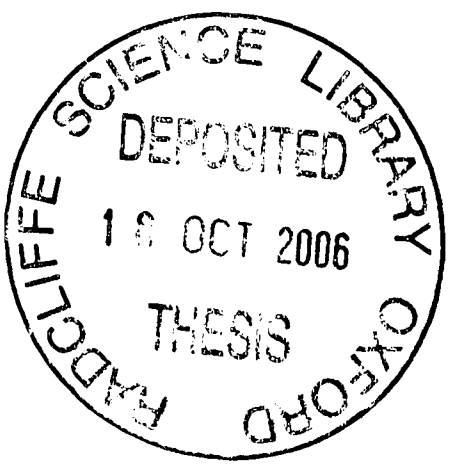
MULTISENSORY ASPECTS OF THE SPATIAL CUING OF DRIVER ATTENTION

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DECLARATION

I hereby declare that this work has not been submitted previously as an exercise for a degree at this or any other university, and that it is entirely my own work.

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Cristy Ho

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SHORT ABSTRACT

The primary goal of the empirical research outlined in this thesis was to examine a number of the factors contributing to the design of more ergonomic multisensory warning signals, that is, signals that elicit efficient and effective responses from interface operators under demanding conditions. To achieve this goal, a series of experiments was conducted in order to examine the nature and consequences of the crossmodal links inherent in spatial attention between various different sensory modalities, such as audition, vision, and touch, in an applied setting. In particular, a laboratory-based simulated driving task was used to investigate the effectiveness of various different auditory and vibrotactile cues in orienting a driver's attention to potential emergency driving events seen through the front windscreen or rearview mirror. The results of the first set of auditory spatial cuing experiments highlighted a significant performance advantage when the target driving events occurred in the cued, rather than the uncued, direction, with the biggest benefits being seen following spatially-predictive auditory or verbal cues. The second set of vibrotactile spatial cuing experiments demonstrated the potential utility of vibrotactile warning signals for presenting spatial information to car drivers, and the results were successfully replicated in a study using a high-fidelity driving simulator. The third set of experiments, incorporating an orthogonal task design, were conducted in order to examine the mechanisms responsible for the advantageous spatial cuing effects reported in the earlier experiments. Taken together, the results demonstrated that

while directional congruency between a warning signal and target driving event may be sufficient to facilitate performance due to the priming of the appropriate response, attentional facilitation (i.e., perceptual enhancement) typically requires the co-location of the cue and target within the same functional region of space. In sum, this thesis demonstrates the potential value of approaching the design of effective multisensory warning signals for human operators by studying the information processing mechanisms in the human brain. The findings outlined here add to the literature concerning the brain's differential representation of stimuli presented in peripersonal as opposed to extrapersonal space. Further experimental chapters detail experiments that examined verbal directional cuing, olfactory cuing, and crossmodal interactions in virtual haptic environments.

EXTENDED ABSTRACT

The research outlined in this thesis was designed to investigate a number of the factors that may help contribute to the creation of ergonomic multisensory warning signals for event perception and safe driving by understanding some of the limitations inherent in the human information processing system. In particular, given robust recent behavioural and neuroscience evidence demonstrating the existence of extensive crossmodal links in spatial attention between all possible combinations of auditory, visual, and tactile stimuli (see Spence & Driver, 2004, for a recent review), the present research was designed to try and demonstrate the possibility of implementing this theoretical knowledge concerning crossmodal spatial attention in practical applications for warning signal design. The thesis starts with an introductory chapter that outlines previous theoretical and empirical studies relevant to the present research. Recent approaches to auditory and tactile interface design are described. The introductory chapter also set the scene by introducing a number of the factors that may prove to be important when it comes to the future design of multisensory warning signals. These factors include limitations in information processing in the human brain at the perceptual, decisional, and motor response levels.

Chapter 2 describes a series of auditory spatial cuing experiments that were designed to assess the relative effectiveness of various different spatial auditory and verbal directional cues in orienting a driver's attention to the appropriate spatial location of potential critical emergency driving events. In particular, these

experiments were designed to examine whether the location and/or informational content of auditory warning signals could be used to facilitate the detection of visual driving events seen in the front and/or in the rearview mirror (representing events actually occurring at the rear). This front versus back dimension has been relatively under-explored in previous attentional cuing studies with the majority of crossmodal research typically examining left versus right cuing instead.

A laboratory-based simulated driving task was designed whereby participants' primary attention was engaged in a rapid serial visual presentation (RSVP) task presented directly in front of them. They were required to detect target digits embedded periodically within a continuous stream of distractor letters. This task was used to model a continuously and uniformly highly attention-demanding situation, which is in a way similar to the visual load on a driver's attention when he/she is primarily concentrating toward the front (Burnett & Joyner, 1997). While the participants were performing the RSVP task, auditory spatial cues were presented randomly. These auditory cues were spatial in the sense that they consisted of either a car horn sound presented spatially from the front or back, or else they consisted of the verbal cues 'front' or 'back'. The cue validity was also varied (either 50% or 80% predictive of the direction of the target visual driving event) in order to assess the effect of cue reliability and the roles of exogenous and endogenous attentional orienting on the crossmodal facilitation effects observed. The redundancy (or integrated) effect of spatial cues was also examined in the final experiment in this chapter by presenting the spatial symbolic verbal cues from the appropriate spatial locations. As soon as the participants heard a cue, they were required to react by checking the front monitor (windscreen) and the rearview mirror (which reflected the image on a second monitor positioned at the rear-left of the participant), and decide if

a potential emergency driving situation was present in the driving videos played in the two monitors. The participants were to give their response by depressing either the accelerator or brake pedal.

The results of this first series of five experiments revealed a significant performance advantage in orienting visual attention to the appropriate direction following an auditory cue coming from the same direction as the visual target, or else with the use of a semantically-meaningful verbal cue. Such an effect of spatial cuing was further enhanced by increasing the informativeness of the cues (i.e., from 50% to 80% spatially-predictive or valid), consistent with previous findings regarding the spatial auditory cuing of visual search performance for pilots. Although the largest magnitude of spatial cuing effects was reported with the presentation of redundant spatial cues, a number of drawbacks associated with implementing linguistic cues in a real driving situation are highlighted in the discussion.

Chapter 3 tackles the issue of verbal directional cuing further by investigating the spatial distribution of a participant's (or interface operator's) attention following the central presentation of spatially-nonpredictive verbal directional cues (the words 'left' or 'right'). A laboratory-based study using the Posner spatial cuing paradigm (Posner, 1978) was conducted to address this question. The visual discrimination of unmasked visual targets was shown to be facilitated following the presentation of visually-presented word cues but not following auditorily-presented word cues. Interestingly, improved visual sensitivity on the auditorily-cued side was observed when the visual targets were masked. These findings are discussed in relation to previous laboratory-based and applied symbolic cuing studies that have investigated the consequences of the presentation of arrow, gaze direction, and/or head orientation directional cues on the spatial distribution of a participant's attention. In particular,

the results would appear to suggest an effortless and automatic shift of spatial attention in the direction of the linguistic cue even when it is spatially uninformative, and that people may not be able to suppress the learned semantic meaning of these directional linguistic cues. Note though that this may only be applicable to people who can understand the language in which the message is spoken, and is dependent on the context or frame of reference of a particular term. These findings have important implications for the designers of interface systems where a large amount of spatial information has to be delivered linguistically and possibly also for drivers using new devices with verbal output (e.g., satellite navigation devices).

The experiments reported in Chapter 4 were designed to investigate the potential to better utilize the sense of touch in interface design. The tactile sense has been argued to be automatically alerting, inherently directional, private to a person, and it has also been suggested that it cannot be 'shut out' voluntarily (Gilmer, 1960). This chapter begins with a laboratory-based study investigating the potential benefit of using vibrotactile spatial cues to present information to drivers in two experiments using a similar design as in the auditory spatial cuing experiments reported in Chapter 2. Spatial vibrotactile stimuli (front vs. back) were delivered to a participant's waist through his/her clothing. The results demonstrated the feasibility of utilizing vibrotactile spatial cuing in a driving situation. Given the potential limitation of limited ecological validity in the laboratory-based experiments described up to this point, the examination of the effectiveness of spatial cuing in a more realistic testing environment was deemed essential in order to validate the advantageous effects reported previously. Therefore, a driving simulator study was conducted in order to investigate whether driver responses to potential front-to-rear-end collision situations

could be facilitated by implementing vibrotactile warning signals that indicate the likely direction of the potential collision.

In a car following scenario in a high-fidelity driving simulator, participants drove along a rural road while trying to maintain a safe headway distance to the lead car using a visual distance display. Participants had to respond as quickly as possible to the sudden deceleration of the lead car which had its brake lights disabled, either with or without vibrotactile cues. The results demonstrated significantly faster braking responses and larger safety margins when the vibrotactile warning signal was presented than when it was not. It is worth noting that the magnitude of the facilitation found in this applied setting (and hence more realistic) was much larger than would have been estimated based on the results of previous laboratory-based studies in the literature and those reported in the earlier parts of this thesis. These results add to a growing body of empirical evidence highlighting the potential practical benefits associated with the use of 'intuitive' vibrotactile in-car displays, in this case, to alert drivers to potential collisions and to provide time-critical directional information.

On the theoretical side, in addition to demonstrating the potential utility of spatial cues in orienting a driver's attention to the appropriate location on the applied level, the successful demonstration of crossmodal links in spatial attention between audition and vision (Chapter 2) and between touch and vision (Chapter 4) together argues against traditional theoretical accounts of modality-specific information processing (Wickens, 1984, 1992). Instead, the mechanisms controlling spatial attention in the various different sensory modalities appear to interact and influence one another. Furthermore, there seems to be a fairly automatic translation of what participants see in the rearview mirror positioned in front to represent an event

happening from behind. This is perhaps the first empirical study to have investigated the cuing of spatial attention to the rear seen only indirectly via a mirror reflection.

In Chapter 5, the level(s) of information processing at which crossmodal cuing effects attributable to the spatial auditory and vibrotactile warning signals were taking place were examined. First, the speeded discrimination of warning signals presented in the various different sensory modalities was investigated in order to explore whether the differences found in the experiments reported in Chapters 2 and 4 were a consequence of the relative speed with which people can detect warning signals presented in a given modality, or whether instead they could be attributed to differences in the efficacy with which people can relate the warning signal to the subsequent visually-specified target driving events. A series of orthogonal cuing experiments (cf. Spence & Driver, 1994) were conducted in order to try and distinguish the relative contributions of response priming (i.e., to performance being facilitated without there necessarily being any change in the perceptual representation of the target) and attentional facilitation (i.e., to a perceptual benefit that facilitates subsequent behavioural responding) in the spatial cuing effects reported in the earlier chapters. The participants in these experiments had to discriminate the colour of a numberplate (red vs. blue) following the presentation of spatially-predictive vibrotactile or auditory warning signals that indicated the likely location (front vs. back) of the visual target. The use of an orthogonal spatial cuing design meant that a potential response priming account of the data could effectively be ruled out. The factor of cue location was also examined, that is, stimuli were presented either from locations far away from the participant's body (coinciding with the source locations of the visual targets), or else from locations close to the head of the participant.

Interestingly, the robust spatial cuing effects reported previously in Chapter 4 were no longer evidenced in the vibrotactile spatial cuing experiment when an orthogonal cuing design (i.e., the responses required were orthogonal to the spatial dimension of interest) was used, suggesting that the presentation of a vibrotactile cue on the body surface may have elicited an automatic response bias, without there necessarily being any shift of spatial attention in the direction indicated by the cue. Moreover, the presentation of auditory spatial cues resulted in attentional facilitation only when they originated from the same source locations as the visual target stimuli (or at least the locations used to portray these events), but not when they were presented from locations close to the participant's head. Taken together, the findings suggest that while directional congruency between a warning signal and a target event may be sufficient to facilitate performance due to the priming of the appropriate response, attentional facilitation of a target representation may require the presentation of a cue from the same functional region of space as the target. The findings imply that response compatibility is an important factor in multisensory interface design since behavioural performance may be facilitated if the cue and target events are directionally-matched. However, additional benefits attributable to attentional facilitation or perceptual enhancement may only occur if the cue and target are located much closer together (i.e., within the same functional region of space).

The experiments reported in Chapter 6 were designed to provide a preliminary investigation of the potential use of olfactory cues in terms of facilitation in dual-task performance in a laboratory setting. In particular, the experiments assessed the effects of the odours of peppermint, lavender, and cinnamon on RSVP and vibrotactile front/back speeded discrimination performance. While peppermint odour was shown to improve concentration, no performance facilitation was found following the

presentation of either of the other two odours in the same task. The results also highlighted the potential modulatory role of task-difficulty in odour-induced task performance facilitation, and tentatively suggests the beneficial use of odours in multisensory interface design.

The thesis concludes with closing remarks discussing the notion of functional regions of space (peripersonal vs. extrapersonal) surrounding a driver and comments concerning the brain's representation of the space seen in the mirror. A number of future directions for multisensory interface research are also proposed. Finally, the Appendix details the results of a separate series of experiments also conducted during this thesis that was designed to study visual-haptic integration in a virtual haptic environment.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Attentional limitations in driving

Humans are inherently limited capacity creatures; that is, we are able to process only a restricted amount of the sensory information that is typically available at any given time (see Broadbent, 1958; Driver, 2001). Although it is unclear what the exact nature of this limited capacity is (see Posner & Boies, 1971; Schumacher et al., 2001), the inability of humans to simultaneously process multiple sources of sensory information places a number of important constraints on their attentional processing (in both the laboratory and in real life).

