Warning Signals Go Multisensory

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Abstract

The potential use of non-visual warning signals to present spatial information to car drivers has been successfully demonstrated in several recent studies (Ho & Spence, submitted, in preparation; Ho, Tan, & Spence, submitted). Among the three types of spatial warning signals investigated (namely auditory, visual, and vibrotactile), spatial vibrotactile cues were found to be particularly effective in directing a driver's visual spatial attention to potentially dangerous events on the road. We conducted the present study in order to examine the factors governing the relative effectiveness of auditory, visual, and vibrotactile warning signals. The speeded discrimination of warning signals presented in the various different modalities was investigated in order to explore whether the differences found in our previous research were a result of the relative speed with which people can detect warning signals presented in a given modality, or whether they were attributable to differences in the efficacy with which people can relate the warning signal to the subsequent visually-specified target driving events.

1 Introduction

The potential application of tactile warning signals and information displays in applied interface environments is currently receiving a great deal of both empirical and commercial interest (e.g., Gallace, Tan, & Spence, in press; Gilliland & Schlegel, 1994; Ho, Tan, & Spence, submitted; Rupert, 2000; van Erp & van Veen, 2004; Wood, 1998; Zlotnik, 1998). The communication of information by touch has been successfully demonstrated in various areas, such as in the field of aerospace where vibrotactile displays have been used to assist spatial orientation in pilots and astronauts. For instance, Rochlis and Newman (2000) provided somatosensory cues to improve the situation awareness of astronauts (who normally rely on visual cues) in confusing situations in altered sensory environments, such as under weightlessness. Van Erp, Jansen, Dobbins, and van Veen (2004) recently reported two case studies demonstrating that directional and distance information can be communicated through a vibrotactile torso display that allowed individuals to successfully pilot a helicopter, or to drive a high speed rigid inflatable boat in a waypoint navigation task.

The rapid growth of interest in tactile interface design is supported by previous applied research on tactile sensation and perception dating back to the early work of Fenton in the 1960's. In Fenton's (1966) study, a tactile control stick was used to present drivers with headway and relative velocity information via the tactile modality. Driving performance in a simulated laboratory car following situation was shown to be facilitated when compared to performance using conventional automobile controls. The findings from a recent study by van Erp and van Veen (2004) also provide evidence demonstrating a reduced subjective workload on the part of drivers when using tactile instead of visual navigation displays. Van Erp and van Veen reported faster responses to navigation messages presented multimodally by both tactile and visual means than when the messages were presented unimodally to either vision or touch, suggesting that redundant information presented simultaneously to different senses may prove useful in the design of multimodal systems (see also Jackson & Selcon, 1997; Spence & Driver, 1999).

In-car interfaces that vibrate have already been implemented in some recently released cars, such as Citroën's lane departure warning system ("The knowledge," 2005) that vibrates a driver's seat when the system detects that the car is about to cross the white line between two lanes without prior indication by the driver at speeds greater than 50 mph (~80.5 km/h). However, limited research has attempted to examine the potential beneficial or detrimental effects of such vibrotactile in-car systems on driving performance, and subsequently, on safety on the road.

2 Recent studies of vibrotactile cuing

Evidence from recent empirical research suggests that spatial vibrotactile signals can improve the detection of, and subsequent responses to, events occurring in the cued direction. Motivated by recent laboratory-based research suggesting the existence of robust crossmodal links in spatial attention between vision and touch (e.g., see Driver & Spence, 2004; Gray & Tan, 2002; Spence, McDonald, & Driver, 2004), Ho et al. (submitted) designed a study to investigate the potential use of vibrotactile warning signals to present spatial information to car drivers. In two experiments on vibrotactile spatial cuing in a simulated driving task, Ho et al. demonstrated that the use of informative spatial vibrotactile warning signals offered an effective means of directing a driver's visual attention to the appropriate distal environmental location. Specifically, responses (i.e., braking or accelerating) to potential emergency driving situations (i.e., the rapid approach of a car from behind or toward the car in front; see Figure 1) seen in either the rearview mirror or from the front windscreen were both faster and more accurate when participants were presented with vibrotactile warning signals coming from the appropriate, rather than from an inappropriate, direction. The vibrotactile warning signals used in their experiments were either spatially-predictive (i.e., the cues indicated the relevant direction of the targets on 80% of trials) or else spatially-nonpredictive (i.e., the cues indicated the relevant direction of the targets on 50% of trials).

