing a mouse button. The duration of the two patterned scenes was termed the "on time." The duration of the blank scene was termed the "off time" and was kept at 120 ms. The role of the blank scene was to eliminate motional cues from scene 1 to scene 2.

The experimental apparatus for haptic cueing consisted of a 3-by-3 vibrotactile display developed at the Purdue Haptic Interface Research Laboratory. The tactor array was draped over the back of an office chair (Fig. 2). For the experiments in the current study, only the four corner tactors (i.e., tactors No. 1, 3, 7, and 9) were used. Each tactor was independently driven by a 60-ms long sinusoidal pulse. The frequency of the pulse corresponded to the resonant frequency of each of the four tactors, and was between 290 and 306 Hz. The intensity of the stimulus was between 26.1 and 27.9 dB SL under unloaded condition (i.e., without the subject pressing their back against the tactors).

2.2. Subjects

Ten college students, 5 females and 5 males, participated in the experiments as paid subjects. The average age of the subjects was 22 years. All subjects had normal or corrected vision. They reported no known abnormalities with tactile perception on their back.

2.3. Procedures

Before the experiments began, the subjects were informed of the nature of the task. Specifically, they were told to locate a rectangular element on the computer screen that was changing its orientation in an orthogonal manner between the alternating scenes. Their task was to *locate* and *identify* this element as quickly as possible.

To ensure that the subjects could clearly feel the stimuli presented by the vibrotactile array and correctly correlate these stimuli with a particular quadrant on the computer screen, a tactor-location identification experiment was performed once for each subject at the beginning of the first session. The subjects' task was to click a large box located in each of the four corners of the monitor. For example, if the vibrotactile stimulus occurred in the vicinity of the right shoulder, the correct response would be to click the box in the upper right corner of the monitor. Each subject had to complete one perfect run of 60 trials before proceeding to the main experiments. All subjects were able to achieve 100% correct tactor-location identification within the first run.

The independent variables employed were the state of the tactors ("on" or "off"), on time (80 and 480 ms), and the validity rate of the haptic cues (20% and 80%). Five subjects were randomly assigned to the 20% validity condition, and the other five to the 80% validity condition. The subjects were told the validity rate at which their experiments were being conducted. They were told to use or ignore the haptic cues as they wished. Each subject completed 22 runs in random order (Table 1). Every time a subject sat down in the haptic chair, one 60-trial run with an on-time of 80 ms and 50% validity rate was conducted as a "warm-up."

On each trial, the subject was tapped once on the back (when the tactor state was "on") 50 ms before the visual sequence began. The subject clicked the left mouse button as soon as the changing element was found, without first moving the cursor over the changing element. The screen then froze and all rectangular elements changed from white to pink in color. The subject was required to move the cursor over the perceived changing element and click the left mouse button. The location of the second mouse click was used to verify that the subject found the correct changing element.

Throughout the experiments, subjects 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 any audible noise from the tactor array and the environment. Each subject typically completed all the runs within 3 sessions.

2.4. Data analysis

The dependent variables were the mean and standard error of detection times. Data from the tactor "off" condition served as a baseline measure for detection time. Data from the tactor "on" condition were separated into two subgroups: those with valid haptic cues and those with invalid haptic cues. We report only the change in detection time (i.e., detection time with valid or invalid cues – detection time with tactor "off"). All error trials, where subjects selected the wrong element, were discarded.

Table 1. Experimental condition for each subject.

Tactor state	On-time (ms)	No. of 60-trial runs
On	80	8
On	480	8
Off	80	3
Off	480	3

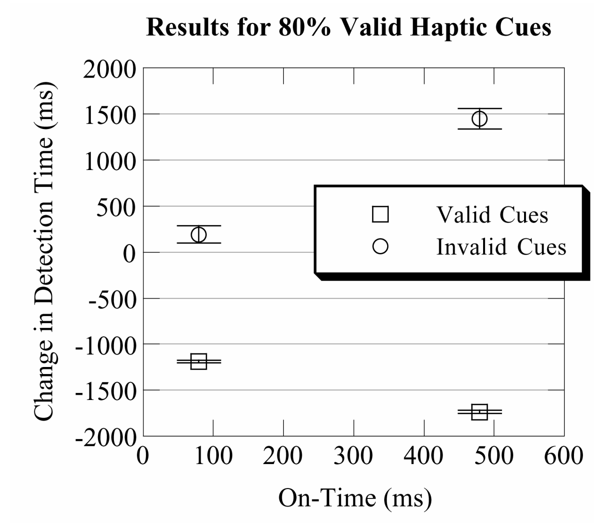

Figure 3. Change in detection time for data pooled over subjects in the 80% validity group. Error bars indicate ±1 standard errors.

