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Using spatial vibrotactile cues to direct visual attention in driving scenes

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Abstract

We report two experiments designed to investigate the potential use of vibrotactile warning signals to present spatial information to car drivers. Participants performed an attention-demanding rapid serial visual presentation (RSVP) monitoring task. Meanwhile, whenever they felt a vibrotactile stimulus presented on either their front or back, they had to check the front and the rearview mirror for the rapid approach of a car, and brake or accelerate accordingly. We investigated whether speeded responses to potential emergency driving situations could be facilitated by the presentation of spatially-predictive (80% valid; Experiment 1) or spatially-nonpredictive (50% valid; Experiment 2) vibrotactile cues. Participants responded significantly more rapidly following both spatially-predictive and spatially-nonpredictive vibrotactile cues from the same rather than the opposite direction as the critical driving events. These results highlight the potential utility of vibrotactile warning signals in automobile interface design for directing a driver's visual attention to time-critical events or information.

Keywords: Spatial attention; Vibrotactile; Driving; Warning signal; Interface design; Visual

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1. Introduction

There has been a rapid growth of interest in the potential use of tactile warning signals and information displays in applied interface environments in recent years (e.g., Gilliland & Schlegel, 1994; Rupert, 2000; Sklar & Sarter, 1999; Triggs, Lewison, & Sanneman, 1974; Van Erp, Jansen, Dobbins, & van Veen, 2004; Zlotnik, 1988). Part of the reason for this growth has been the increasing visual overload reported by the users of many modern interfaces (e.g., Sorkin, 1987; Zlotnik, 1988). Researchers have identified a range of different uses for tactile displays: For example, to provide information, as in the case of tactile-visual sensory substitution systems (Bach-y-Rita, 2004; White, 1970); to provide directional, or way-finding, information (Eves & Novak, 1998; Kuc, 1989; Tan, Gray, Young, & Traylor, 2003; Van Erp et al., 2004; Van Erp & van Veen, 2001; Van Veen, Spapé, & van Erp, 2004); to facilitate orientation awareness in microgravity or deep-sea diving environments (Bhargava et al., 2005; Rochlis & Newman, 2000; Rupert, 2000; Traylor & Tan, 2002; Van Erp & van Veen, 2003); to stimulate tactile receptors in haptic virtual reality displays (Wood, 1998); and to support situational awareness, by capturing a person's attention (Gilliland & Schlegel, 1994; Sklar & Sarter, 1999; Tan et al., 2003).

In the present study, we investigated the possibility of using spatially-distributed vibrotactile warning signals to direct a person's attention to the front or rear in a simulated car driving task (see also Enriquez & MacLean, 2004; Fenton, 1966; Van Erp & van Veen, 2001). The motivation for our study comes from recent laboratory-based research that has revealed the existence of robust crossmodal links in spatial attention between vision and touch (see Spence & Driver, 2004, for a review). For instance, Butter, Buchtel, and Santucci (1989) demonstrated that the presentation of spatially-predictive vibrotactile cues to either the left or right hand will lead to a shift of visual attention to the cued side (or hand). Participants detected visual targets on the cued side 14 ms faster than when the targets appeared on the uncued side. However, given the informative nature of the cues used in Butter et al.'s study (the cue predicted the side of the visual target on 80% of trials), it is unclear whether these results reflect endogenous orienting, exogenous orienting, or some unknown combination of the two effects (see Spence, Pavani, & Driver, 2000).

Subsequent studies have typically examined the nature of any crossmodal links in spatial attention between vision and touch separately for the case of endogenous and exogenous orienting. Researchers have examined *exogenous*, or stimulus-driven, orienting by presenting vibrotactile (or visual) cues that are spatially-nonpredictive of the location of the visual (or vibrotactile) targets (Kennett, Eimer, Spence, & Driver, 2001; Kennett, Spence, & Driver, 2002; Spence, Nicholls, Gillespie, & Driver, 1998; Tassinari & Campara, 1996). These studies have shown that the presentation of a vibrotactile cue to one hand or the other leads to a short-lasting shift of attention to the cued hand, facilitating the processing of visual (as well as tactile and auditory) stimuli subsequently presented from the cued direction (see Spence, McDonald, & Driver, 2004, for a review).

Meanwhile, researchers interested in the nature of any *endogenous* links in spatial attention have typically used either centrally-presented spatially-predictive symbolic cues (such as an arrow pointing to the left or right) to direct a participant's attention to one side or the other (Posner, Nissen, & Ogden, 1978; Spence et al., 2000), or else a blocked-cuing design in which a certain location is made more likely for each target modality over a whole block of trials (Spence et al., 2000; Spence, Shore, & Klein, 2001). These studies have shown that people can also voluntarily direct their spatial attention to a particular location, and that maintaining attention on one side of space in one modality typically results in a shift of attention in the other modality in the same direction (see Driver & Spence, 2004, for a review).