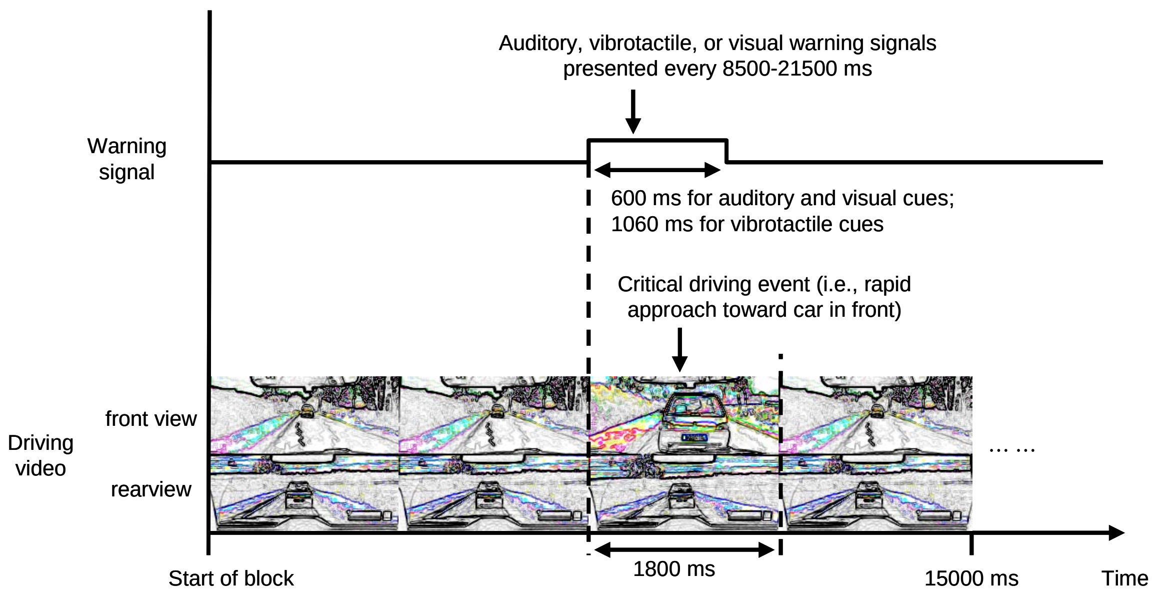

Figure 1: An illustration of a critical driving scenario in Ho and Spence's (submitted, in preparation) and Ho et al.'s (submitted) studies.

Analysis of the data from these experiments revealed significant spatial cuing effects (see Figure 2). Participants responded significantly more rapidly and accurately following a vibrotactile cue from the same direction as the critical driving event, as compared to performance when the opposite (i.e., inappropriate) direction was cued. These results build on recent audiovisual cuing studies (Ho & Spence, submitted) in showing that the presentation of spatial vibrotactile cues (as well as spatial auditory cues) can lead to a rapid crossmodal shift of visual attention in the direction indicated by the cue. Ho et al.'s (submitted) study demonstrated that the presentation of a vibrotactile stimulus on the torso in peripersonal space can lead to a shift of visual attention that facilitates time-critical responses to distal events (i.e., occurring in extrapersonal space). The indirect mapping or translation of what a driver sees via the rearview mirror (visually inspected from the front) to events occurring from behind is also an interesting one, given that Ho et al.'s results suggest that the association may be a well-learnt and automatic one (at least in the case of driving).