3. Results

Results for subjects receiving valid haptic cues 80% of the time show that detection time decreased significantly with valid haptic cues, and increased significantly with invalid haptic cues. Data pooled over all five subjects are shown in Fig. 3. Overall, at 80-ms on-time, detection time for the visual change-detection task decreased by 1191 ms (47.0%) with valid haptic cues, and increased by 190 ms (7.5%) with invalid haptic cues. At 480-ms on-time, detection time decreased by 1737 ms (45.9%) with valid haptic cues, and increased by 1448 ms (38.3%) with invalid haptic cues. A three-way ANOVA indicated that changes in detection time were significantly dependent on the three main factors of subject [$F(4, 4760) = 16.08$, $p<.0001$], on-time [$F(1, 4760) = 626.33$, $p<.0001$] and invalid/valid cue condition [$F(1, 4760) =$

519.57, p<.0001]. The two-way and three-way interactions were all found to be significant. The standard errors for detection times were significantly lower with valid haptic cues (16.0 and 17.5 ms for 80-ms and 480-ms on time, respectively) than with invalid haptic cues (92.4 and 110.9 ms, respectively) or with no haptic cues (63.6 and 75.7 ms, respectively). These results indicate that the subjects in the 80% validity group were able to detect the changing element faster with valid haptic cues. They were slowed down by invalid haptic cues. What is more, the variability in their detection time was significantly reduced by valid haptic cues, despite inter-subject differences.

Results for subjects receiving valid haptic cues 20% of the time fall into three distinct outcomes: positive, negative or no cueing effect. The mean changes in detection time for S1-S5 are listed in Table 2. The asterisks indicate a statistically significant decrease (for negative entries) or increase (for positive entries) in detection time. Subjects S2 and S3 exhibited "positive" cueing effect in the sense that their detection times decreased with valid haptic cueing and increased with invalid cueing. Subject S4, on the other hand, exhibited "negative" cueing effect in the sense that his detection times increased with valid haptic cueing. This subject revealed that he deliberately looked away from the quadrant of the haptic cues knowing that they were invalid most of the time. This explains why detection time increased with valid haptic cues. It is also consistent with the result that invalid haptic cueing had no significant effect on detection time. Subject S5 exhibited "no cueing effect" in the sense that none of the changes in detection time was significant. This subject felt the taps on his back but, unlike S4 who used the haptic cueing location to look elsewhere, chose (and was able) to completely ignore the haptic cues. Subject S1's results were mixed: valid haptic cues at 80-ms on time had no effect on her detection time, but invalid cues did. At an on time of 480 ms, her detection time decreased with both valid and invalid haptic cues.

A comparison of the 80% and 20% validity groups was made by comparing the changes in detection times (Fig. 4). For the 20% group, only the results from the two subjects showing "positive" cueing effects (S2 and S3) were included in the analysis. Results from Fig. 3 are plotted here again for ease of comparison. With valid haptic cues, the reduction in detection time was significantly greater for the 80% group than for the 20% group at an on time of 80 ms, but not at 480 ms. With invalid haptic cues, the increase in detection time was greater for the 20% group than for the 80% group at an on time of 80 ms, but the reverse was true at 480 ms. In fact, for the 80% group and at an on time of 480 ms, the increase in detection time with invalid haptic cues was almost of the same magnitude as the reduction in detection time with valid cues. In general, there is a trend that haptic cueing is more effective for the 80% group than for the 20% group.

Table 2. Average change in detection time with valid and invalid haptic cues for the 20% validity group. Unit for detection times is ms. Asterisks indicate statistically significant results (Student's t-test; p<0.025).