Although these studies all support the existence of robust crossmodal links (both exogenous and endogenous) in spatial attention between touch and vision, the magnitude of these effects has typically been quite small (e.g., from a maximum cuing effect of 10 ms in Tassinari & Campara's, 1996, study to 48 ms in Spence et al.'s, 2000, studies). Thus, while such results inform theoretical accounts of the nature of any crossmodal links in spatial attention, it is unclear whether they are large enough to have any consequences in more applied settings, such as, for example, in the case of multisensory warning signals in driving situations.

The implementation of vibrotactile in-car interfaces has already been seen in some specialized commercial vehicles, such as lane departure warning systems that can monitor the lateral distance of a vehicle to traffic lane markings (e.g., McGehee & Raby, 2003). While the majority of these in-car systems present tactile signals to drivers via the steering wheel (e.g., Enriquez, Afonin, Yager, & Maclean, 2001; Steele & Gillespie, 2001) or the driver's seat (e.g., Van Erp & van Veen, 2004), we can also foresee the possibility of presenting information, such as the distance to the vehicle in front, via tactile stimulators mounted in the seat belt.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Sixteen participants (7 males and 9 females; mean age of 23 years, range 19–35) participated in this experiment. All participants had a valid UK driving licence, and had, on average, been driving for 4.8 years (range 0.5–12). Thirteen of the participants were right-handed, two were left-handed, and one was ambidextrous by self-report. The participants reported normal, or corrected-to-normal, vision. The experiment lasted for 60 min.

2.1.2. Apparatus and materials

The participants were seated in the center of a 220 × 142 cm experimental booth and were instructed to hold a Logitech® MOMO® Racing Force Feedback Wheel (Logitech Inc., CA, USA) mounted on a desk situated directly in front of them. The footpedals linked to the steering wheel were placed in a comfortable position on the floor in front of the participants. A mirror positioned directly in front of the participants (at a distance of 50 cm) was used to display the RSVP stimuli (see Fig. 1). A monitor showing an image of the windscreen was positioned 70 cm from the participants (visible over the top of the mirror). A car rearview mirror (6 × 15 cm; RV-32, Summit Automotive, England) was attached to the upper-left corner of the monitor. The participants could see the rear video shown on a second monitor placed 120 cm away via the reflection in the rearview mirror. The tactors (2.54 × 1.85 × 1.07 cm, VBW32, Audiological Engineering Corp., Somerville, MA, USA) used to present the vibrotactile signals were attached to a Velcro belt fastened around the participant's waist. One tactor was positioned on the front in the middle of the participant's stomach while the other was positioned in the middle of the participant's back. The belt and the tactors were fastened directly over the top of the participant's clothing. The tactors

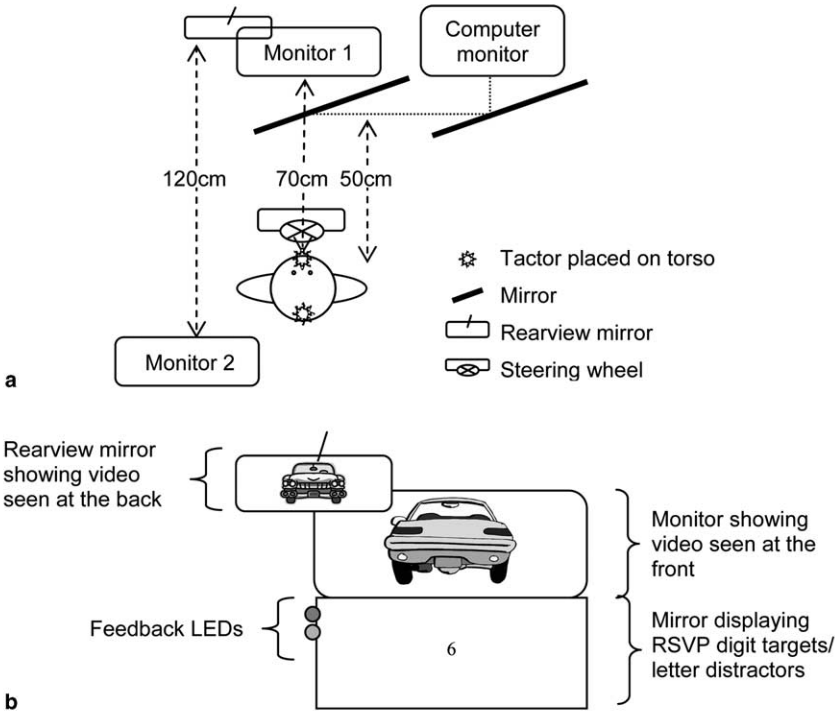

Fig. 1. (a) Schematic bird's-eye view and (b) participant's-eye view of the experimental set-up used in Experiments 1 and 2.

were driven by a 290 Hz sinusoidal signal at an intensity sufficient to deliver clearly perceptible vibrotactile stimuli, even through several layers of clothing. The noise level of the tactors was about 42 dB(A) when measured from the participants' ear level with the tactor belt placed around their waist. White noise was delivered through cordless headphones (SBC-HC8355, Philips, USA) at about 60 dB(A) to mask the noise caused by the operation of the tactors.