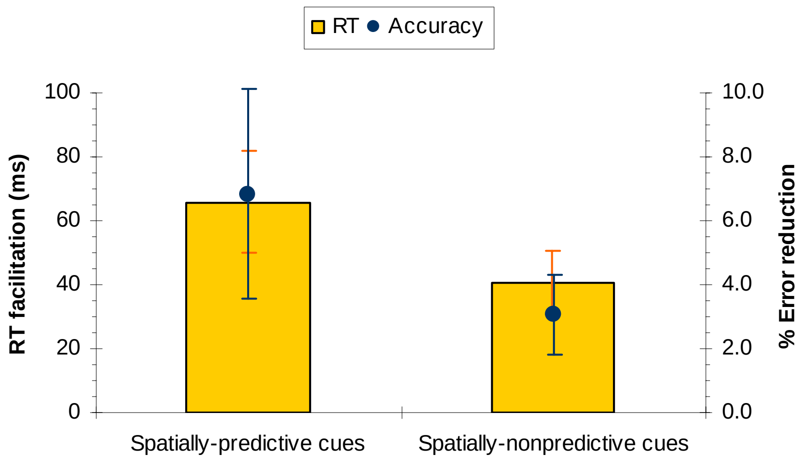

Figure 2: Summary of the spatial cuing effects in the reaction time (RT) and error data from Ho et al.'s (submitted) recent study of the effectiveness of vibrotactile warning signals (either spatially-predictive or else spatially-nonpredictive) in capturing a driver's visual attention, as assessed by performance on a task requiring rapid acceleration/braking responses by drivers.

Somewhat surprisingly, Ho et al. (submitted) found no significant difference between the effectiveness of spatially-predictive and spatially-nonpredictive vibrotactile warning signals. This may be attributable to the lack of trust and reliance on the part of the participants to the spatially-predictive vibrotactile cues, which were predictive on 80% of the trials. That is, it is possible that a significant difference would be evidenced between the use of spatially-nonpredictive (i.e., 50% valid) and 100% spatially-predictive (i.e., highly reliable and informative) vibrotactile cues. In fact, many human factors studies have specifically looked into the issue of alarm reliability (e.g., see Bliss & Acton, 2003; Parasuraman, Hancock, & Olofinboba, 1997; Sorkin, 1988) and its effects on alarm compliance by operators. As a general rule, a balance between high detection sensitivity and low false alarm rates has to be maintained in order to foster an appropriate sense of trust by interface operators. For instance, in one recent study where the driver received increased resistance on the gas pedal if the vehicle was too close to the car in front (Enriquez & MacLean, 2004), drivers did not appear to trust the feedback signal unless the false alarm rate was close to zero. Nevertheless, Ho et al.'s 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.

3 Speeded discrimination of auditory, visual and tactile warning signals

One important factor to consider when comparing the effectiveness of various different classes of warning signal is how long it takes people to respond to them, given the well-documented differences in transduction latencies for stimuli presented in different sensory modalities (e.g., Spence & Squire, 2003). Research suggests that people respond more rapidly to tactile stimuli presented to their hands than to visual stimuli (see Spence, Nicholls, & Driver, 2001). However, given that reaction times are likely to be slower for vibrotactile stimuli presented to the torso (than to the fingertip, as studied in the majority of previous studies), this is an important question that will need to be addressed in future research (see Bergenheim, Johansson, Granlund, & Pedersen, 1996; Harrar & Harris, submitted). A preliminary comparison across the mean reaction times (RTs) recorded in our previous research (Ho & Spence, submitted, in preparation; Ho et al., submitted) would appear to suggest that when people are multi-tasking, they can respond more rapidly to visual events following auditory warning signals, than following either vibrotactile or visual signals (see Figure 3). We conducted the present study to compare the speeded discrimination of the warning signals used in our previous research in order to examine the relative speed with which people can respond to auditory, tactile, and visual warning signals. The results of this study will enable us to compare the relative effectiveness of the various warning signals across different modalities[1], that is, whether the differences in response latency are governed by the speed with which people can respond to warning signals presented in a given modality, or by the efficacy of the translation from detecting the warning signals to looking at the visual events.