Subject	On-time=80 ms		On-time=480 ms	
	Valid	Invalid	Valid	Invalid
S1	209.4	200.9*	–575.3*	–207.6*
S2	–757.8*	376.8*	–1455.7*	132.9*
S3	–891.7*	502.2*	–1591.8*	476.2*
S4	579.9*	98.5	876.4*	26.1
S5	–58.8	28.4	282.2	–19.8

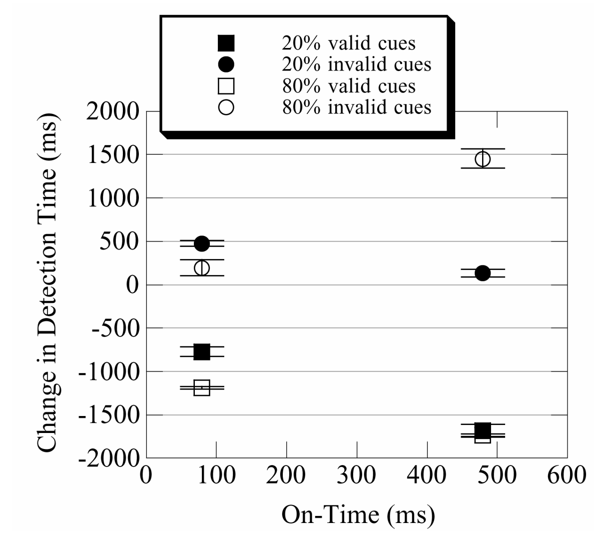

Figure 4. Comparison of results from the 20% validity group (S2, S3) and the 80% validity group (S6-S10). Error bars indicate ±1 standard errors.

4. Conclusions

In this study, we set out to investigate whether the visuotactile spatial cueing effect observed in our previous studies was due to involuntary or voluntary reorienting of visual attention following haptic stimulation. We reasoned that if subjects shifted their visual attention involuntarily upon a tap on their back, then their ability to do so would presumably be robust against any prior knowledge about the validity of haptic cues. If, on the other hand, subjects voluntarily associated the location of a haptic tap with that of a visual scene, then their ability to utilize the haptic spatial cues might be affected by the validity of such cues. Two groups of subjects were tested with a visual change-detection task with haptic cues that were valid on either 80% or 20% of the trials. We found that all subjects in the 80% group benefited (in terms of reduced detection times) from valid haptic cues, and suffered (in terms of increased detection times) from invalid haptic cues. Despite the intersubject differences in the baseline (i.e., no haptic cues) detection times, the standard error of detection times with valid haptic cues were quite small (about 1% of the mean). Subjects in the 20% group, however, exhibited positive, negative, or no haptic cueing effects. Their data were consistent with the strategies employed to utilize the (mostly inaccurate) haptic cues. Therefore, we conclude that the use of haptic cues to reorient a person's visual spatial attention is natural and intuitive, but not entirely involuntary.

The present findings differ from previous work by [10] that demonstrated consistent tactile-visual cueing effects across subjects for spatially uninformative cues (analogous to our 20% validity condition). This discrepancy is most likely due to differences in methodology. Subjects in the [10] experiment were required to detect single flashes of light rather than perform a complex change detection task, and in their study the cue and target were in the same spatial location (near the hand) on all valid trials.

In an earlier study [5], we used 50% valid haptic cues in the same visual change-detection task. We found that on average, reaction time decreased by 40.6% with valid haptic cues, and increased by 18.9% with invalid haptic cues. These results are similar to those obtained from the present study with the 80% validity group. Future studies will investigate whether subjects can be instructed to deliberately ignore haptic cues at high validity rate, and whether differential results can be obtained with the same validity rate by manipulating the *a priori* information provided to the subjects.

Our results have implications for designers of large visual displays who need an effective mechanism to direct a user's visual attention to a particular region of the display. For example, a haptic chair with embedded tactor display can be used to prompt an air traffic controller to look at an air space that needs attention. In an automobile, a haptic display embedded in the driver's seat can alert the driver to look, say, to the right of the vehicle for a fast approaching vehicle. Although we currently do not yet have any data for the achievable resolution of a haptic cueing system, our results do suggest that a tactor array as coarse as 2-by-2 can cut down the time required to detect a visual change by almost a half if the user knows that the haptic cues are valid most of the time.

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