The RSVP stimuli consisted of 17 distractor letters and six target digits (cf. Soto-Faraco & Spence, 2002). A computer monitor, occluded from the direct view of the participants, was used to present the RSVP stimuli. The monitor display was reflected by means of two mirrors so that participants could see the letters and digits on the mirror directly ahead of them (see Fig. 1). The RSVP characters were 8.3 × 8.5 mm in size in the mirror.

The video of the windscreen was filmed from behind the driver's seat, and showed a car in front being followed at a roughly constant distance at a speed of approximately 50 km/h. The rear video was also filmed from behind the driver's seat, and showed the same car following at approximately the same distance and speed. The critical clips in the video included the sudden fast approach (by the car in which the video camera was placed) toward the car in front at approximately 100 km/h, or the sudden rapid approach from the car behind. The noncritical clips included the car in front moving away at the normal speed or the car behind retreating (see Fig. 2). Two critical and two noncritical driving clips were created. A red light-emitting diode

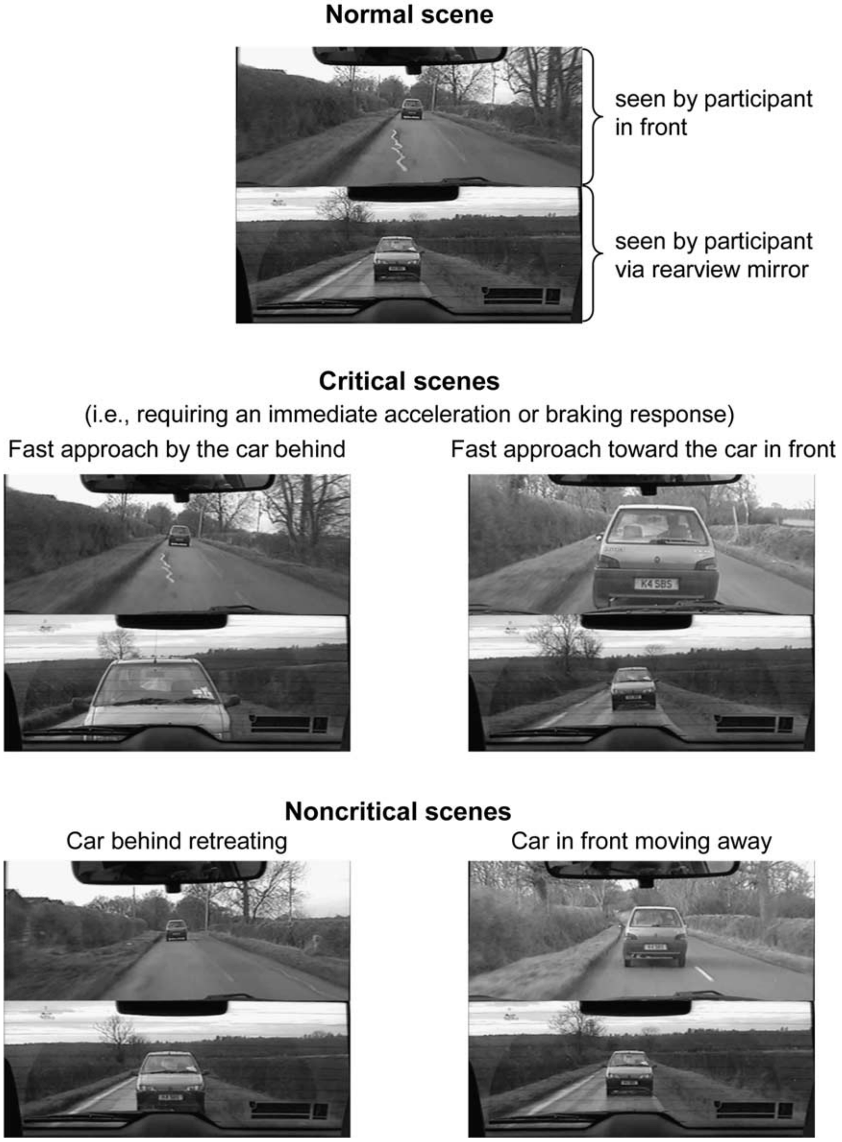

Fig. 2. Sample video stills taken from the video clips used in Experiments 1 and 2. The upper half of each still shows the view of the windscreen seen directly in front of the participants, while the lower half shows the rear view seen by the participants in the rearview mirror. Note that in the experiment itself, the participants would only see the upper half of the video from the front, and the lower half of the video from behind via the rearview mirror.