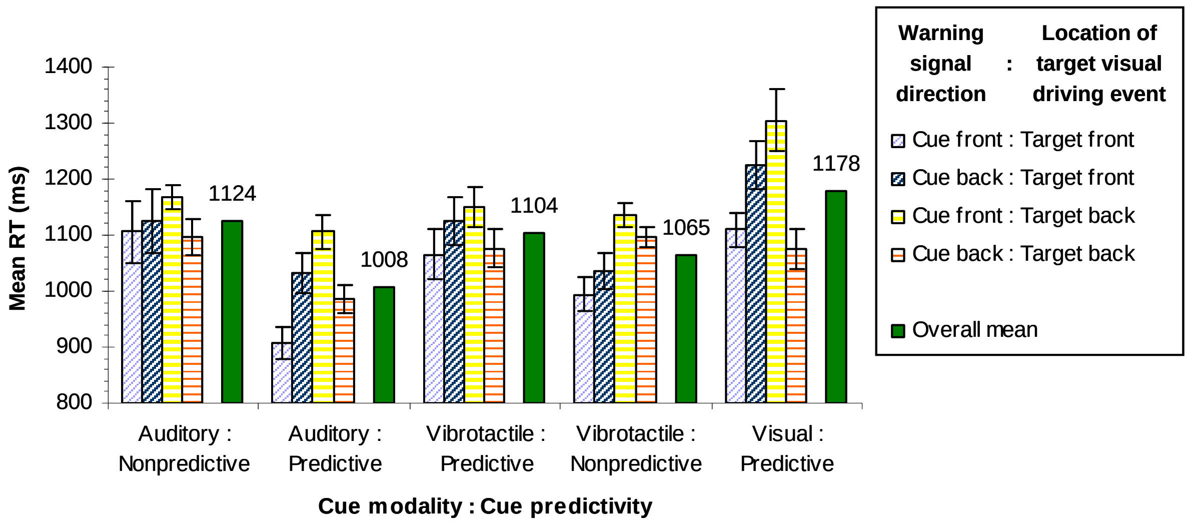

Figure 3: Summary results of mean RTs as a function of Warning signal direction (front vs. back) and Location of target visual driving event (front vs. back) reported in recent studies conducted in our laboratory (Ho & Spence, submitted, in preparation; Ho et al., submitted), investigating the effectiveness of various warning signals presented from different modalities.

3.1 Methods

3.1.1 Participants

Twelve participants (8 males and 4 females; mean age of 26 years, age range from 22-29 years) took part in this experiment. Eleven of the participants were right-handed, and one was left-handed by self-report. The participants reported normal, or corrected-to-normal, vision, touch, and hearing. The experiment lasted for 30 minutes, and all participants were recruited by word of mouth. The experiment was conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford.

3.1.2 Apparatus and materials

The experiment was conducted using the same experimental set-up as that reported in our previous research (see Ho & Spence, submitted, in preparation; Ho et al., submitted). In particular, the auditory stimuli consisted of the sound of a real car horn (600 ms duration; 8000 Hz; 66 dB(A)), presented through one of two loudspeaker cones placed on a virtual circle (70 cm in diameter) centered on the participants' head, one to the front and the other to their rear left-hand side, as in Ho and Spence's (submitted) Experiments 1 and 2 (see Figure 4 for a schematic illustration of the experimental set-up). The vibrotactile stimuli were delivered to participants using the same tactor belt as that used previously by Ho et al. One tactor was positioned in the middle of the participant's stomach with the other tactor positioned in the middle of their back. These vibrotactile stimulators were capable of delivering clearly perceptible vibrotactile stimuli (1060 ms in duration) to participants over their clothing. White noise was delivered through