Attention has been defined in many different ways, for example, as the '*ability to concentrate perceptual experience on a selected portion of the available sensory information to achieve a clear and vivid impression of the environment*' (Motter, 2001, p. 41). One important element of attention is its selectivity (see Driver, 2001, for a review). Among all of the various different dimensions along which selective processing of information may occur, the spatial distribution of sensory inputs in the environment represents an area that is of great interest to many researchers, both theoretically and from an applied perspective.

The capacity limitation of spatial attention in humans raises important constraints on the design and utilization of, for instance, vehicular information systems (e.g., Brown, Tickner, & Simmonds, 1969; Burke, Gilson, & Jagacinski, 1980; Chan & Chan, 2006; Mather, 2004; Spence & Driver, 1997b). The act of driving represents a highly complex skill requiring the sustained monitoring of integrated perceptual and cognitive inputs (e.g., Hills, 1980). The ability of drivers to selectively attend and divide their attention among all the competing sensory inputs has important consequences for driver performance, which links inevitably to the topic of car accidents. For instance, a driver may fail to detect the sudden braking of the vehicle in front since he/she is distracted by a passenger's conversation (or by the conversation with someone at the other end of a mobile phone; e.g., Spence & Read, 2003), resulting in a collision with the vehicle in front. In addition, these attentional limitations on driver performance are currently being exacerbated by the ever-increasing availability of complex in-vehicle technologies (Ashley, 2001; Lee, Hoffman, & Hayes, 2004; Wang, Knipling, & Goodman, 1996; though see also Cnossen, Meijman, & Rothengatter, 2004), such as navigation systems (e.g., Burnett & Joyner, 1997; Dingus, Hulse, Mollenhauer, Fleischman, McGehee, & Manakkal, 1997; Fairclough, Ashby, & Parks, 1993), cellular phones (e.g., Patten, Kircher, Ostlund, & Nilsson, 2004; Spence & Read, 2003; Strayer, Drews, & Johnston, 2003), email (e.g., Lee, Caven, Haake, & Brown, 2001) and evermore elaborate sound systems (e.g., Jordan & Johnson, 1993). Somewhat surprisingly, this proliferation of in-vehicle interfaces has taken place in the face of extensive research highlighting the visual information overload suffered by many drivers (e.g., Bruce, Boehm-Davis, & Mahach, 2000; Dewar, 1988; Dukic, Hanson, & Falkmer, 2006; Hills, 1980; though see also Sivak, 1996).

Given the many competing demands on a driver's limited cognitive resources, it should come as no surprise that driver inattention, including drowsiness, distraction, and 'improper outlook', has been identified as one of the leading causes of vehicular accidents, estimated to account for 26% (Wang et al., 1996) to 56% (Treat et al., 1977) of all road traffic accidents (see also Ashley, 2001; Gibson & Crooks, 1938). Fortunately, however, the last few years have also seen the development of a variety of new technologies, such as sophisticated advanced collision avoidance systems, designed to monitor the traffic environment automatically, and to provide additional information to drivers in situations with a safety implication. In fact, the development of these new technologies, known collectively as intelligent transport systems (ITS), means that more information than ever before can now potentially be delivered to drivers in a bid to enhance their situation awareness and ultimately improve road safety.

One of the most common types of car accident, estimated to account for around a quarter of all collisions, is the front-to-rear-end collision (McGehee, Brown, Lee, & Wilson, 2002; see also Evans, 1991). Research suggests that driver distraction (or inattention) represents a particularly common cause of this kind of accident (no matter whether the lead vehicle is stationary or moving; Wang et al., 1996; see also Rumar, 1990). The potential benefits of improving the situation awareness of drivers to road dangers such as impending collisions are therefore huge. To put this in perspective, it has been estimated that the introduction of a system that provided even a modest decrease in the latency of overall driver responses of, say, around 500 ms, would reduce front-to-rear-end collisions by as much as 60% (Suetomi & Kido, 1997). Given that a number of different forward collision warning systems now exist, it has become increasingly important to determine the optimal means of helping drivers to

avoid such collisions (e.g., Graham, 1999). Current strategies differ in terms of their degree of intervention, varying from pro-active collision avoidance systems that can initiate automatic emergency braking responses, to collision warning systems that simply present warning signals to drivers prompting them to adjust their speed voluntarily instead (Hunter, Bundy, & Daniel, 1976; Janssen & Nilsson, 1993).

In fact, the technology has now been developed to enable 'intelligent' cars to detect dangerous road situations (e.g., such as adaptive radar cruise control systems), which in theory means that the car could potentially take control away from the driver and become autonomous (Knight, 2006). However, at present, car manufacturers appear to prefer that the control of the car remains in the hands of the drivers primarily owing to legal implications, such as relate to liability issues should an accident occurs during automatic cruising (see Hutton & Smith, 2005; Knight, 2006). Therefore, investigations into the design of optimal warning signals that can alert drivers to potential dangers are essential.

A great deal of empirical effort has gone into studying how best to alert and warn inattentive drivers to impending danger. For example, a number of researchers have suggested that auditory and/or tactile (rather than visual) warning signals could be used in interface design (e.g., Deatherage, 1972; Hirst & Graham, 1997; Horowitz & Dingus, 1992; Lee et al., 2004; Sorkin, 1987; Stokes, Wickens, & Kite, 1990). The potential advantages of using such non-visual signals include the fact that: 1) People can typically respond more rapidly to auditory and tactile signals than to visual signals (e.g., Jordan, 1972; Nelson, McCandlish, & Douglas, 1990; Todd, 1912); 2) The presentation of such signals should not overload the driver's 'visual' system (McKeown & Isherwood, in press; though see Spence & Driver, 1997b; Spence & Read, 2003); 3) It has been argued that auditory and tactile signals are inherently

more alerting than visual stimuli (e.g., Campbell et al., 1996; Gilmer, 1961; Posner, Nissen, & Klein, 1976); 4) Unlike visual cues, auditory and tactile warning signals are not dependent for their effectiveness on the current direction of a driver's gaze (Hirst & Graham, 1997; Stanton & Edworthy, 1999), and can be perceived even when the drivers' eyes are closed, such as during blinking, or when the visual system is effectively 'turned off', such as during saccades that typically occur several times each second (Bristow, Haynes, Sylvester, Frith, & Rees, 2005); and 5) Tactile (or haptic) displays tend to be judged as less annoying than many other kinds of warning signal (e.g., Lee et al., 2004; McGehee & Raby, 2003).

1.2 Multisensory integration

One way to design effective in-car interfaces is by understanding the limitations of the human brain's information processing system. Traditional theories of human information processing have typically considered individual sensory modalities, such as audition, vision, and touch, as being independent. For instance, the most influential multiple resource theory on human workload and performance proposed by Wickens (1980, 1984, 1992) a number of years ago postulates separate attentional resources for visual and auditory information processing. Accordingly, when people are engaged in concurrent tasks that consume their visual and auditory resources in parallel, such as talking on the mobile phone while driving, there should be no dual-task cost because the conversation is processed by the auditory-verbal-vocal pathway, while the act of driving is processed by the visual-spatial-manual pathway. Therefore, these two processes should not, in theory, conflict with each other.

However, recent evidence from both behavioural and neuroimaging studies has argued against this traditional point of view. Instead, the multisensory integration approach to human information processing puts forward the view that people integrate multiple streams of sensory signals coming from their various different senses, such as vision, audition, touch, olfaction, and taste, in order to generate a coherent multisensory perceptual representation of the external world (e.g., see the chapters in Calvert, Spence, & Stein, 2004). Linking back to the limited capacity of human information processing, interference or bottlenecks in attention could therefore occur at at least two different stages, specifically, at a modality-specific level and/or a crossmodal level that is shared across different sensory modalities (as well as at perceptual; see Lavie, 2005, and at the response selection stages; see Levy, Pashler, & Boer, 2006; Pashler, 1991).

1.3 Crossmodal links in spatial attention

Recent laboratory-based research has provided extensive evidence for the existence of robust crossmodal links in spatial attention between different sensory modalities (see Spence & Driver, 2004, for a recent review). In particular, research suggests that the efficiency of human multisensory information processing can be enhanced by presenting relevant information to the different senses from approximately the same spatial location (see Driver & Spence, 2004). This suggests that it may be harder to selectively attend to one sensory signal if a concurrent signal coming from another sensory modality is presented from approximately the same location. This also implies that it may be harder to ignore a sensory signal if it is presented at (or near) the current focus of a person's spatial attention.

Crossmodal links in spatial attention have been found between all possible combinations of auditory, visual, and tactile stimuli (Spence & Driver, 2004). These links in spatial attention have been demonstrated to influence both exogenous and endogenous attentional orienting (see Klein, 2004; Klein & Shore, 2000; Posner, 1980). Exogenous orienting refers to a stimulus-driven bottom-up shift of attention whereby reflexive orienting occurred as a result of external stimulation, while endogenous orienting refers to a voluntary shift of attention driven internally by top-down control. Research suggests that independent mechanisms may control these two kinds of attentional orienting (e.g., Berger, Henik, & Rafal, 2005; Hopfinger & West, 2006; Klein & Shore, 2000; Spence & Driver, 2004).

The existence of such crossmodal links in spatial attention may have a number of consequences for interface design, an area that has seen a rapid growth of research interest over recent years (e.g., see Oviatt, 1999, 2002; Oviatt, DeAngeli, & Kuhn, 1997; Spence & Driver, 1997b). For instance, Oviatt (1999) suggested that users may be more inclined to interact multimodally with spatial applications, such as dynamic map systems, when given the option to choose between, for example, speech input, pen input, or both, rather than being forced to use a strictly unimodal input. Traditional modality-specific accounts of information processing (e.g., Wickens, 1980, 1984, 1991; see also Kieras & Meyer, 1997) have typically proved inadequate in accounting for such user preferences for integrating inputs and outputs from multiple sensory modalities. As described earlier, the modality-specific view assumes separate attentional resources for the processing of auditory, visual, and tactile information (see also Duncan, Martens, & Ward, 1997). When the input and output are handled by different sensory modalities, coordination (switching) between the different modalities may therefore be costly (e.g., Spence, Nicholls, & Driver, 2001b), and thus

less efficient than in the case where a common multisensory attentional resource account is assumed. Indeed, the evidence now suggests that auditory and visual spatial attention do not represent separate resources but are instead linked (see Driver & Spence, 2004, for a review). Research into the design of multisensory interface systems may therefore offer the potential to enhance the efficiency of human-computer interaction in a variety of spatial application domains (e.g., Oviatt, 1999; Spence & Driver, 1997b).

1.4 Current approaches to auditory warning signal design

Over the years, a number of different approaches to the design of effective warning signals have been proposed. These include the use of spatially-localized auditory warning signals (e.g., Begault, 1993, 1994; Bliss & Acton, 2003; Bronkhorst, Veltman, & van Breda, 1996; Campbell et al., 1996; Humphrey, 1952; Lee, Gore, & Campbell, 1999), the use of multisensory warning signals (e.g., Hirst & Graham, 1997; Kenny, Anthony, Charissis, Darawish, & Keir, 2004; Mariani, 2001; Mowbray & Gebhard, 1961; Selcon, Taylor, & McKenna, 1995; Spence & Driver, 1999; see also Haas, 1995), and the use of synthetic warning signals (known as auditory earcons; e.g., Lucas, 1995; McKeown & Isherwood, in press) that have been artificially-engineered to deliver a certain degree of perceived urgency.

To date, these approaches have met with mixed success (see Lee et al., 1999; cf. Rodway, 2005): For example, researchers have found that people often find it difficult to localize auditory warning signals, especially when they are presented in enclosed spaces such as inside a car, hence often negating any benefit associated with the spatial attributes of the warning sound (see Bliss & Acton, 2003). Meanwhile,

other researchers have reported favourably on the potential use of directional sounds in confined spaces (e.g., Cabrera, Ferguson, & Laing, 2005; Catchpole, McKeown, & Withington, 2004).

Moreover, it often takes time for interface operators to learn the arbitrary association between a particular auditory earcon and the appropriate response, as the perceived urgency is transmitted by the physical characteristics of the warning signal itself (such as the rate of presentation, the fundamental frequency of the sound, and/or its loudness, etc.; e.g., Edworthy, Loxley, & Dennis, 1991; Graham, 1999; Haas & Casali, 1995; Haas & Edworthy, 1996). It would therefore appear that unless auditory earcons are associated with intuitive responses (Graham, 1999; Lucas, 1995), they should not be used in dangerous situations to which an interface operator may only rarely be exposed, since he/she may fail to recall the appropriate actions immediately (see also Guillaume, Pellieux, Chastres, & Drake, 2003).

Given these limitations on the use of traditional warning signals, a number of researchers have attempted to investigate whether auditory icons (i.e., sounds that imitate real-world events; Gaver, 1986) might provide more effective warning signals, the thinking being that they should inherently convey the meaning of the events that they are meant to signify (e.g., Blattner, Sumikawa, & Greenberg, 1989; Gaver, 1989; Gaver, Smith, & O'Shea, 1991; Lazarus & Höge, 1986; McKeown, 2005). Over the years, the effectiveness of a variety of different 'urgent' warning sounds have been evaluated in terms of their ability to capture attention, and perhaps more importantly, to elicit the appropriate behavioural responses from an interface operator (e.g., see Deatherage, 1972; Oyer & Hardick, 1963).