(LED) was placed on the mirror directly in front of the participants to provide feedback whenever they made an incorrect response in the driving task. An amber LED placed below the red LED was illuminated whenever participants failed to keep the accelerator depressed appropriately during the experiment.

2.1.3. Design

The experimental session consisted of eight blocks lasting for 6 min each. The RSVP stimuli consisted of a continuous stream of distractor letters with target digits periodically embedded within it. Sixty-six targets were presented in each block in the RSVP task with each of the six target digits being presented eleven times. Each item in the RSVP stream was presented for 40 ms, with a blank gap of 80 ms before the onset of the next stimulus. The presentation of the stimuli was synchronized to the next refresh of the monitor (screen refresh rate = 75 Hz). The temporal gap between successive target digits was 2040–6360 ms.

For the driving task, 24 randomized scenarios were presented in each block. Each scenario consisted of a 15000 ms video clip and a vibrotactile cue lasting for 1060 ms. Each of the four possible critical driving scenarios was presented five times, with the four noncritical driving scenarios each presented once. The onset of the vibrotactile cue coincided with the start of the critical driving event (defined as the initiation of the reduction of the inter-car distance that lasted for 1800 ms—at which time the two cars would have collided). The temporal gap between successive vibrotactile cues was 8500–21,500 ms (see Fig. 3). Each scenario transited to the next one with fade-out and fade-in effects, so the transitions between clips were not noticeable. In total, there were 528 RSVP targets and 192 driving trials. 83.3% of all the driving trials were critical trials that required either a braking or acceleration response, while the remaining 16.7% required no response. The vibrotactile cues correctly predicted the direction of the visual driving event on 80% of trials. On the remaining 20% of trials, the visual driving event occurred in the direction opposite to the cue.

The participants were given two practice blocks in which to familiarize themselves with the experiment. In the first block, the participants only had to perform the RSVP task. Initially, each visual stimulus was presented for 98 ms with a blank interval of 109 ms between successive stimuli.

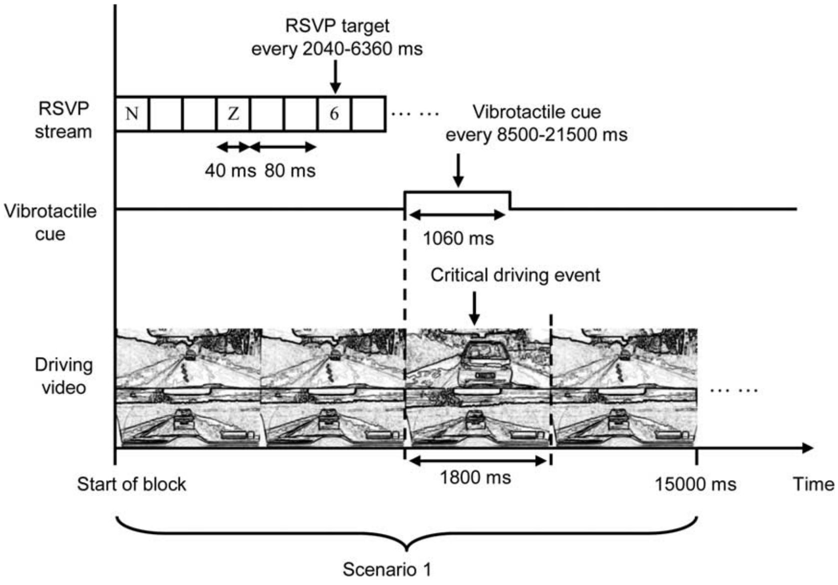

Fig. 3. A schematic timeline showing the temporal sequence of events in Experiments 1 and 2.

The rate of stimulus presentation increased gradually during the block, with the duration of visual stimulus presentation being reduced by 2 ms and the blank being reduced by 1 ms, until the experimental rate of stimulus presentation was attained (though note that the actual presentation duration was limited by the refresh rate of the monitor). In the second block, the participants performed the RSVP as well as the driving task. The stimulus timings used in this block were the same as those used in the subsequent experimental blocks.