[1] Note that the differences between the various sensory modalities reported in the present study were governed not only by differences in transduction latencies but also by other factors such as the distance from the source stimuli (e.g., tactile stimuli were presented on the body, while the auditory and visual information originated from a source 70 cm from the body), and the specific parameters (e.g., intensity, stimulus duration) chosen.

cordless headphone (SBC-HC8355, Philips, USA) at approximately 60 dB(A) in the block of trials where the tactors were used to mask the noise caused by their operation. A red light-emitting diode (LED) was attached to the middle of the top of the front monitor and a green LED was placed on the middle of the top of the rearview mirror, as in Ho and Spence's (in preparation) study investigating the comparative effectiveness of visual warning signals at capturing a driver's visual attention. The red LED (600 ms in duration) was used to indicate target visual driving events taking place in the front, while the green LED (600 ms in duration) indicated target visual events at the rear.

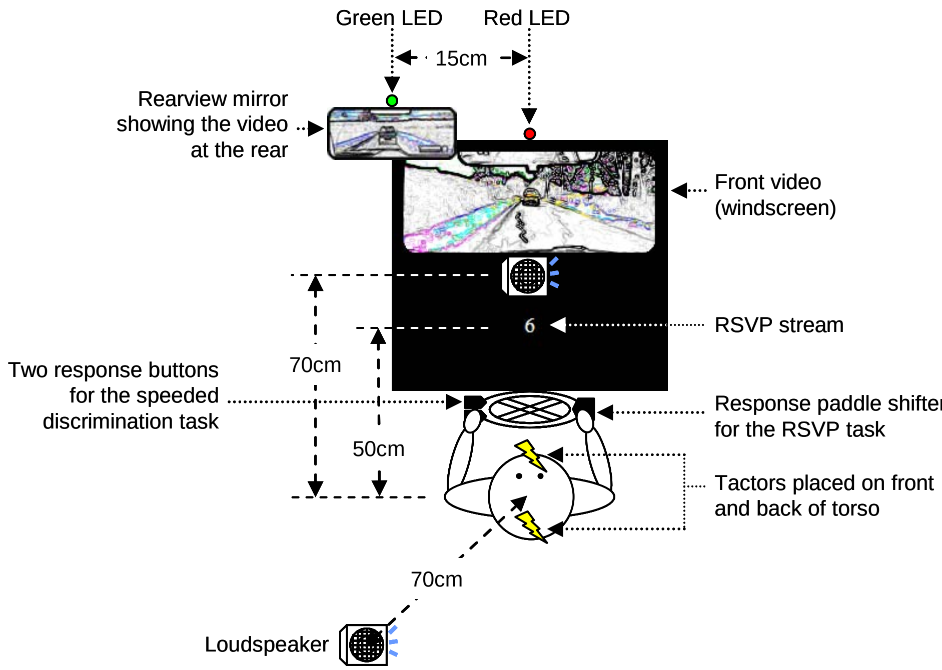

Figure 4: A schematic diagram of the experimental set-up.

3.1.3 Design

The experimental session consisted of three 6-minute blocks of experimental trials, one auditory, one tactile, and the other visual, with the order of presentation counterbalanced across participants. As in our previous studies (e.g., Ho & Spence, submitted, in preparation; Ho et al., submitted), the rapid serial visual presentation (RSVP) task consisted of a continuous stream of distractor letters with target digits periodically embedded within it. A total of 66 target digits were presented in each block of experimental trials. The temporal gap between successive target digits was in the range of 2040-6360 ms. The RSVP task, used extensively in laboratory-based attention research (e.g., Soto-Faraco & Spence, 2002), was chosen to ensure a uniformly highly-attention-demanding visual task throughout each of the experimental blocks.