Auditory icons have the advantage over auditory earcons in that their meaning should be more immediately apparent to an interface operator and so people should

require less time in order to learn the appropriate behavioural responses to such signals (e.g., Begault, 1994; Lucas, 1995). However, while research has shown that people do indeed tend to respond more rapidly to auditory warning signals as the perceived level of urgency increases (e.g., Burt, Bartolome, Burdette, & Comstock, 1995; Haas & Casali, 1995), the use of urgent auditory icons is not without its problems. For example, while the screeching car tyre and car horn sounds used in a study reported by Graham (1999) elicited faster responses by drivers than the more typical tonal alert or verbal warning signals, the presentation of these auditory icons also resulted in participants making more inappropriate responses than following the tonal or verbal alerts. It would appear therefore that highly urgent signals may elicit such rapid responses that interface operators can end up responding to the warning signal before they have had sufficient time to evaluate the situation properly in order to know what the most appropriate response would have been (see Bliss & Acton, 2003; Graham, 1999). Furthermore, the empirical evidence to date does not provide unequivocal support for the claim that auditory icons necessarily make particularly effective urgent warning signals.

The use of urgent auditory alarm icons may be further limited by the fact that auditory icons that are perceived as conveying a high degree of urgency are also likely to be perceived as unpleasant (McKeown & Isherwood, in press; see also Oyer & Hardick, 1963). For example, in one recent study, McKeown and Isherwood assessed the perceived unpleasantness of twenty different environmental sounds and found a high correlation between the perceived urgency of the sounds and how unpleasant people rated them. Therefore, while the approach of trying to develop auditory warning signals that elicit an intuitive response from drivers seems like a good one, the fundamental problem appears to be that any sound that is perceived by users as

urgent will most likely also be judged as unpleasant, and thus is unlikely to be accepted by the end user of an interface (see McKeown & Isherwood, in press; cf. Lazarus & Höge, 1986).

One interesting class of auditory warning signals is constituted by speech warnings. Verbal warning signals have the advantage that minimal training is required in order for an operator who understands the language to comprehend and act upon them efficiently (see Edworthy & Hellier, 2006; cf. Bruce, et al., 2000; Simpson, McCauley, Roland, Ruth, & Williges, 1987). As suggested by Edworthy and Hellier in their comprehensive recent review of complex auditory warnings, the intelligibility of speech warnings as perceived by listeners can be affected by the environment. Given that while driving, a person may be involved in other concurrent speech tasks such as conversing with the passenger or on the mobile phone, and/or listening to the radio (see Ramsey & Simmons, 1993), the utility of in-car speech warnings (particularly directional signals such as those given by navigation systems) may be somewhat limited (see Strayer & Johnston, 2001). Note also the limited utility of such warning signals for drivers whose first language happens to be different from the one in which the warning signal is presented.

With respect to the timing of warning signal presentation, McGehee et al. (2002) assessed the effectiveness of presenting auditory signals to warn distracted drivers of an impending collision with a stationary vehicle on the road ahead in a driving simulator study. They found that the presentation of an 'advance' auditory warning signal facilitated driver responses relative to either a 'late' warning signal (giving only 1 s, as opposed to 1.5 s, advance warning), or else to a no warning signal baseline condition. The performance facilitation reported in their study included shorter accelerator release times and fewer, and less severe, crashes. While results

such as these highlight the potential benefits of presenting auditory warning signals to enhance the situation awareness of drivers, it is important to note that a number of potential limitations have also been identified with the presentation of 'early' warning signals. For instance, although an early warning signal would allow the driver more time to prepare and execute the appropriate behavioural response, research has shown that the more advance notice a warning signal provides to an interface operator of a potentially-dangerous upcoming event, the more likely it is that the signal will be classified as a false alarm (McGehee et al., 2002; Parasuraman, Hancock, Olofinboba, 1997; Shinar, 1978). What's more, as soon as the false alarm rate for a warning signal becomes too high, interface operators may perceive it as a nuisance and start to ignore it. Thus, the danger is that interface operators may become desensitized to future warning signals (see Bliss & Acton, 2003; Breznitz, 1984). As Sorkin (1988) notes, some interface operators may even go so far as to try and disable alarm signals that they consider to be too distracting or aversive (see also King & Corso, 1993). Thus, it is important for the collision warning signal to intervene at the appropriate moment in time (the question of what constitutes the appropriate moment, of course, being an area for further research).

1.5 Collision avoidance in driving

A two-second gap between a driven vehicle and a lead vehicle is recommended in the United Kingdom (Driving Standards Agency, 2004) in order to allow sufficient time for a car to stop in the case of an emergency. This minimum time-to-collision estimate has been broken down into 'thinking distance' (i.e., perceptual) and 'braking distance' (i.e., motor response). A review by Hills (1980)

suggested that the 'thinking distance' required to brake while driving a car corresponds to a response time (RT) of 700 ms following the onset of a critical event (see also Campbell et al., 1996; Rockwell, 1988). This two-second rule has often been criticized as being inadequate to account for the majority of drivers, with researchers arguing that the 85th percentile driver would require a standard of 3.2 s for event perception and braking reaction (see Dewar, 1988). Some researchers have even reported that 70% of drivers involved in front-to-rear-end accidents failed to stop a car when the lead vehicle had stopped some 2-6 s prior to the crash incident (see Horowitz & Dingus, 1992).

Further, in a meta-analysis of braking RT studies, Green (2000) reported a RT of 700 ms for a fully-expected event and a RT of 1.5 s for an unexpected event. In his analysis, he decomposed the total perception-brake RT into three major components, specifically, mental processing time (a combination of sensation, perception, and response selection and programming), movement time, and device RT. While device RT is clearly a technological problem, movement time (i.e., lifting the foot off the accelerator pedal to depress the brake pedal) can possibly be improved by training. For instance, according to Schneider and Shiffrin (1977), one could be trained to produce 'automatic' responses, although that might require considerable amounts of consistent training. Thus, the key question in warning signal design is concerned with speeding up the mental processing time of drivers (i.e., at the perceptual and decisional stages of human information processing).

1.6 Recent developments in tactile warning signal design

In addition to the traditional visual and auditory interface design, 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., Gilliland & Schlegel, 1994; Rupert, 2000b; van Erp & van Veen, 2004; Wood, 1998; Zlotnik, 1988). The communication of information by touch has been successfully demonstrated in a number of different areas, such as in the aerospace domain, where the potential of vibrotactile displays has been shown in terms of their function in assisting spatial orientation of pilots and astronauts (e.g., Rochlis & Newman, 2000; Rupert, Guedry, & Reschke, 1994). For instance, Rochlis and Newman 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 pilot a helicopter successfully, or to drive a high speed rigid inflatable boat in a waypoint navigation task. It should be noted that despite these applied research efforts, no such systems are currently in place in aeroplanes. Therefore, the automobile industry may represent a more pragmatic application domain (i.e., one less constrained by industrial standardization and regulatory control) where innovation may be easier to get through design process.

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 (i.e., 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 suggesting a reduced subjective workload on the part of drivers when using tactile instead of visual navigation displays. However, although their participants responded more rapidly to bimodal navigational messages than to unimodal tactile messages, and vice versa in their other study (van Erp & van Veen, 2001), statistical analyses of their data failed to reach statistical significance. Overall, these findings therefore suggest 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 with vibrating functions have already been implemented in several recently released models of car, such as Jaguar's touch display for radio station control and 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; taken to indicate that the driver may have fallen asleep at the wheel). However, limited published 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. In particular, although the effects of tactile stimulation have been investigated on a wide array of different

body parts, such as stimuli presented to the torso (e.g., Linderman, Yanagida, Sibert, & Lavine, 2003), head (e.g., Gilliland & Schlegel, 1994), hands (e.g., Burke et al., 1980; Jagacinski, Miller, & Gilson, 1979; Vitense, Jacko, & Emery, 2003), wrists (e.g., Sklar & Sarter, 1999), buttocks (e.g., Lee et al., 2004; McGehee & Raby, 2003), and feet (e.g., Godthelp & Schumann, 1993; Janssen & Nilsson, 1993; Janssen & Thomas, 1997), no one has yet attempted to systematically examine the relationship between the body site stimulated and the nature of the task being performed. Thus, it is uncertain whether tactile stimulation, regardless of the body part being stimulated, will necessarily result in the same degree of improvement on a particular task. Note though that research on stimulus-response compatibility effects suggests that there may, in fact, be important synergies between the stimulation of particular body parts and specific task requirements (e.g., see Fitts & Seeger, 1953; Kantowitz, Triggs, & Barnes, 1990; Proctor, Tan, Vu, Gray, & Spence, 2005). It is also interesting to mention at this point that it remains an open question as to whether tactile icons ('tactons') exist (see Brewster & Brown, 2004; Brown, Brewster, & Purchase, 2005), as they might potentially provide a whole new spectrum of possibilities for interface designers in terms of the artificially engineering of complex messages to convey information to users via the sense of touch.

Several studies have explicitly assessed the utility of vibrotactile cues in simulated driving scenarios. For example, Janssen and Thomas (1997) reported that increasing the counterforce (i.e., combined proprioceptive and tactile cuing) on the accelerator pedal had beneficial effects in a collision avoidance system (see also Janssen & Nilsson, 1993; Tijerina, Johnston, Parmer, Pham, Winterbottom, & Barickman, 2000). On the other hand, Schumann, Godthelp, Farber, and Wontorra (1993) contrasted various different kinds of tactile feedback to auditory warnings as a

means of signalling to drivers whether to remain in lane when passing manoeuvres. They found that drivers were more responsive to tactile or proprioceptive cues, such as steering wheel vibrations or force feedback cues resisting the driver's control input to change lanes, as compared to auditory warnings. Lee et al. (2004) also compared the effectiveness of auditory and haptic collision warnings presented either in a graded or single-staged manner on drivers' braking performance. Their results showed that haptic warnings were judged as being less annoying, and that graded haptic alerts presented via a vibrating seat seemed to be particularly effective in providing a greater margin of driver safety.

1.7 Critical factors for effective collision warning signal design

It is important to note that it will not be sufficient for future driver warning signals simply to be optimized for their ability to capture a driver's attention (Spence, 2001). Instead, they must also be optimized for (i.e., compatible with) the most appropriate driver response in any given situation. Typically, psychologists and other research scientists tend to divide behavioural phenomena into their perceptual, decisional, and response-related sub-components (e.g., see Kantowitz et al., 1990; Proctor et al., 2005; Spence, 2001). The future design of multisensory warning signals should therefore be optimized to elicit the most effective response by combining an understanding of the different brain pathways involved in multisensory information processing and the particular combinations of multisensory signals that are most appropriate for specific classes of actions (e.g., for braking, accelerating, mirror checking, turning, etc.). This means that designers have to combine the available

knowledge regarding each of the sub-processes involved in multisensory attention, event perception, response selection, and response execution.

Taken together, the existing evidence from both behavioural and neuroscience studies suggests the possibility of applying the insights gained from recent studies of crossmodal links in spatial attention to the design of applied multisensory interfaces (e.g., Spence & Driver, 1997b, 1999). In particular, one of the central aims of this thesis was to investigate the role of spatial attention in the domain of developing more ergonomic multisensory warning signals for car drivers (i.e., to try and develop signals that elicit more efficient and effective responses from car drivers). With respect to the issue of intermodality transfer, given that it has been argued that driving is predominantly visual (cf. Sivak, 1996), it is important to examine whether the use of non-visual warning signals is effective in orienting visual attention to the appropriate location. This thesis also attempts to investigate the stage(s) in information processing at which the facilitatory effects elicited by such spatial multisensory warning signals occur. It is particularly important to examine the relative improvements in information processing at the perceptual, decisional, and/or motor response levels, in order to understand the underlying causes of any performance enhancement that is documented.

The structure of the subsequent chapters in this thesis is as follows: Chapter 2 investigates the relative effectiveness of the presentation of various spatial auditory warning signals to alert drivers to potential time-critical events, in particular, the cuing of driver attention in the front-back dimension. Note that the space behind a driver is typically inspected indirectly by the driver via the rearview mirror (i.e., by 'looking' forward); Chapter 3 focuses specifically on word cues and examines the effect of directional verbal cues on the spatial distribution of an interface operator's

attention; Chapter 4 examines the effectiveness of spatial vibrotactile cues as collision warning signals in driving both in a laboratory-based set-up and in a high-fidelity driving simulator; Chapter 5 examines the relative contributions of the various possible mechanisms (i.e., perceptual and/or decisional) underlying the spatial cuing effects reported in Chapters 2 and 4; The experiments reported in Chapter 6 investigate the potential for olfactory cuing, in particular, by assessing the effects of peppermint, lavender, and cinnamon odours on dual-task performance in a laboratory setting; and finally, Chapter 7 highlights the findings and future direction for multisensory interface research. The Appendix details the results of an independent series of experiments conducted in association with Prof. Hong Tan (Purdue University, USA) looking at multisensory integration in a virtual haptic environment.

CHAPTER 2

AUDITORY SPATIAL CUING IN DRIVING

Spence and Read (2003) recently investigated the consequences of crossmodal links in endogenous spatial attention between audition and vision under complex experimental conditions. Participants in their study had to shadow (i.e., repeat aloud) triplets of two-syllable words presented from one of two loudspeaker cones placed either in front, or from the side, while trying to ignore an irrelevant speech stream presented from an intermediate location. At the same time, the participants had to drive around suburban and inner-city roads on a fixed-base driving simulator. The results showed that participants found it easier to shadow the words presented from the front rather than from the side even in trials when they did not have to perform the driving task (illustrating the so-called frontal speech advantage, e.g., Hublet, Morais, & Bertelson, 1976, 1977). This spatial effect was found to be more pronounced when participants were simultaneously engaged in a demanding driving task (i.e., when the perceptual load of the participant's task was high; Lavie, 2005; Rees & Lavie, 2001). Spence and Read's results therefore suggest that when people have to attend to multiple sources of information at the same time, it can be advantageous to present the various sources of input to the different sensory modalities from the same, rather than from different, spatial locations (see also Spence & Driver, 1997b; though see Soto-Faraco, Morein-Zamir, & Kingstone, 2005).