2.1.4. Procedure

The participants responded to target digits in the RSVP task by pressing the right lever-mounted paddle situated directly behind the steering wheel. For the driving task, the participants were instructed to model a real driving situation in which a fixed speed was maintained by normally keeping the accelerator partially depressed. The amber LED (see Fig. 1(b)) was illuminated whenever the accelerator was depressed inappropriately. When the participants felt a vibrotactile stimulus presented from either the back or the front, they were instructed to check whether a car was approaching rapidly from behind, or if they were rapidly approaching the car in front. The corresponding appropriate responses to these two kinds of critical driving event were to accelerate by pressing the accelerator all the way down to the floor with their right foot, or to brake by pressing the brake pedal with their left foot, respectively. (This design was chosen to avoid the possible noise in the data that would have been introduced by moving the right foot from the accelerator to depress the brake pedal, though see Van Winsum & Brouwer, 1997; Van Winsum & Heino, 1996.) The red LED was illuminated for 1000 ms following an incorrect response. For noncritical driving events, where the video showed a gradually increasing inter-car distance, the participants simply had to carry on as before without making any specific response in the driving task.

2.2. Results

On average, 5.5% of the trials were removed across participants due to no response being made within 1800 ms of the onset of the critical visual driving event.[1] Trials with an incorrect response were discarded from the reaction time (RT) analysis. An analysis of variance (ANOVA) performed on the RT data from the driving task, with the two within-participants factors of Vibrotactile cue location (front vs. back) and Visual stimulus location (front vs. back), revealed no main effect of Vibrotactile cue location or Visual stimulus location, both $F(1,15) < 1$, n.s. There was, however, a significant interaction between these two factors, $F(1,15) = 16.54$, $p = .001$, with faster responses to critical visual driving events being reported when validly spatially-cued by the vibrotactile stimuli than when invalidly spatially-cued (see Fig. 4). Subsequent paired comparison t-tests revealed that participants responded significantly more rapidly to validly-cued than to invalidly-cued targets, both when critical visual driving events occurred at the front, $t(15) = 3.36$, $p = .004$, and when they occurred at the rear, $t(15) = 3.26$, $p = .005$.

Analysis of the error data (where participants made an incorrect response on the driving task) again revealed no main effect of Vibrotactile cue location or Visual stimulus location, both $F(1,15) < 1$, n.s. There was, however, a borderline significant interaction between these two

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[1] These data were not included in the analysis because no clear defining line could be drawn as to whether a missed response was due to "failed to look", "saw but failed to respond", or "saw but responded too slowly".

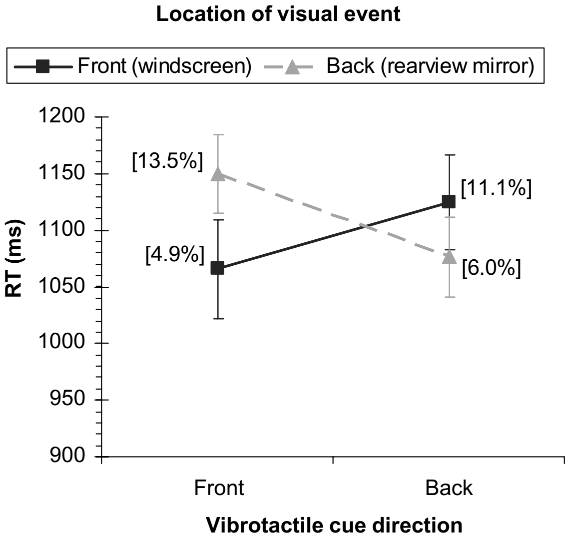

Fig. 4. Interaction between the location of the spatially-predictive vibrotactile cue and the location of the critical visual events in the driving task in Experiment 1. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate standard errors of the RTs.

factors, $F(1,15) = 4.31$, $p = .06$, with participants making fewer errors in the validly-cued than invalidly-cued trials. This effect was borderline significant when the critical visual driving events were presented from the front, $t(15) = 2.14$, $p = .05$, but failed to reach significance when they were presented from the rear, $t(15) = 1.54$, $p = .14$. Given this trend in the error data, we were able to rule out a speed-accuracy trade-off account of the spatial cuing effects in the RT data (Müller & Findlay, 1987).

Performance in the concurrent RSVP task was also measured with responses occurring 1500 ms after the presentation of a target digit considered to be invalid. The mean percentage of correct detection responses was 70.1% (SE = 3.3%), with a mean RT of 602 ms (SE = 13 ms) and a false alarm rate of 5.5% (SE = 1.7%). Most of the errors (30.1%) occurred within 2000 ms of the onset of the vibrotactile stimuli, with the remainder (69.9%) distributed fairly evenly over the following 10,500 ms prior to the onset of the next target.