Forty target warning signals, requiring a speeded discrimination response, were presented in each experimental block. In the auditory block, half of the auditory targets were presented from the front loudspeaker, and the remainder from the rear. In the tactile block, half of the vibrotactile targets were presented to the front of the participant's torso, and the remainder to their back. In the visual block, half of the visual targets were red, and the remainder green, corresponding to the front windscreen and the back rearview mirror spatial positions, respectively (see Ho & Spence, in preparation). The temporal gap between successive target stimuli was 4800-10800 ms. A video showing the view through the windscreen of a car following a leading car in front (recorded from a driver's position in a real driving environment), and the rear view of a car following from behind (as seen indirectly via a rearview mirror by the driver), was presented continuously in the background, just as in our previous studies (see Ho & Spence, submitted, for a more detailed description of the driving videos used).

The participants were given two practice blocks in which to familiarize themselves with the experimental set-up. In the first practice block, the participants only had to perform the RSVP task which was presented at a slower rate than in the experimental blocks to facilitate task acquisition. In the second practice block, the participants performed ten trials (five targets from each of the two possible target positions) of each of the three subsequent experimental blocks while performing the RSVP task at the stimulus timings used in the experimental blocks.

3.1.4 Procedure

The participants responded to target digits in the RSVP task by pressing the right paddle shifter on the steering wheel. For the speeded discrimination task, half of the participants were instructed to press the upper left button (mounted next to the left paddle shifter on the steering wheel) when they detected a red visual target or an auditory or vibrotactile target coming from the front, and to press the lower left button (mounted 2.5 cm vertically below the upper button) for a green visual target or for an auditory or vibrotactile target presented from the rear. The other half of the participants performed the speeded discrimination task using the opposite response mapping. All of the participants were instructed to respond as rapidly and accurately as possible to the target stimuli. They were also instructed to keep the accelerator depressed slightly throughout the experiment in order to model realistic driving conditions.

3.2 Results

Table 1 highlights the mean RTs and percentages of correct responses for the speeded discrimination task. False alarm responses constituted less than 1% of trials overall and were discarded from the data analysis. Trials with an incorrect response were discarded from the RT analysis. A repeated measures analysis of variance (ANOVA) was performed on the RT data to assess whether the spatial location from which the target warning signals were presented had any effect on our participants' ability to detect them, and whether the detection of, and subsequent responses to, warning signals presented in the three different sensory modalities differed. The two within-participants factors were Target Modality (auditory, tactile, or visual) and Target Position (front or back).

Table 1: Mean RTs (in ms) and percentages of correct responses, and their standard errors (in parentheses), in the speeded target discrimination task as a function of Target Modality and Target Position.

	Target Position					
	Front		Back		*Mean = (Front + Back) / 2*	
Target Modality	RT	% correct	RT	% correct	*RT*	*% correct*
Auditory	872 (27)	92.9 (1.8)	790 (34)	92.9 (2.6)	831 (28)	93.0 (1.9)
Tactile	780 (36)	93.8 (3.1)	745 (31)	95.8 (1.5)	762 (32)	95.1 (1.8)
Visual	842 (33)	92.5 (1.6)	740 (36)	90.4 (3.2)	791 (33)	91.8 (1.5)
Overall Mean	831 (28)	93.0 (1.6)	758 (30)	93.0 (1.4)		

Analysis of the RT data revealed a significant main effect of Target Modality, $F(2,22) = 4.6$, $MSE = 6272$, $p=.02$, with participants responding more rapidly to vibrotactile targets ($M = 762$ ms), than to visual targets ($M = 791$ ms), and with participants responding most sluggishly to auditory targets ($M = 831$ ms). Subsequent paired comparison t-tests revealed a significant difference between the auditory and tactile conditions, $t(11) = 3.1$, $p<.01$, while the differences between the visual and both the auditory, $t(11) = 1.7$, $p=.12$, and tactile stimuli, $t(11) = -1.3$, $p=.23$, failed to reach statistical significance. There was also a significant main effect of Target Position, $F(1,11) = 30.3$, $MSE = 3142$, $p<.001$, with participants responding more rapidly to targets presented from the rear ($M = 758$ ms) than from in front ($M = 831$ ms). The interaction between Target Modality and Target Position was, however, not significant, $F(2,22) = 2.5$, $MSE = 2853$, $p=.10$ (see Table 1).