In their recent review of crossmodal links in exogenous spatial attention, Spence, McDonald, and Driver (2004) highlighted the extensive evidence documenting the influence of spatially-nonpredictive auditory cues on visual target discrimination performance, and vice versa, from both behavioural and electrophysiological studies. Taken together, the available evidence now supports the view that performance on a variety of visual tasks can be facilitated by the presentation of an auditory cue from the same location shortly beforehand. Given that auditory cues can be used to exogenously capture a participant's visual attention in the laboratory, it seems plausible to apply such insights in the context of multisensory interface design, for instance, in the domain of developing maximally-effective warning signals for car drivers (e.g., Spence & Driver, 1999).

Begault (1993) reported one of the few studies to have investigated the potential utility of using spatially-localized auditory warning signals to attract visual attention in an applied setting. The spoken advisory warning alert 'traffic, traffic' was presented over a 3-dimensional head-up auditory warning display (typically used by flight crews) to pilots. These spatial auditory cues were presented from one of seven possible visual locations that predicted (with 100% validity) the direction from which targets would appear in a visual search task presented through a cockpit window. Visual search times were significantly faster (by a magnitude of 2200 ms), and no less accurate, when spatial auditory cues were used, as compared to the performance seen when nonspatial auditory cues (presented to one ear to a control group of participants via a headset) were used. Interestingly, the facilitation of visual search times for spatial relative to nonspatial auditory cues was much larger than that typically seen in laboratory studies of crossmodal cuing (e.g., see Spence et al., 2004), and could potentially be critical for an aircraft pilot attempting to avoid an approaching object,

such as another aircraft or a flock of birds. Begault's results therefore demonstrate that the crossmodal orienting of visual spatial attention elicited by the presentation of an auditory cue can also influence visual performance in an applied setting.

Consistent with Begault's (1993) findings, Perrott, Sadralodabai, Saberi, and Strybel (1991) also demonstrated a performance enhancement for participants in a visual search task when aided by a spatially correlated auditory cue (a 10 Hz click train). They found that the advantage was more pronounced (a facilitation of 200 ms in response latency) when the visual targets were presented in the periphery, although it was still present for targets presented from closer to fixation (where a 10-25 ms advantage was seen). Perrott et al. suggested that acoustic events might serve to orient the gaze of a person engaged in a different task. That is, they might lead to a crossmodal shift of overt[2.1] (and presumably also covert) spatial attention (see also Perrott, Saberi, Brown, & Strybel, 1990). In another similar visual search study, the relative effectiveness of 2- and 3-dimensional auditory spatial cues and 2-dimensional visual cues were compared to a baseline condition of unaided (i.e., uncued) visual search (Perrott, Cisneros, McKinley, & D'Angelo, 1996). Once again, auditory spatial cues were found to be particularly effective in aiding visual search performance (even more effective, in fact, than visual cues).

The studies described thus far clearly demonstrate the potential benefits for interface design that may come from exploiting exogenous and/or endogenous crossmodal links in spatial attention between audition and vision (and presumably other modalities, such as touch, as well; see Chapter 4). However, it is unclear whether the facilitatory effects from the use of spatially-predictive auditory warning

[2.1] Overt orienting refers to a shift of attention associated with eye and/or head movements that are observable, while covert orienting refers to a shift of attention in the absence of any of such physical movements, meaning that the shift cannot be directly observed by an external observer (see Klein, 2004).

cues reported in these earlier studies (e.g., in the studies of Begault, 1993; Perrott et al., 1990, 1991, 1996) reflect the consequences of crossmodal links in exogenous orienting, crossmodal links in endogenous orienting, or perhaps more likely, some unknown combination of the two effects (see Spence, 2001). One of the primary aims of the experiments reported in this chapter was therefore to try and quantify the benefits of using exogenous, endogenous, and combined exogenous plus endogenous auditory spatial cuing on visual task performance in a complex visual environment involving a simulated driving task. In particular, the five experiments reported in this chapter were designed to investigate whether the location and/or informational content of auditory warning signals could be used to facilitate the detection of potential emergency situations seen in the rearview mirror and/or from the front in a driving situation.

2.1 Methodological considerations

Given that the auditory cues used in most auditory spatial cuing studies published to date (e.g., pure tones or white noise bursts; see Spence et al., 2004) are not associated with any particular semantic meaning, they may be inappropriate for use in more realistic situations in which various different (often semantically-meaningful) sounds are frequently designed to convey independent messages and which may simultaneously compete for an interface operator's attention (cf. Shinn-Cunningham & Ihlefeld, 2004). Therefore, in Experiment 1, the sound of a car horn was chosen in order to assess its effectiveness in attracting a driver's attention (cf. Oyer & Hardick, 1963). A car horn sound was chosen instead of any other arbitrary auditory cue sound because, as reported by Graham (1999), the use of auditory icons

that are analogous to everyday events can be comprehended more quickly and easily than can abstract sounds, such as white noise bursts or pure tones. That is, the sound of a car horn carries an inherent meaning (understood by some participants in Experiment 1 to be mirror-checking) as well as a perceived urgency (see also Edworthy et al., 1991). (In this regard, one might wonder whether car horn sounds are in some sense inherently symbolic cues, a point that will be discussed later.)

In an attempt to simulate an attention-demanding situation, a rapid serial visual presentation (RSVP) task was chosen, consisting of a continuous stream of distractor letters with target digits embedded periodically within it. The RSVP task has been used extensively in laboratory-based dual-task attention research to maintain the cognitive load on participants (e.g., Soto-Faraco & Spence, 2002), and to measure the temporal distribution of attention under conditions of task-switching (e.g., Allport & Hsieh, 2001; Klein & Dick, 2002). Given that the main goal of the experiments reported in this chapter was to assess the effectiveness of various types of auditory cues to alert a driver of an event occurring at an unattended location, the location at which the RSVP stimuli was presented served as the attended location at which the participants' attention was primarily engaged. The RSVP task was used to model a continuously and uniformly highly attention-demanding situation (see Shapiro, 2001) such as when the visual load of a driver's attention is concentrated toward the front (Burnett & Joyner, 1997; Lansdown, 2002).[2.2]

[2.2] In pilot testing for this thesis, the possibility of using driving video games as a closer approximation to real driving than the RSVP task was investigated. However, it was found that the variations in cognitive load during game playing (and gaming experience of participants) were too great for present purposes. For the purpose of the present research, a good model system that consistently engaged the attention of participants so that a whole array of different frequently-occurring warning signals could be tested was needed. Moreover, once the potentially effective signals were narrowed down, they would be tested in later experiments using a more realistic setting (i.e., in a driving simulator environment; see Experiment 10). Again, once the optimal warning signals were found, it would be necessary to start reducing the incidence of critical driving events to check whether beneficial effects of the presentation of warning signal still hold.

According to Graham (1999), the sound of a car horn does not necessarily have any inherent association with dangerous driving situations, which might, for example, be implicit in the sound of skidding tires. Instead, the car horn sound is typically understood by drivers simply as indicating the presence of another vehicle in the vicinity (cf. Edworthy & Hellier, 2006). Experiment 1 was designed to assess whether the very presence of a car horn sound might lead to a general alerting effect in drivers. The effectiveness of this nonspatial-nonpredictive auditory cue, which was always presented from the same spatial location directly under the participant's seat, in alerting/redirecting visual attention served as a baseline measurement for comparisons with subsequent experiments in which spatial auditory cues were used. These auditory cues were spatial in the sense that the cues coincided with, or predicted, the direction of the target visual driving events on a certain percentage of these trials. It was hypothesized that the spatially-neutral cue might act as a nonspatial alerting signal (see Posner, 1978; Zeigler, Graham, & Hackley, 2001), that would result in a general facilitation of response latencies in the visually-mediated driving task.

In order to examine any crossmodal facilitation effects of auditory car horn sounds on visual attention, a second experiment was conducted in which spatially-nonpredictive car horn sounds were presented to orient participants' attention to subsequent visual driving events presented from in front versus from behind (and seen via a rearview mirror). The spatial auditory cue was spatially-nonpredictive in that it came from the (relevant) direction of the target visual driving event on 50% of the trials, and from the inappropriate (i.e., opposite) direction on the remaining 50% of the trials. Experiment 3 investigated whether the effectiveness of such spatial auditory cues would be enhanced if their occurrence was made predictive of the likely location

of any subsequent critical visual events. Specifically, the direction of the car horn sound predicted the correct location of the critical visual event on 80% of the trials. It was hypothesized that the magnitude of any interaction between the relative locations of the auditory and visual stimuli would be more pronounced in Experiment 3 than in Experiment 2, as the presentation of the auditory cues should elicit both an exogenous and an endogenous shift of spatial attention in the cued direction (see Spence & Driver, 1994, 1997a, 2004). Experiment 4 was designed to investigate the relative efficacy of the semantic component of symbolic spatial verbal instructions ('front' and 'back') in orienting spatial attention when they were predictive of the likely critical driving event. Finally, Experiment 5 examined the effectiveness of redundant (or integrated) spatial cues by presenting the symbolic spatial verbal instructions used in Experiment 4 from the appropriate spatial locations (i.e., the word 'front' from the front, and the word 'back' from the rear).

2.2 Experiment 1

2.2.1 Methods

2.2.1.1 Participants

Twelve participants (mean age of 19 years, age range from 18-20 years; 4 males and 8 females) took part in Experiment 1. All of the participants reported normal hearing and normal, or corrected-to-normal, vision. The average driving experience of the participants was 1.7 years (range from 4 months to 3 years). All of the participants were right-handed by self-report. The experiment lasted for

approximately 60 min. The participants received course credit for their participation. The experiments were conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford.

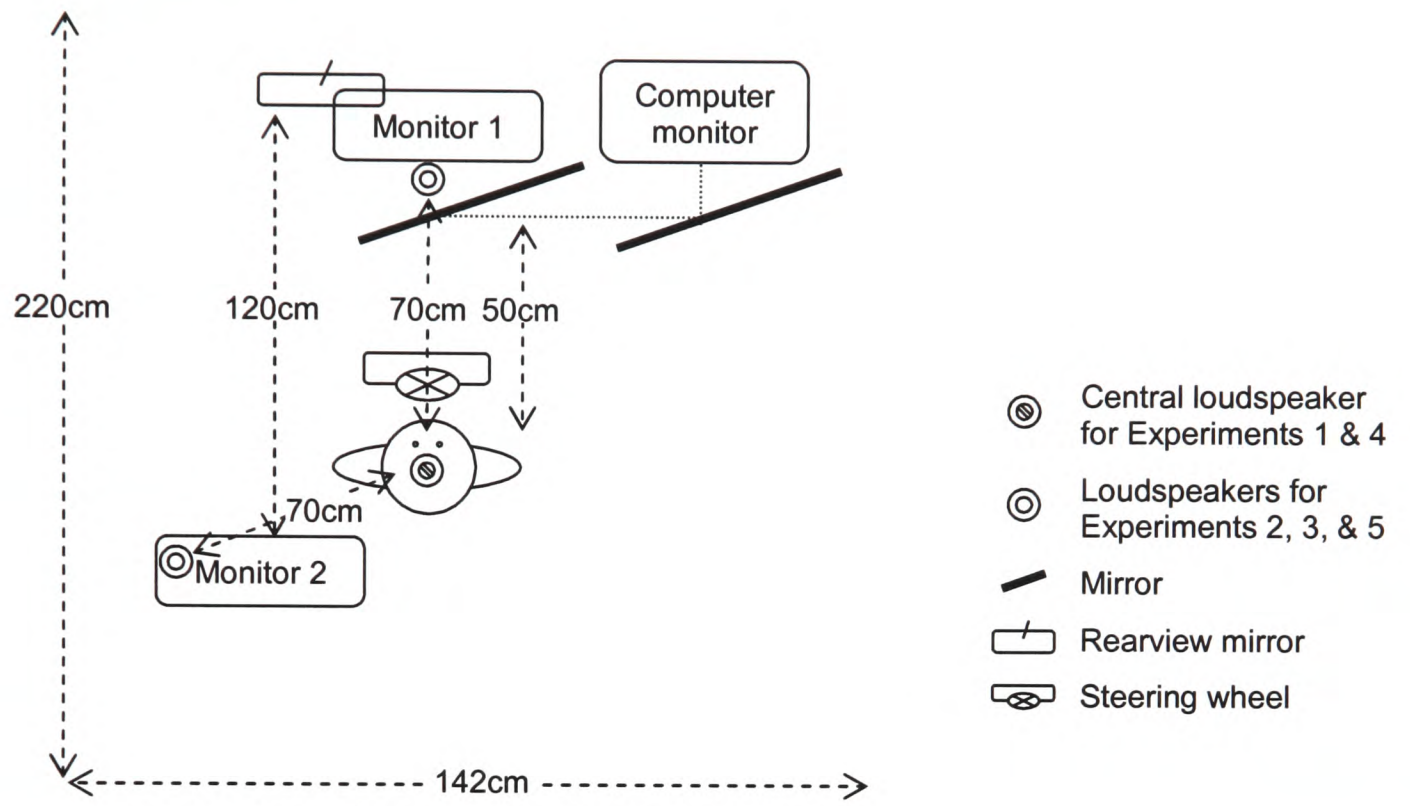
2.2.1.2 Apparatus and materials

The experiment was conducted in a 220 x 142 cm experimental booth. The participants were seated in the centre of the room and were instructed to hold a Logitech® MOMO® Racing Force Feedback Wheel (Logitech Inc., Fermont, CA) 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 stimuli in the RSVP task (see Figure 2.1). A monitor showing a video image taken through a car windscreen was also positioned 70 cm in front of the participants. A car rearview mirror (6 x 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. A loudspeaker cone was positioned directly below the participant's chair, thus eliminating any exogenous cuing effects that might have been associated with the spatial location from which the cue sound itself was presented (Spence & Driver, 1994).