2.3. Discussion

The results of Experiment 1 show that participants responded both more rapidly, and somewhat more accurately, to critical visual driving events preceded by a valid vibrotactile cue from the same direction than when preceded by an invalid cue from the opposite direction. Our results suggest that the presentation of the spatially-predictive vibrotactile cues led to a rapid crossmodal shift of visual attention in the direction indicated by the cue. Our results go beyond previous crossmodal cuing studies, which typically have only considered left versus right cuing (normally on the hands; e.g., Butter et al., 1989; Kennett et al., 2001, 2002; Spence et al., 1998, 2000, 2001), in showing that attention can also be cued to the front versus rear. Our results are noteworthy for two reasons: First, they show that vibrotactile stimuli presented on the body surface (i.e., on the torso in peripersonal space) can be used to direct visual attention to distal events occurring several metres away in extrapersonal space. What's more, the link between vibrotactile cues presented on the back and critical visual driving events occurring from the rear is a not straightforward one, given that the rear car could only be seen via the rearview mirror (that was visually inspected from the *front*; cf. Gregory, 1998; Maravita, Spence, Sergent, & Driver, 2002).

It may be that the link between what is seen in the rearview mirror and what goes on behind the car in which one is driving is so well-learnt that the mapping has become automatic. Alternatively, however, participants might have used the informational content of the vibrotactile cues to direct their attention endogenously (rather than exogenously), and hence it was the informational content of the cues that was crucial, rather than the specific position from which they happened to have been presented. Given the spatially-predictive nature of the vibrotactile cues in Experiment 1, it is unclear whether the attentional cuing effects reported in our first study reflect *endogenous* orienting, *exogenous* orienting, or a combination of these two effects (Spence et al., 2000).

3. Experiment 2

Experiment 2 was designed to investigate whether similar spatial cuing effects would still be observed if the vibrotactile cues were made nonpredictive with regard to the likely location of any visual driving events. The vibrotactile cues were now just as likely to be presented from the opposite direction to any critical visual driving events as from the same direction. If the magnitude of any spatial cuing effects reported in our second experiment remained unchanged (despite the fact that the cue was no longer spatially-predictive), then this would suggest that it was the exogenous attention-capturing attributes of the vibrotactile cues that were responsible for the cuing effects. By contrast, if the magnitude of any spatial cuing effect was substantially reduced, or even eliminated, then this would suggest that it was the informational content of the cues (and the consequent endogenous orienting of spatial attention) that was responsible for the cuing effects reported instead.

3.1. Methods

Sixteen new participants (8 males and 8 females; mean age of 24 years, range 18–30) took part in this experiment. One of the participants was replaced because his mean RT in the driving task was more than 2.5 SD lower than the average mean RT for all the participants. All of the participants had a valid UK driving licence, and had, on average, been driving for 5.7 years (range 0.5–11). The participants reported normal, or corrected-to-normal, vision. Thirteen of the participants were right-handed, two were left-handed, and one was ambidextrous by self-report. The apparatus, materials, design, and procedure were exactly the same as in Experiment 1, with the sole exception that the vibrotactile cues were now nonpredictive with regard to the direction of the critical driving events, being presented from the same direction as the critical visual driving events on 50% of trials and from the opposite direction on the remainder of the trials.

3.2. Results

On average, 5.8% of the trials were removed across participants due to no response being made within 1800 ms of the onset of the critical driving target event. A two-way within-participants ANOVA was performed on the RT data from the driving task with the factors of Vibrotactile cue location (2) and Visual stimulus location (2). This analysis revealed no main effect of Vibrotactile cue location, $F(1, 15) < 1$, n.s. The main effect of Visual stimulus location was significant, $F(1, 15) = 10.64$, $p = .005$, with participants responding more rapidly to visual driving events presented from the front ($M = 1014$ ms) than from the rear ($M = 1116$ ms). The interaction between Vibrotactile cue location and Visual stimulus location was significant, $F(1, 15) = 16.7$, $p = .001$. Participants responded more rapidly to critical visual driving events when they were preceded by a vibrotactile cue from the same direction than when they were preceded by a cue from the opposite direction (see Fig. 5). Subsequent paired comparison t-tests revealed significant spatial cuing effects for visual targets presented both from the front, $t(15) = 4.34$, $p = .0006$, and from the rear, $t(15) = 2.43$, $p = .03$.

A similar analysis of the error data showed no main effect of either Vibrotactile cue location or Visual stimulus location, both $F(1, 15) < 1$, n.s. The interaction between these two factors was significant, $F(1, 15) = 6.05$, $p = .03$ (see Fig. 5). Paired comparison t-tests showed that participants made fewer errors when responding to visual events presented from the front when preceded by a valid vibrotactile cue than when preceded by an invalid cue, $t(15) = 2.13$, $p = .05$. The participants also made fewer mistakes on validly-cued trials than on invalidly-cued trials for visual events presented from the rear, $t(15) = 2.14$, $p = .05$, once again ruling out a speed-accuracy trade-off account of the spatial cuing effects in the RT data.