For a given trial in the speeded discrimination task, only the first response made by a participant after the onset of the warning signal was considered in the subsequent data analyses. Thus, an error was defined as an incorrect first response made after the onset of a target warning signal. A similar analysis of the error data revealed no significant main effects or interactions, all Fs < 1, *n.s.* Importantly, however, it is worth noting that participants made fewer errors in response to tactile targets than to either the auditory or visual targets, thus allowing us to rule out a speed-accuracy trade-off account of the RT data (e.g., Müller & Findlay, 1987).

Performance in the concurrent RSVP task was also analyzed to examine if participants performed the attention-demanding visual task equally well across all three experimental blocks. Separate ANOVAs with the within-participants factor of Target Modality (auditory, tactile, or visual) on the mean percentage of correct detection responses data and the mean RT data revealed no significant main effect of Target Modality, $F(2,22) < 1$, *n.s.*, and $F(2,22) = 2.1$, p=.15, respectively. That is, the participants performed the RSVP task equally well in all three experimental blocks, detecting an average of 85% (*SE* = 3%) of the target digits, with a mean response latency of 596 ms (*SE* = 11 ms). Interestingly, a subsequent comparison of performance on the RSVP task as a function of the time after the onset of a target warning signal indicated that the largest time-locked dual-task interference effect was elicited by the visual target warning signals (i.e., participants failed to respond appropriately to the RSVP task as they were distracted by a target warning signal in the speeded discrimination task) of a duration of approximately 900 ms. The interference effect elicited by the presentation of the auditory warning signals lasted for approximately 300 ms (cf. Soto-Faraco & Spence, 2002). Somewhat surprisingly, no interference was elicited by the presentation of the vibrotactile warning signals (cf. Soto-Faraco, Spence, Fairbank, Kingston, Hillstrom, & Shapiro, 2002). The general pattern seems to suggest that vibrotactile cues had the least disturbance to the concurrent visual task.

3.3 Discussion

The results of the experiment reported here demonstrate that participants can respond more rapidly to vibrotactile warning signals, than to either visual or auditory warning signals. Given that increasing interface operator overload in the visual system reported in many interface settings (e.g., Sorkin, 1987; Spence & Driver, 1997), the use of non-visual warnings may seem more effective than visual warning signals in alerting a person engaged in a primarily visual task such as driving (e.g., Morris & Montano, 1996; Sorkin, 1987; though see also Sivak, 1996). Some researchers have actually suggested that visual overload may arise not only from the operator having to deal with too much information, but also from a lack of information regarding which of the available visual information is actually most relevant at any given point in time (e.g., Perrott, Cisneros, McKinley, & D'Angelo, 1996).

Participants in the present study reacted significantly more rapidly, and somewhat more accurately, to vibrotactile target stimuli delivered to their torso than to auditory stimuli presented a short distance away from their ears. In fact, the use of vibrotactile cues in an automobile setting may be more advantageous than auditory cues not only because people can react to them more rapidly, but also because they are private to the driver, thus other passengers in the car should not be disturbed by their occurrence (see Triggs, Levison, & Sanneman, 1974; van Erp & van Veen, 2001, 2004, for a discussion of the potential use of vibrotactile displays in automobiles and aeronautical applications). Vibrotactile cues also have the advantage that they should not be affected by the level of background noise in the driving environment to the same extent as auditory cues (although of course their detectability might be masked somewhat by vehicular vibrations; cf. Kemeny & Panerai, 2003). One reason for the slow discrimination responses reported in response to the auditory targets in the present study may be related to the fact that people find it more difficult to localize sounds within confined spaces such as in a car (e.g., Catchpole, McKeown, & Withington, 2004; Moore & King, 1999). Psychophysical studies of tactile perception, on the other hand, have shown that participants can accurately localize vibrotactile stimuli presented at up to twelve sites on their abdomen, with localization accuracy dependent on how close the vibrotactile stimuli are to the spine or navel, and how close any two given sites are to each other (Cholewiak, Brill, & Schwab, 2004). Future research should consider whether there are other body sites (perhaps closer to the brain; cf. Bergenheim et al., 1996; Gilliland & Schlegel, 1994; Harrar & Harris, submitted) where vibrotactile RTs would be even faster than those observed in the present study, given that the waist may not be the optimal site for vibrotactile stimulation (e.g., see Weinstein, 1968).