The RSVP distractor set consisted of 17 letters (B, C, D, E, F, J, K, L, M, N, P, R, S, T, X, Y, and Z) while the target set consisted of six digits (2, 3, 4, 5, 6, and 9; cf. Soto-Faraco & Spence, 2002). A computer monitor, occluded from the direct view of the participants, was used to present the stimuli in the RSVP stream. 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 Figure 2.1). The RSVP characters were 8.3 x 8.5 mm in size on the mirror as seen by the participants.

(a)



(b)

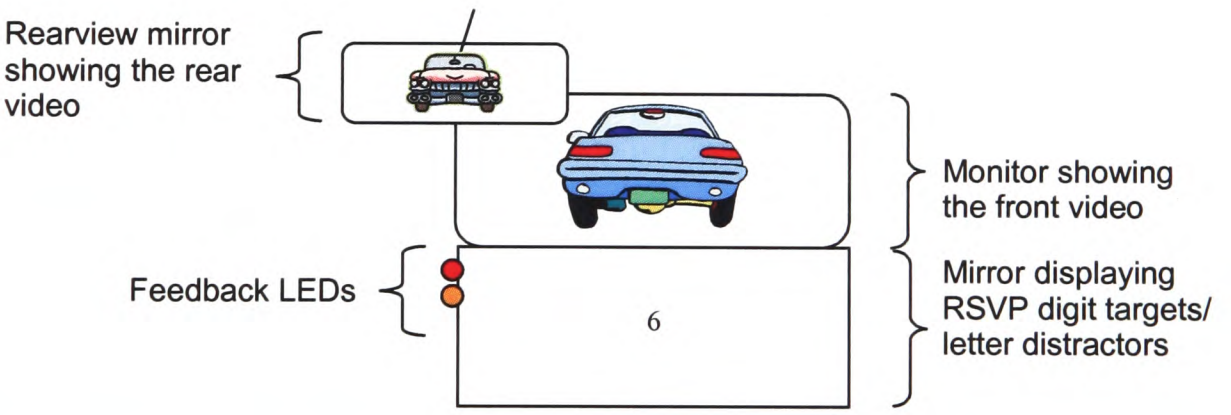


Figure 2.1 (a) Schematic bird's-eye view and (b) participant's-eye view of the experimental set-up used in Experiments 1-5.

The video clips were recorded in a countryside area in rural Oxfordshire, England. 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 mounted) toward the car in front at approximately 100 km/h, or the sudden rapid approach by the car behind. The noncritical clips included the car in front moving away at the normal speed (i.e., 50 km/h) or the car behind retreating (see Figure 2.2 for samples of stills taken from the video clips). Two critical and two noncritical clips were created. The sound of a real car horn (600 ms duration; 8000 Hz; 66 dB(A)) downloaded from the Internet (retrieved from http://www.a1freesoundeffects.com/carhornshort.wav; downloaded on 28-11-2003) was used as the auditory cue in Experiment 1. A red light-emitting diode (LED) was placed on the mirror directly in front of the participants to provide them with feedback whenever they made an incorrect response in the driving task (see Figure 2.1b). An amber LED placed directly below the red LED was illuminated whenever a participant failed to keep the accelerator pedal depressed appropriately during the experiment.

2.2.1.3 Design

The experimental session consisted of eight blocks that lasted for 6 min each. The RSVP stimuli consisted of a continuous stream of distractor letters with target digits periodically embedded within it. 66 targets were presented in each block in the RSVP task with each of the six target digits being presented eleven times in total. 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 (the screen refresh rate was 75 Hz, i.e., 13⅓ ms per frame). The temporal gap between successive target digits in the RSVP stream was in the range of 2040-6360 ms.

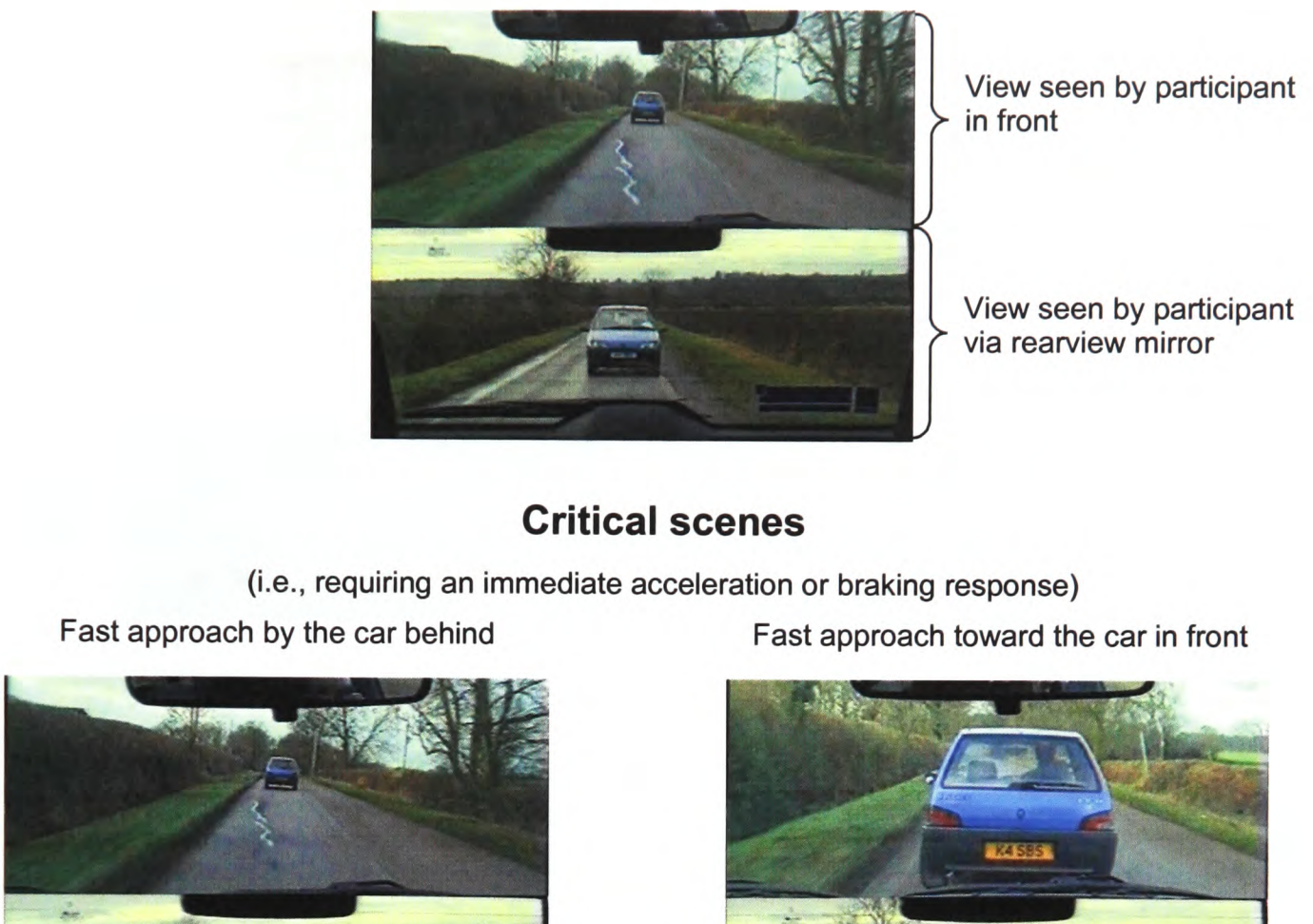


Figure 2.2 Simple video stills taken from the video clips used in Experiments 1-5. The upper half of each still shows the view of the windscreen seen directly in front of participants, whereas the lower half shows the rear view seen by the participants in the rearview mirror. Note that in the experiment itself, the participants only saw the upper half of the video from the front and the lower half of the video from behind via the rearview mirror.

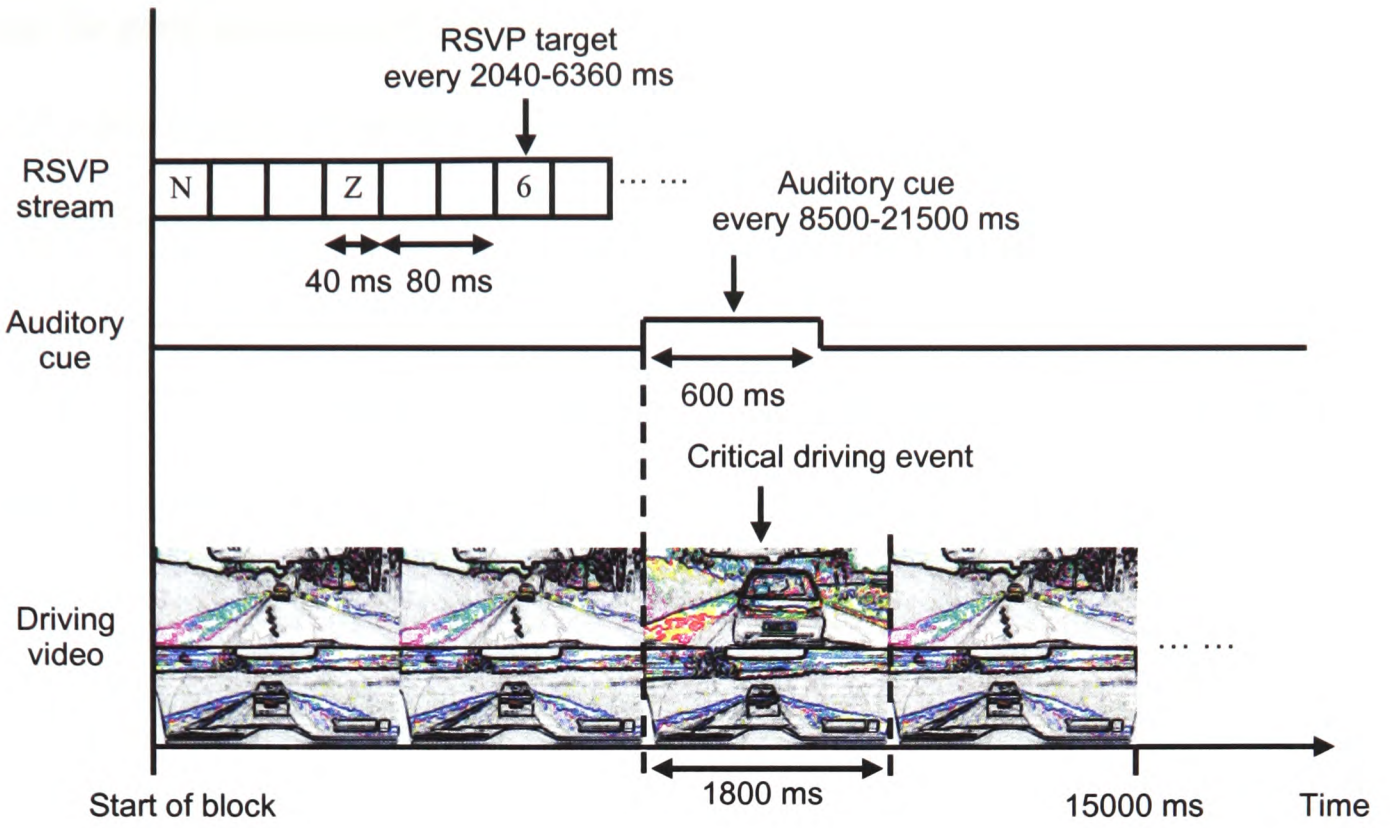


Figure 2.3 A schematic timeline showing the temporal sequence of events in Experiments 1-5.

For the driving task, 24 randomized scenarios were presented in each experimental block. In a given experimental block, each of the two critical driving scenarios was presented ten times, with each of the two noncritical driving scenarios being presented twice (i.e., the ratio of critical to noncritical trials was 83:17). Each scenario consisted of a 15000 ms video clip together with an auditory cue. The onset of the auditory cue coincided with either 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 point the two cars would have collided), or in the case of a noncritical driving event, the initiation of an increase in the inter-car distance (see Figure 2.3). The temporal gap between successive auditory cues was 8500-21500 ms. Each scenario transited to the next one with fade-out and fade-in effects (using Adobe® Premiere® 6.0; Adobe Systems Incorporated, San Jose, CA), and all transitions began and ended with the same clip of the car in front and the car from behind at a constant distance. Editing was performed in order to ensure that the transitions were not noticeable and

that the participants could not anticipate the critical events in the driving clips. In total over a participant's experimental session, there were 528 targets in the RSVP task and 192 driving trials (i.e., 160 critical and 32 noncritical trials).