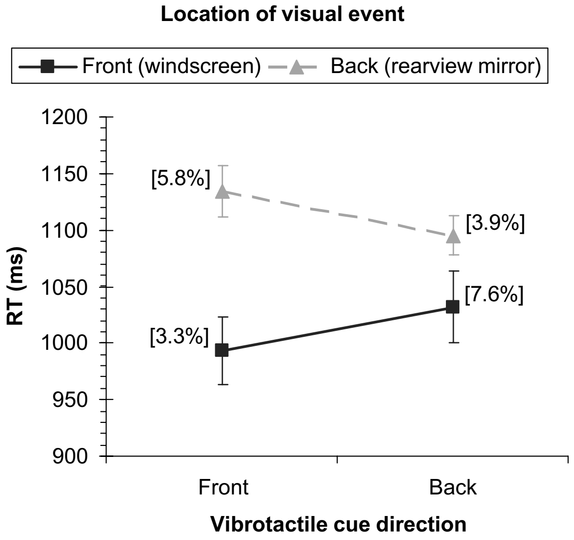

Fig. 5. Interaction between the location of the spatially-nonpredictive vibrotactile cue and the location of the critical visual events in the driving task in Experiment 2. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate standard errors of the RTs.

The mean percentage of correct detection responses in the concurrent RSVP task was 75.4% (SE = 2.7%), with a mean RT of 568 ms (SE = 13 ms) and a false alarm rate of 5.5% (SE = 0.9%). Most of the errors (33.4%) once again occurred within 2000 ms of the onset of the vibrotactile stimuli, with the remainder (66.6%) distributed fairly evenly over the following 10500 ms prior to the next target. These results, which are comparable to those obtained in Experiment 1, are consistent with the view that the presentation of the vibrotactile cue may lead to a temporary shift of visual attention away from the RSVP stream, resulting in a sort of crossmodal attentional blink (Soto-Faraco et al., 2002).

3.3. Discussion

The participants in Experiment 2 responded more rapidly and accurately to critical visual driving events preceded by vibrotactile cues from the same spatial direction rather than from the opposite direction. Given that these cuing effects were elicited by cues that were spatially-nonpredictive with regard to the location of the critical visual driving events, this suggests that the presentation of the vibrotactile cues in our study resulted in an exogenous shift of visual attention in the cued direction. Interestingly, although the magnitude of the crossmodal cuing effects in Experiment 2 (mean cuing effect of 41 ms, 3.1%) were numerically somewhat smaller than those reported in Experiment 1 (mean cuing effect of 66 ms, 6.8%), between-experiments analyses revealed that the advantage of spatially-predictive over spatially-nonpredictive cues failed to reach significance in either the RT or error data, $t(30) = 1.32$, $p = .20$, and $t(30) = 1.06$, $p = .30$, respectively. There are several possible explanations for this: First, it may be that the benefits of voluntarily orienting spatial attention to the direction of the predictive cues in Experiment 1 were of a similar magnitude to those resulting from the exogenous orienting of attention to the cued direction in Experiment 2. Alternatively, however, it is also possible that the participants in Experiment 1 might simply have ignored the instruction to attend to the direction of the vibrotactile cues, perhaps because the cues were not 100% predictive of the location of any critical driving events (in fact, the vibrotactile cues were followed by critical visual driving events in the same direction on only 67% of trials in Experiment 1), and/or because of the highly attention-demanding nature of the RSVP and driving tasks (cf. Bliss & Acton, 2003). Finally, however, it may also be the case that participants in Experiment 2 endogenously directed their attention in the direction of the cue, despite the fact that the vibrotactile cue was spatially-nonpredictive, because of the ‘intimate’ nature of the vibrotactile stimuli being applied to their torso.

It should be noted that the facilitation of responses reported in the present study was measured at the behavioural level. It will be important for future research to investigate whether the performance enhancement reflects a consequence of response priming (i.e., a priming of the appropriate responses by the cues regardless of their spatial location relative to the critical driving events), a perceptual enhancement attributable to the spatial aspect of the cues coinciding with that of the targets, or some unknown combination of the two effects (see Proctor et al., in press). In applied terms, both aspects of cuing are important for the design of the most effective multisensory interfaces. Nevertheless, an understanding of the relative contributions of each of the two effects on performance should help to improve the efficacy of interface development in the future (Ho et al., submitted).

Finally, in order to assert the effectiveness of the vibrotactile cuing of visual attention per se, we also conducted a control experiment ($N = 12$ participants) involving a no-cue condition in which participants had to monitor and respond to targets in both the RSVP and driving tasks without any vibrotactile cue being presented (the design was otherwise identical to that reported in Experiments 1 and 2). This no-cue experiment served to establish a baseline level of performance attained by participants taking part in the two main experiments (i.e., in the absence of any warning signals). Note though that there is a question as to whether the task demands in this situation would make a strict comparison between this control experiment and the other two experiments somewhat problematic. For instance, participants in our no-cue control study had to allocate their attention to both tasks, while participants in Experiments 1 and 2 could focus primarily on the RSVP task, and switch their attention to the driving task only when cued to do so by the vibrotactile stimuli. In other words, participants in Experiments 1 and 2 were passively anticipating a vibrotactile event, while participants in the no-cue experiment were actively seeking a visual event (a critical driving event on the windscreen or the rearview mirror).