Our results show that participants were able to respond more rapidly to both auditory and vibrotactile warning signals presented to the back than to the front. This finding allows us to rule out the argument that the overall slower responses to the rearview mirror in Ho et al.'s (submitted; Experiment 2) study were due to the fact that vibrations to the back were somehow less salient (in fact, the present results suggest that they may actually be more salient) than vibrations presented to the front. In future studies, it may be worth investigating how the ability to detect stimuli presented simultaneously to different modalities may be influenced by the position from which they are presented (i.e., front vs. back), given that our attention is predominantly focused to the front of our body in most situations (though see Kitagawa, Zampini, & Spence, in press).

The results of the present study allow us to draw basic comparisons between the results of our previous research on the auditory, visual, and tactile spatial cuing of driver attention (Ho & Spence, submitted, in preparation; Ho et al., submitted). Our results show that the efficiency with which participants can respond to dangerous road events signaled by auditory, visual, or vibrotactile warning signals depends not just on the speed with which participants can discriminate the position from which the warning signals are presented. For instance, in contrast to the faster discrimination latencies seen for vibrotactile rather than auditory warning signals in the present experiment, participants in our spatially-predictive auditory experiment (Ho & Spence, submitted, Experiment 2) were, on average, numerically somewhat faster (M = 1008 ms) overall than participants in our spatially-predictive vibrotactile experiment (Ho et al., Experiment 1; M = 1104 ms). The contrasting pattern of results reported in these two studies suggests that cue and target modalities may interact to determine the resultant effectiveness of warning signals in applied settings. Furthermore, there are also costs associated with the shifting of attention from one sensory modality (that of the warning signal) to another (i.e., that of the critical driving event) that also need to be taken into account (Spence et al., 2001) when considering in which modality it is most appropriate to introduce a given warning signal.

In conclusion, our research now shows that it is both feasible and practical to convey spatial or directional information effectively to drivers using vibrotactile spatial signals, both as warning signals for alerting or redirecting attention (e.g., Ho et al., submitted), and as in-car navigation messages for guidance (e.g., van Erp & van Veen, 2004). Future research should examine the coding of information by location and/or temporal rhythms to convey different types of information (cf. Arrabito, Mondor, & Kent, 2004; Patterson, 1990). Given that humans have only limited cognitive resources (Lavie, 2005), the finding that information presented spatially in one sensory modality can enhance subsequent responses to information presented in a relevant direction or location in a different sensory modality has important implications for multisensory interface design, particularly for situations of high informational load, as is often the case for driving. Moreover, as O'Regan, Rensink, and Clark (1999) have pointed out, dangerous events may occur without being noticed if these events happen to coincide temporally with other harmless disturbances, such as small stones hitting on the car windscreen (see also Batchelder, Rizzo, Vanderleest, & Vecera, 2003; Simons & Rensink, 2005; Velichkovsky, Dornhoefer, Kopf, Helmert, & Joos, 2002). Given that such time-locked information processing deficits also occur crossmodally (see Colavita, 1974), it is important for car manufacturers to design and install multisensory (non-visual) warning devices that can facilitate the appropriate deployment of a driver's attention, such as with the proposed vibrotactile spatial signals.

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