The participants were given two practice blocks in which to familiarize themselves with the experimental set-up and the operation of the response pedals. In the first practice 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. 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 following the presentation of each target being reduced by 1 ms throughout the practice block, 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). The stimulus timings used in the second practice block were the same as those used in the subsequent experimental blocks.

2.2.1.4 Procedure

The participants responded to targets in the RSVP task by pressing the right paddle shifter on the steering wheel. For the driving task, they were instructed to keep the accelerator depressed slightly throughout the experiment in order to model realistic driving conditions. The amber LED placed directly in front of the participants was illuminated whenever the accelerator was depressed inappropriately. When the participants detected a car approaching rapidly from behind (following the presentation of an auditory cue), they were instructed to accelerate by pressing the accelerator all the way down to the floor with their right foot. By contrast, when the participants detected that they were rapidly approaching the car in front, they were

instructed to brake by pressing the brake pedal with their left foot instead. (This design was chosen to avoid the possible noise in the data that would have been introduced by participants having to move their right foot from the accelerator to depress the brake pedal, though see van Winsum & Brouwer, 1997; van Winsum & Heino, 1996. Given that the majority of cars in the UK have manual transmission, and that drivers normally use their right foot to operate the brake and accelerator, and their left foot for the clutch, the participants were familiar with the need to press down on the clutch pedal with their left foot during emergency braking.) For noncritical trials, where the video showed the inter-car distance to be increasing, the participants simply had to carry on driving normally without making any specific response (i.e., they were supposed to keep the accelerator depressed).

2.2.2 Results

Table 2.1 shows the mean RT data and the percentages of errors in the driving task in Experiment 1 (together with the data from Experiments 2-5). Trials in which participants made an incorrect response were discarded from the RT analysis. 3.8% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual driving event. (These data were not included in the analysis because no clear dividing 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'.) For a given critical trial in the driving task, only the first response made by a participant after the onset of the visual driving event was considered in the subsequent data analysis. Thus, an error was defined as an incorrect first response made after the onset of the critical visual driving event. Paired comparison *t*-tests were performed on the RT and error data from Experiment 1 in order to compare responses to the front and

rear critical driving events. The results revealed that participants responded significantly more rapidly to critical visual driving events occurring at the front than from the rear, $t(11) = 4.9$, $p < .001$. The error data, however, showed no significant difference between the front and rear, $t(11) = 0.2$, $p = .85$, suggesting that participants did not make any more mistakes in response to driving events occurring in a particular direction.

Table 2.1 Mean RTs (ms) and percentages of errors (and their standard errors in parentheses) in the driving task as a function of the location of the visual driving event in Experiments 1-5.

				Location of Visual Event			
				Front (windscreen)		Back (rearview mirror)	
Expt	Cue Sound	Cue Type	Cue Validity	RT	% error	RT	% error
1	Car horn	Nonspatial (alerting)	N/A	911 (46)	4.9 (2.2)	1083 (41)	5.1 (1.3)
2	Car horn	Spatial	50%	1115 (56)	5.8 (1.7)	1133 (24)	5.9 (1.5)
3	Car horn	Spatial	80%	970 (32)	4.0 (1.3)	1046 (26)	3.7 (0.7)
4	Verbal directional cues	Symbolic	80%	805 (62)	9.6 (3.7)	985 (43)	7.6 (3.0)
5	Verbal directional cues	Spatial symbolic	80%	780 (32)	10.7 (2.8)	957 (29)	8.5 (3.3)

Performance in the concurrent RSVP task was also measured to ensure that participants performed the central attention-demanding visual task as instructed. Responses occurring 1500 ms or more after the presentation of the target digit were

considered invalid (i.e., they were treated as false alarms). The mean percentage of correct detection responses in the RSVP task was 78.2% (*SE* = 2.6%), with a mean RT of 577 ms (*SE* = 10 ms) and a false alarm rate of 5.1% (*SE* = 1.1%).

2.2.3 Discussion

The results of Experiment 1 provide a baseline measure of the effectiveness of the presentation of a spatially uninformative car horn sound in alerting participants to the fact that they should orient their attention to the visual driving events taking place outside their own car. The faster responses to events occurring from the front of the participants than from the rear were as expected given the smaller distance between the location of the stimuli in the RSVP task to the front monitor than to the rearview mirror, which was situated further to the left of the participants, and that participants' visual attention was focused primarily toward the front.

In real-world driving, the visual attention of a driver is, as in Experiment 1, primarily focused toward the front, with events at the rear typically only monitored by means of rearview and side mirrors (cf. Binkofski et al., 2003; Burnett & Joyner, 1997). Even so, there are blind spots around a vehicle that will fall outside of a driver's sight at any given time. The attention paid to the rear therefore depends, to a great extent, on the frequency with which a driver checks his/her mirrors. In one of the few studies to have been conducted in this area, Brookhuis, de Vries, and de Waard (1991) evaluated the effects of introducing dual-task demands (mobile telephoning) on driving performance. They used mirror-checking as a performance measure to estimate how much attention participants were paying to other traffic. They found that the frequency of mirror checking depended primarily upon the road situation (e.g., on a busy ring-road, less attention was paid to the mirrors as compared

to the situation of driving on a quiet motorway). Interestingly, the dual task demands of telephoning and driving simultaneously did not seem to affect the frequency of mirror checking (i.e., of attention being directed to the rear).

2.3 *Experiment 2*

Given that most drivers have extensive experience of the fact that the rearview mirror represents the space behind their car, an auditory signal from the rear might be expected to facilitate the detection of a critical situation from behind albeit seen from the front via the rearview mirror. This hypothesis was based on the assumptions that: 1) Crossmodal links in exogenous spatial attention between audition and vision can facilitate the appropriate deployment of spatial attention; and 2) There appears to be an automatic and effortless translation between visual events seen in front (but via the rearview mirror) and the awareness of driving events occurring at the rear. No previous study of exogenous crossmodal spatial attention has looked at the representation of the space seen indirectly in a mirror, although there is growing interest in cognitive neuroscience as to how (and whether) attention can be directed to the space seen indirectly via mirror reflection (e.g., Binkofski, Buccino, Dohle, Seitz, & Freund, 1999; Gregory, 1998; Maravita, Spence, Sergent, & Driver, 2002; von Fieandt, 1966). As well as being of applied interest, the results of the experiments reported in this thesis should therefore also inform the understanding of this aspect of spatial representation and cognition.

Experiment 2 was therefore designed to assess the effectiveness of spatially-nonpredictive auditory cues (i.e., indicating the directions of the critical driving events on 50% of the trials). The responses to target driving events occurring in the cued

direction were expected to be faster than those taking place in the uncued direction even though the cues were uninformative with regard to the likely location of the target visual events (just as was the case for the alerting nonspatial-nonpredictive cues used in Experiment 1). This expectation was based on the hypothesis that the presentation of the cue would elicit an exogenous shift of crossmodal spatial attention.

2.3.1 Methods

Twelve participants (mean age of 25 years, age range from 21-33 years; 6 males and 6 females) took part in Experiment 2. All reported normal hearing and normal, or corrected-to-normal, vision. All of the participants had a valid UK driving license, and had, on average, been driving for 6.4 years (range from 2-15 years). All of the participants were right-handed by self-report. None of the participants had taken part in Experiment 1. They were recruited by word of mouth and did not receive any recompense for their participation.

The apparatus, materials, design, and procedure of the experiment were exactly the same as in Experiment 1, with the exception that the location from which the auditory cues were presented now varied between two possible loudspeaker cones. The two loudspeakers were placed on a virtual circle (140 cm in diameter) centred on the participants' head, one to the front and the other to their rear left-hand side (see Figure 2.1a). Auditory cues from the rear were presented from the left (rather than from directly behind the participant) in order to avoid any potential front-back confusions (e.g., Geissler, 1915; Stevens & Newman, 1936; cf. Kitagawa, Zampini, & Spence, 2005). The presentation of the auditory cues from the rear-left was spatially-compatible in terms of the side to which participants had to turn their heads in order to fixate the rearview mirror. The auditory cues were now presented from the same

direction as the critical visual driving events on half of the trials (and from the opposite direction on the remaining 50% of trials). In other words, the auditory car horn sound had a spatial cue validity of 50%.

2.3.2 Results

Table 2.2 Mean RTs (ms) and percentages of errors (and their standard errors in parentheses) in the driving task as a function of the location of the visual driving event and the direction of the auditory cue in Experiments 2-5.

				Location of Visual Event							
				Front (windscreen)				Back (rearview mirror)			
				Front Auditory Cue		Rear Auditory Cue		Front Auditory Cue		Rear Auditory Cue	
Expt	Cue Sound	Cue Type	Cue Validity	RT	% error	RT	% error	RT	% error	RT	% error
2	Car horn	Spatial	50%	1106 (56)	6.3 (1.7)	1124 (57)	5.2 (1.9)	1168 (23)	5.5 (1.6)	1098 (32)	6.2 (1.9)
3	Car horn	Spatial	80%	907 (30)	1.8 (0.7)	1033 (36)	6.3 (1.9)	1107 (30)	3.7 (1.2)	985 (25)	3.7 (0.5)
4	Verbal directional cues	Symbolic	80%	770 (60)	2.7 (0.8)	840 (67)	16.5 (6.9)	1025 (50)	10.9 (4.5)	945 (41)	4.3 (1.7)
5	Verbal directional cues	Spatial symbolic	80%	695 (26)	2.0 (0.6)	865 (41)	19.5 (5.2)	1052 (38)	13.0 (5.8)	862 (24)	4.1 (1.0)

Table 2.2 shows the mean RT data and the percentages of errors in the driving task in Experiments 2-5. As in Experiment 1, trials with an incorrect response were discarded from the RT analysis. 6.5% of the trials on average were removed across participants due to no response being made within 1800 ms of the onset of the critical

visual driving event. An analysis of variance (ANOVA) was performed on the RT data to assess whether the spatial location from which the auditory cues were presented had any effect on the participants' ability to respond to critical visual events seen in either the rearview mirror or from directly ahead (corresponding to events normally seen through the windscreen). The two factors in the within-participants design were auditory cue direction (front vs. back) and visual stimulus location (front vs. back).

The analysis of the RT data revealed no significant main effect of either auditory cue direction, $F(1,11) = 3.12$, $MSE = 2518.8$, $p = .11$, or visual stimulus location, $F(1,11) < 1$, *n.s.* The interaction between these two factors was, however, significant, $F(1,11) = 5.9$, $MSE = 3976.8$, $p = .033$, with participants responding more rapidly to critical visual driving events cued by an auditory cue from the appropriate (or valid) spatial direction than from the inappropriate (or invalid) direction (see Figure 2.4). The mean RT on valid trials (i.e., when the auditory cue and the visual stimulus were both presented from the same direction) was 1102 ms while that for invalid trials (i.e., when the auditory cue was presented from the opposite direction to the visual stimulus) was 1146 ms. Subsequent paired comparison *t*-tests revealed this spatial cuing effect to be significant for targets presented in the rearview mirror (i.e., for visual stimuli at the back, mean cuing effect of 70 ms), $t(11) = 2.4$, $p = .039$, but the trend toward a spatial cuing effect failed to reach significance for target events seen through the front windscreen (i.e., for visual stimuli at the front, $M = 18$ ms), $t(11) = -1.4$, $p = .20$. Given previous claims that a driver's attention is normally directed toward the front (cf. Burnett & Joyner, 1997), spatially-nonpredictive auditory cuing might be expected to produce a more pronounced benefit when used to direct attention toward the rear (i.e., toward the normally unattended, or less attended,

direction) than when directing attention toward the front (where attention is likely to have been focused anyway; cf. Spence, Shore, & Klein, 2001c).