The increased cognitive demand in the no-cue experiment was reflected by an increase in misses in the RSVP task, and an increased failure to respond within 1800 ms after the onset of the critical visual driving events (15.7% of trials overall). The mean percentages of correct responses in the RSVP task was 57.5% (SE = 4.4%), which is significantly lower than that reported in Experiment 1, $M = 70.1\%$, $t(26) = -2.33$, $p = .03$, and Experiment 2, $M = 75.4\%$, $t(26) = -3.66$, $p = .001$. The comparison of performance in the no-cue control experiment with that reported in our two main experiments therefore shows that the presence of any form of vibrotactile warning signal resulted in participants detecting (and consequently, responding to) more of the critical driving events than when no cue was presented. The results of this no-cue experiment therefore support the conclusion that it is better to have warning signals to assist people engaged in dual- or multi-tasking, even if they are sometimes invalid with respect to the direction of the critical driving event than to have no warning signal at all.

4. Conclusions

Taken together, the results of the two main experiments reported here demonstrate that the presentation of a vibrotactile stimulus on the torso (i.e., in peripersonal space) can lead to a shift of visual attention that facilitates time-critical responses to visual events seen in distal space (cf. Tan et al., 2003; Van Erp, 2001; Van Erp & van Veen, 2004; Van Veen & van Erp, 2001). Our results converge with Sklar and Sarter's (1999) study of pilots in showing the potential utility of vibrotactile cues as warning signals in applied interface design. Our findings also converge with previous demonstrations that presenting spatial orientation information to pilots and astronauts can lead to improved performance and consequently safety (see Van Erp & van Veen, 2003; Van Veen & van Erp, 2001). The present study extends these results by highlighting the potential use of vibrotactile warning signals in automobile interface design, such as the design of more complex tactile warning systems for indicating one or more impending collisions (which may be particularly important for specialized industrial or agricultural vehicles; cf. McGehee & Raby, 2003). In parallel with auditory warning signal design (e.g., Horowitz & Dingus, 1992), it will be important in future research to examine the quantity and quality of information that can be communicated via touch. Such information transfer can be supported by varying the intensity of the tactile stimuli, or by presenting various patterns of stimulation to represent different signals. For instance, while people seem to have no difficulty in localizing vibrotactile stimuli presented to their torso (Van Erp, 2005), Gallace, Tan, and Spence (in press) have recently shown that participants who have little prior experience of vibrotactile displays cannot correctly count (i.e., at above chance level) when more than four vibrotactile stimuli were presented at any one time.

Note that the RSVP task in the present study was used to simulate a continuously and uniformly highly attention-demanding situation (see Shapiro, 2001), such as when a driver's visual attention is concentrated toward the front. This task has been used extensively in dual-task attention research to maintain the cognitive load on participants, and it allows researchers to measure the temporal distribution of attention under conditions of task-switching (e.g., Allport & Hsieh, 2001; Klein & Dick, 2002). It will be interesting in future research to examine whether vibrotactile cues can also facilitate performance in a more realistic driving situation (cf. Van Erp & van Veen, 2001, 2004), such as in a driving simulator (see Kemeny & Panerai, 2003; Reed & Green, 1999), where drivers may experience a higher cognitive demand than that exerted by the RSVP task in the present study.

One can also interpret the driving task in the present study as a car following scenario on a highway where a driver is constantly attempting to maintain a safe distance both to the car in front and to the car behind. Even though the participants in our study only had to decide whether the driving event was a critical (i.e., car in front or behind coming close) or noncritical (i.e., car moving away) situation, the driving task served as a simplified version of what drivers do in real driving situations. The design of vibrotactile warning systems of this kind that inform drivers of the safe braking distance between front and rear cars is also useful, particularly on the highway where drivers may not pay attention to their increasing speed relative to the distance that they can brake without impacting the car in front should it suddenly slow down (cf. Smith, Najm, & Lam, 2003). Some other examples of the recent growing potential for tactile or haptic in-car interface designs include a shape-changing haptic controller (Michelitsch, Williams, Osen, Jimenez, & Rapp, 2004), and a haptic steering wheel for driving around curves and overtaking (Schumann, Godthelp, & Hoekstra, 1992; Schumann & Naab, 1992). It will also be particularly important to assess any detrimental effects of vehicle vibration on the salience and/or localizability of vibrotactile warning signals (cf. Haigney & Westerman, 2001). In conclusion, our results suggest that the crossmodal links in spatial attention between touch and vision identified in previous laboratory studies may have a number of real-world applications in the future design of multisensory interfaces.

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