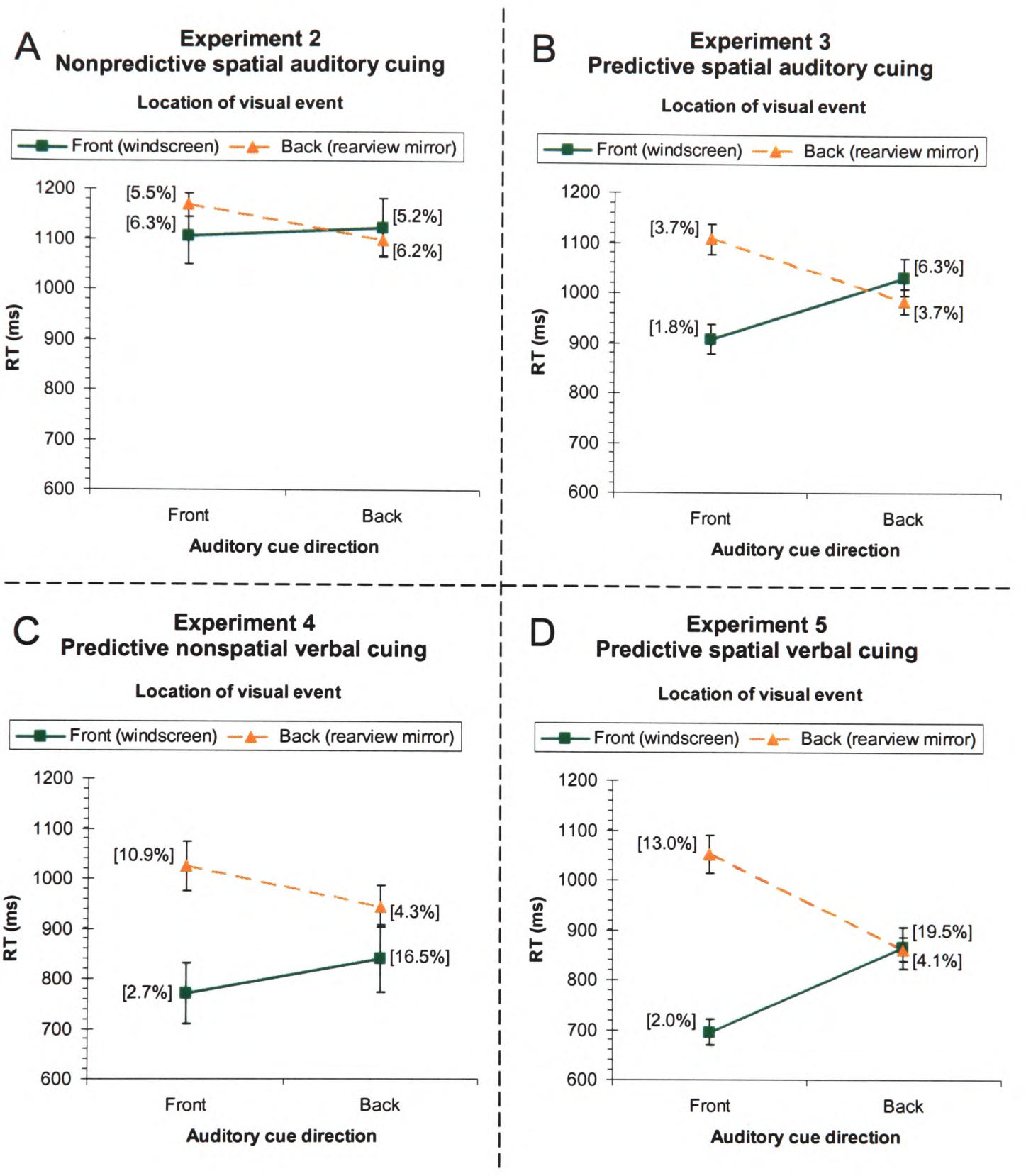


Figure 2.4 Summary of the interactions between the direction of the auditory cue and the location of the critical visual event in the driving task in Experiments 2 (A), 3 (B), 4 (C), and 5 (D). Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs. The slope of the lines indicates the magnitude of the spatial cuing effects that were observed.

A similar analysis of the error data from Experiment 2 revealed no significant main effect of auditory cue direction or visual stimulus location, nor any significant interaction between these two factors, all Fs < 1, *n.s.* Note, however, that the trend in the error data was for participants to make more errors in the invalidly cued trials than in the validly cued trials, thus ruling out a speed-accuracy trade-off account of the cuing effect reported in the data (see Duncan, 1980; Müller & Findlay, 1987).

Performance in the concurrent RSVP task was analysed using the same criteria for invalid responses as adapted in Experiment 1. The mean percentage of correct detection responses in the RSVP task was 71.9% (SE = 3.8%), with a mean RT of 594 ms (SE = 13 ms) and a false alarm rate of 6.0% (SE = 2.0%). These results are similar to those obtained in Experiment 1.

2.3.3 Discussion

The results of Experiment 2 show that participants reacted more rapidly to critical visual driving events seen in the rearview mirror when they were preceded by an auditory cue from the same direction (i.e., from the rear) than from the opposite direction (i.e., from the front). These results therefore suggest that drivers tend to associate what they see in the rearview mirror with the space behind them (rather than from in front where the visual information is actually presented when one looks in a rearview mirror; cf. Higashiyama & Shimono, 2004; Higashiyama, Yokoyama, & Shimono, 2001). By contrast, the results of Experiment 2 show only marginally faster responses for critical visual driving events seen in front through the windscreen when the auditory cue came from the front rather than from behind. It is possible that auditory cues might have had less effect on responses to visual driving events seen from the front (rather than from the rear), given that the visual attentional focus of

drivers is typically directed to the front under normal driving conditions (Burnett & Joyner, 1997; cf. Farnè & Làdavas, 2002). This focusing of visual attention toward the front was simulated in the experiment reported here by the use of the RSVP task. The results of Experiment 2 complement the previous findings of Perrott et al. (1990, 1996) in demonstrating the usefulness of spatial auditory cues in aiding visual search performance in complex visual scenes (see also Doyle & Snowden, 2001). Experiment 2 extended this finding to demonstrate similar effects when visual attention was directed to the rear in a simulated driving task.

A spatial cuing effect was observed with the use of a spatially-nonpredictive car horn sound cue in Experiment 2. At one level, the spatially-nonpredictive car horn sounds used in Experiment 2 can be considered as being very similar to the nonspatial-nonpredictive sounds used in Experiment 1 since they were both uninformative with regard to the likely location of the target visual events. However, the redundant information elicited by the spatial variability in the location of the car horn sound might have required extra processing time, thus slowing down the participants' reactions (see Wallace & Fisher, 1998). This suggests that the invalid or incongruent spatial directional cue can impair performance while the correct spatial directional cue may facilitate it.

It should, however, be noted that the driving task used in the experiments reported in this chapter was a relatively simple one. That is, the participants only had to judge whether there would be a potential collision and react to this information by either accelerating, braking, or else making no response. This may have limited the magnitude of the facilitatory effect of the spatial cues because the participants only had to make the distinction between four possible road scenarios (i.e., front-critical, rear-critical, front-noncritical, and rear-noncritical), which may have been quite easy

to learn. In a real driving situation, by contrast, drivers may need more time in order to perceive and analyse the situation and so give an appropriate response even if a spatial warning signal can direct their visual attention in a particular (presumably appropriate) direction. Doyle and Snowden (2001) have suggested that spatial auditory information may be more useful in situations where the information presented visually is more demanding. Indeed, it has been argued elsewhere that crossmodal links in spatial attention may become more pronounced in general as task load increases (e.g., see Spence, Ranson, & Driver, 2000c). Note also that when drivers are on the road, they typically have to monitor the information available to many different senses simultaneously (e.g., not just vision and audition, as studied here, but also proprioception and vestibular inputs; see Kemeny & Panerai, 2003), and hence the attentional load of the situation may be higher (e.g., see Lavie, 2005; Rees & Lavie, 2001; though see also Sivak, 1996).

2.4 Experiment 3

The use of spatially-nonpredictive auditory cues (i.e., coming from the relevant direction on only 50% of the trials) in Experiment 2 allowed for the isolation of any crossmodal attentional facilitation effects associated with purely exogenous (or stimulus-driven) orienting (see Spence, 2001; Spence & Driver, 1997a). If this spontaneous reaction to the rearview mirror can be readily acquired by drivers as the results reported so far would appear to suggest, it might provide some ideas regarding the future design of spatial auditory warning signals in cars. Given that unreliable cues in real life situations have been shown to adversely affect performance (e.g., see Bliss & Acton, 2003; Sorkin, 1988), Experiment 3 was designed to investigate

whether the effectiveness of such auditory warning signals would be enhanced by making the location of their occurrence predictive of the likely location of any critical visual driving event that might occur subsequently. The location of the auditory cue now predicted the location of the critical visual event correctly on 80% of trials (the cue being invalid on the remaining 20% of trials). Note that this experimental manipulation of cue validity is also ecologically-valid given that most warning cues in realistic situations are designed to be informative (cf. Sorkin, 1988).

2.4.1 Methods

Twelve new participants (mean age of 22 years, age range from 18-34 years; 4 males and 8 females) took part in Experiment 3. All of the participants reported normal hearing and normal, or corrected-to-normal, vision. The average driving experience of the participants was 3.5 years (range from 5 months to 15 years). Nine participants were right-handed, two were left-handed, and one was ambidextrous by self-report. None of the participants had taken part in either of the two preceding experiments. Seven participants received course credit for their participation, the rest received a chocolate bar.

The apparatus, materials, design, and procedure of the experiment were exactly the same as those used in Experiment 2, with the sole exception that the auditory cues were now presented from the relevant location with respect to the visual events on 80% of the trials. The location of the cue was invalid on the remaining 20% of trials. The instructions given to the participants emphasized the fact that the cues were spatially-predictive (i.e., 80% valid) to ensure that participants formed an appropriate expectation regarding the reliability and potential informativeness of the auditory cues. The participants were instructed prior to the start of the experiment to

try and direct their visual attention in the direction indicated by the auditory spatial cues.

2.4.2 Results

The results of Experiment 3 were analysed in a similar manner to those of Experiment 2. 1.3% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual driving event. A two-way within-participants ANOVA was performed on the RT data with the factors of auditory cue direction and visual stimulus location (see Table 2.2). This analysis revealed no significant main effect of auditory cue direction, $F(1,11) < 1$, *n.s.*, but a significant main effect of visual stimulus location, $F(1,11) = 7.3$, $MSE = 9406.9$, $p = .021$, with participants responding more rapidly to visual driving events presented from the front ($M = 970$ ms) than from the rear ($M = 1046$ ms). The interaction between auditory cue direction and visual stimulus location was also significant, $F(1,11) = 72.2$, $MSE = 2531.6$, $p < .001$, showing that participants responded more rapidly to critical visual driving events when they were validly cued by an auditory cue from the same direction than when they were invalidly cued by an auditory cue from the opposite direction to the visual driving events (see Figure 2.4). Paired comparison *t*-tests revealed significant differences (i.e., significant spatial cuing effects) for targets presented both from the front, $t(11) = -6.7$, $p < .001$, and from the rearview mirror, $t(11) = 8.1$, $p < .001$. This means that responses to visual stimuli seen either through the windscreen or via the rearview mirror were significantly faster when cued by an auditory signal from a valid (as opposed to an invalid) direction. (Note, by contrast, that the spatial cuing effect only reached statistical significance for driving events occurring at the rear in Experiment 2, but not for events occurring from the front.)

A similar analysis of the error data revealed a significant main effect of auditory cue direction, $F(1,11) = 7.5$, $MSE = 7.9$, $p = .019$, with participants making fewer mistakes when the car horn sounds came from the front ($M = 2.8\%$) than when they were presented from the rear ($M = 5.0\%$). There was, however, no significant main effect of visual stimulus location, $F(1,11) < 1$, *n.s.*, nor any significant interaction between these two factors, $F(1,11) = 5.0$, $MSE = 13.2$, $p = .06$. Subsequent paired comparison *t*-tests showed a significant difference in the percentage of errors made in response to critical visual events presented from the front cued by car horn sounds from the front versus from the rear, $t(11) = 3.3$, $p = .008$, but not for critical visual events presented from the rear, $t(11) = -0.01$, $p = .99$.

The mean percentage of correct detection responses in the concurrent RSVP task was 78.0% ($SE = 3.9\%$), with a mean RT of 595 ms ($SE = 15$ ms) and a false alarm rate of 3.3% ($SE = 1.1\%$), similar to the results obtained in Experiments 1 and 2.

2.4.3 Discussion

The results of Experiment 3 confirm the potential usefulness of spatially informative auditory cues as a means of capturing a driver's visual attention. The results show that responses to critical driving events presented both from the front and from the rear were facilitated by valid (as opposed to invalid) spatial pre-cuing by a car horn sound. Once again, this facilitation of response latencies cannot be accounted for in terms of a speed-accuracy trade-off in the data because participants also responded significantly more accurately on validly cued, as opposed to invalidly cued, trials overall.

In order to assess the consequences of increasing the reliability of the warning signal on driver reactions to the auditory cues, the results of Experiment 2 were

compared with those from Experiment 3 (50% vs. 80% cue validity, respectively). As predicted, the increase in the reliability of the warning signals resulted in a larger spatial cuing effect in Experiment 3 than in Experiment 2. As shown in Table 2.2, participants in Experiment 3 reacted, on average, faster in all conditions than the participants in Experiment 2.

A three-way mixed ANOVA was performed on the RT data from these two experiments to assess the consequences of increasing the predictive validity of the auditory cue on task performance. The between-participants factor was cue validity (50% in Experiment 2 vs. 80% in Experiment 3), and the within-participants factors were auditory cue direction and visual stimulus location, as before. This analysis revealed a significant main effect of cue validity, $F(1,22) = 7.4$, $MSE = 43677.6$, $p = .012$, indicating faster overall performance when the cues were spatially-predictive (i.e., 80% valid with regard to the likely location of the target visual event; mean response latency of 1008 ms) than when the cues were spatially-nonpredictive (i.e., 50% valid; $M = 1124$ ms) with respect to the location of the critical visual driving event (see Table 2.2). The interaction between these three factors was also significant, $F(1,22) = 11.5$, $MSE = 3253.2$, $p = .003$, presumably reflecting the fact that the spatial cuing effect for driving events occurring at the front was significant in Experiment 3 but not in Experiment 2. An independent samples t-test comparison showed that the mean cuing effect for each participant was significantly larger in Experiment 3 ($M = 123$ ms, $SE = 15$ ms) than in Experiment 2 ($M = 44$ ms, $SE = 18$ ms), $t(22) = -3.4$, $p = .003$. There was no significant main effect of auditory cue direction, $F(1,22) = 2.0$, $MSE = 1734.8$, $p = .17$, or visual stimulus location, $F(1,22) = 2.4$, $MSE = 21760.1$, $p = .14$. It should of course, however, be noted that there might be some possible

confounds in terms of the demographic differences of the participants when drawing comparisons between these two experiments.

A similar analysis of the error data revealed no significant main effect of cue validity, $F(1,22) = 1.3$, $MSE = 70.6$, $p = .27$. There was, however, a significant interaction between auditory cue direction, visual stimulus location, and cue validity, $F(1,22) = 4.9$, $MSE = 12.4$, $p = .038$. An independent samples t-test comparison on the mean cuing effect in the error data showed a significantly larger cuing effect in Experiment 3 ($M = 2.2\%$, $SE = 1.0\%$) than in Experiment 2 ($M = -0.9\%$, $SE = 1.0\%$), $t(22) = -2.2$, $p = .038$. Participants made more errors overall in Experiment 2 than in Experiment 3. These results seem to suggest an improvement in performance when the participants directed their endogenous spatial attention in the direction indicated by the cue (i.e., when it was informative; Experiment 3), in addition to any exogenous shifts of attention elicited by the very presentation of the auditory cue itself from a particular spatial location (Experiments 2 and 3). These results are similar to those reported previously by Spence and Driver (1994) in a series of experiments on auditory spatial attentional orienting, where the use of an informative auditory pre-cue was found to facilitate auditory target discrimination responses more than the presentation of the same cuing stimuli when they were spatially nonpredictive (see also Mondor & Amirault, 1998). Note though that both Spence and Driver and Mondor and Amirault studied *covert* orienting mechanisms (i.e., in the absence of eye movements), while the experiments reported here were concerned primarily with the *overt* crossmodal orienting of visual attention using auditory cues.

2.5 Experiment 4

Very few studies have attempted to vary the semantic meaning of auditory warning signals in order to see what effect, if any, this factor has on the exogenous capture of spatial attention (though see Selcon et al., 1995; Oyer & Hardick, 1963). Given this fact, it would seem reasonable that an investigation of the effectiveness of different types of auditory warnings would enhance our understanding of the ability of operators (e.g., car drivers) to use everyday knowledge when responding to warning signals (cf. Edworthy et al., 1991; Horowitz & Dingus, 1992).

In an elaborate early study of the relative effectiveness of various different auditory warning signals, Oyer and Hardick (1963) investigated the optimum acoustical dimensions of auditory alerting signals. Sounds including animal and human noises (such as elephants stampeding and baby cries), horns, sirens, bells, buzzers, pure tones, whistles, and noises of various types were assessed for their potential alerting effect by different segments of the population of the United States. The participants rated the sounds along the dimensions of pleasant-unpleasant, startling-nonstartling, and bizarre-ordinary. From their results, Oyer and Hardick were able to specify the frequency, intensity, and time ranges within which the optimal warning signals should appear. Among all of the alerting sounds evaluated, one of the car horn sounds was rated as the fifth most effective alerting signal, preceded only by the sounds of a missile alarm, yelper siren, British air raid siren, and falcon horn. Note though that the current approach to ergonomic alarm design has tended to put a greater emphasis on the informative nature of alarms (as opposed to their capacity simply to alert as was the case in the 1960s; cf. Edworthy & Hellier, 2006). The

spatial auditory warning signals used in Experiments 2 and 3 lie closer to the informational end on the inform-alert continuum, as the cues did not simply startle the participants, but provided spatial information of the visual target events (though to a lesser extent in Experiment 2). Interface designers need to examine the effectiveness of different warning signals further when specifying the most appropriate signals for the particular applications concerned, both in terms of their ability to alert or arouse an interface operator, and also in terms of their ability to direct their attention in the appropriate internal (i.e., interface display) or external (i.e., potential road danger) event.

Given that words convey explicit meanings in everyday language, Experiment 4 was designed to use verbal cues (the words 'front' and 'back') to examine the effectiveness of verbal instructions in orienting a driver's visual attention. While most previous studies of verbal spatial cuing have investigated the effects of the presentation of the words 'left' and 'right' or 'top' and 'bottom' on the distribution of spatial attention (e.g., Hommel, Pratt, Colzato, & Godijn, 2001; Hunt & Kingstone, 2003; Selcon et al., 1995), no study has as yet specifically examined the effects of the words 'front' and 'back' upon perception and/or performance. Nevertheless, recent research suggests that verbal directional cues may, in fact, act in a manner similar to that of social directional cues, such as eye-gaze direction or head orientation, that can automatically capture visual attention and lead to a rapid reflexive or exogenous shifts of attention to the side where a person's face is looking (e.g., Langton, Watt, & Bruce, 2000; see Chapter 3 for a further discussion).

2.5.1 Methods

Twelve new participants (mean age of 27 years, age range from 20-40 years; 7 males and 5 females) took part in Experiment 4. All reported normal hearing and normal, or corrected-to-normal, vision. The average driving experience of the participants was 6.5 years (range from 1-12 years). Eleven of the participants were right-handed and one was left-handed by self-report. None of them had taken part in any of the preceding experiments and all received a bar of chocolate in return for their participation.

The apparatus, materials, design, and procedure were exactly the same as in Experiment 3, with the sole exception that the frontal auditory car horn cue was replaced by the word 'front' (64 dB(A)) while the rear car horn cue was replaced by the word 'back' (62 dB(A)) as pronounced by a male voice in the Merriam-Webster Online Dictionary (retrieved from http://www.m-w.com/cgi-bin/audio.pl?front001.wav=front and http://www.m-w.com/cgi-bin/audio.pl?back0001.wav=back; downloaded on 28-02-2004). The verbal cues were always presented from the same loudspeaker cone positioned directly below the participant's chair (as in Experiment 1). The verbal instructions given to participants again emphasized the fact that the cue would correctly predict the target direction on 80% of the trials, and so they should endeavour to direct their visual attention in the direction indicated by the cue first.

2.5.2 Results

The results of Experiment 4 were analysed in a similar manner to those of Experiments 2 and 3. 6.9% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual driving event. A two-way within-

participants ANOVA on the RT data showed no significant main effect of auditory cue direction, $F(1,11) < 1$, *n.s.* (see Table 2.2). There was, however, a significant main effect of visual stimulus location, $F(1,11) = 15.0$, $MSE = 25913.3$, $p = .003$. Participants responded more rapidly to visual events seen occurring in front (i.e., requiring a braking response, $M = 805$ ms) than to events occurring in the rearview mirror (i.e., requiring an acceleration response, $M = 985$ ms). The interaction between these two factors was significant, $F(1,11) = 13.5$, $MSE = 5003.9$, $p = .004$, revealing that participants responded more rapidly to critical visual driving events cued by an appropriate verbal directional cue ($M = 858$ ms) than by an invalid verbal directional cue ($M = 933$ ms; see Figure 2.4). Paired comparison *t*-tests revealed significant differences for both the front, $t(11) = -2.5$, $p = .028$, and the rearview mirror, $t(11) = 2.5$, $p = .031$, showing a beneficial effect of valid spatial cuing for both visual stimulus locations, just as reported in Experiment 3.

A similar analysis of the error data revealed no significant main effect of auditory cue direction, $F(1,11) = 1.4$, $MSE = 111.4$, $p = .26$, or visual stimulus location, $F(1,11) < 1$, *n.s.* The interaction between these two factors was, however, significant, $F(1,11) = 5.8$, $MSE = 216.8$, $p = .035$. Given that the pattern of errors coincided with the RT effects, a speed-accuracy trade-off account of the RT differences reported above can once again be ruled out.

Participants correctly detected 68.5% ($SE = 3.8\%$) of the targets on the concurrent RSVP task, with a mean RT of 597 ms ($SE = 18$ ms) and a false alarm rate of 9.8% ($SE = 2.3\%$). These results were similar to those obtained in Experiments 1-3.

2.5.3 Discussion

The results of Experiment 4 suggest that participants could rapidly comprehend the meanings of the verbal warning signals and direct their attention appropriately. Previous studies of auditory verbal warning signals have shown that verbal warning signals can communicate more information than non-speech warnings about an upcoming event to an operator, especially under situations of high cognitive load, where abstract cues may not convey any explicit meaning (e.g., Graham, 1999; Selcon et al., 1995). In order to examine the relative benefits of using verbal versus spatial informative cuing, a three-way mixed ANOVA was performed on the RT data to compare the relative effectiveness of the verbal cues used in Experiment 4 to the spatial auditory car horn sounds used in Experiment 3. The between-participants factor was cue type (car horn or verbal; note that the cue validity was 80% in both experiments), and the within-participants factors were auditory cue direction and visual stimulus location. This analysis revealed a significant main effect of cue type on the RT data, $F(1,22) = 4.3$, $MSE = 71348.1$, $p = .050$, with participants responding more rapidly overall in Experiment 4 ($M = 895$ ms) than in Experiment 3 ($M = 1008$ ms), together with an insignificant interaction between these three factors, $F(1,22) = 3.7$, $MSE = 3767.7$, $p = .07$. With reference to Figure 2.4 (compare panels B and C), it can be seen that when cued by a verbal instruction to the likely position of the visual event, participants responded more rapidly than when nonverbal cues were used across all four combinations of auditory cue direction and visual stimulus location. This was, however, accompanied by an increase in errors.

A similar analysis of the error data failed to reveal any significant main effect of cue type, $F(1,22) = 2.2$, $MSE = 248.2$, $p = .15$, nor any three-way interaction,

$F(1,22) = 3.3$, $MSE = 115.0$, $p = .08$, although participants did make more errors overall in the verbal ($M = 8.6\%$) than in the car horn ($M = 3.9\%$) cuing condition. Taken together, it seems that the spatial and verbal predictive cues may have affected a driver's attention in different ways. Participants were quicker but less accurate to respond with verbal cues than with nonverbal cues, in a manner reminiscent of to Hirst and Graham's (1997) finding that speech warnings caused greater annoyance to participants in their study.

Crucially, a three-way mixed ANOVA performed on the inverse efficiency data $(IE)^{2.3}$ from the two experiments (calculated by dividing the RT data by the proportion of correct responses for each condition for each participant; Townsend & Ashby, 1983), with the between-participants factor of experiment and the within-participants factors of target position and cue validity, revealed no significant main effect of experiment, $F(1,22) < 1$, *n.s.*, nor any interaction between the three factors, $F(1,22) < 1$, *n.s.*, suggesting that the spatial and verbal predictive cues may have been equally effective in directing a driver's attention toward the correct direction. Future research should further examine the directional property of verbal cues (as compared to other nonverbal well-learnt cues) and interface operators' compliance with verbal instructions produced by an interface (see Simpson et al., 1987).

2.6 *Experiment 5*

Experiment 5 investigated whether combined verbal spatial warning signals (such as the word 'front' presented from the front, and the word 'back' presented from

[2.3] By combining RT and error rate data into a single performance measure, inverse efficiency provides a global estimate of performance that is particularly useful when analysing speed and accuracy results that go in different directions.

the back) would be even more effective in orienting a driver's attention than the spatial or verbal cues used in Experiments 3 and 4 (cf. Selcon et al., 1995).

2.6.1 Methods

Sixteen new participants (mean age of 21 years, age range from 19-30 years; 6 males and 10 females) took part in Experiment 5. All reported normal hearing and normal, or corrected-to-normal, vision. All of the participants had a valid UK driving license and had, on average, been driving for 3.8 years (range from 1.5-13 years). Fifteen participants were right-handed, and one was left-handed by self-report. All of the participants were naïve as to the purpose of the experiment, and all received a chocolate bar in return for their participation. The apparatus, materials, design, and procedure were exactly the same as those used in Experiment 4, with the exception that the verbal cues 'front' and 'back' were always presented from the front and rear loudspeaker cones, respectively, just as in Experiment 3 (rather than from the central loudspeaker as in Experiment 4).

2.6.2 Results

The results of Experiment 5 were analysed in a similar manner to those of Experiments 2-4. 4.2% of the trials on average were removed across participants due to no response being made within 1800 ms of the onset of the critical visual driving event. A two-way within-participants ANOVA on the RT data revealed a significant main effect of visual stimulus location, $F(1,15) = 28.9$, $MSE = 17264.6$, $p < .001$, with participants responding more rapidly to visual driving events presented from the front ($M = 780$ ms) than from the rear ($M = 957$ ms). There was, however, no significant main effect of auditory cue direction, $F(1,15) < 1$, *n.s.* The interaction between

auditory cue direction and visual stimulus location was significant, $F(1,15) = 78.6$, $MSE = 6601.1$, $p < .001$. Subsequent paired comparison t-tests revealed significant cuing effects for targets presented both from the front (mean cuing effect of 170 ms), $t(15) = -6.5$, $p < .001$, and from the rear ($M = 190$ ms), $t(15) = 7.0$, $p < .001$, thus showing the beneficial cuing effect of an appropriate verbal cue coming from the appropriate (or valid) direction, as opposed to an inappropriate verbal cue coming from an invalid direction (see Figure 2.4).

A similar analysis of the error data revealed no significant main effect of auditory cue direction, $F(1,15) = 3.2$, $MSE = 93.4$, $p = .09$, or visual stimulus location, $F(1,15) < 1$, *n.s.* The interaction between auditory cue direction and visual stimulus location was, however, significant, $F(1,15) = 9.1$, $MSE = 307.3$, $p = .009$ (see Figure 2.4). Paired comparison t-tests showed a significant difference in the percentage of errors made on critical visual driving events presented from the front cued by a valid 'front' cue ($M = 2.0\%$) than by an invalid 'back' cue ($M = 19.5\%$), $t(15) = 3.7$, $p = .002$. Participants were also numerically somewhat less accurate following an invalid 'front' cue ($M = 13.0\%$) than a valid 'back' cue ($M = 4.1\%$) for critical visual driving events presented from the rear, although this trend failed to reach statistical significance, $t(15) = -1.7$, $p = .11$.

The mean percentage of correct detection responses in the concurrent RSVP task was 79.3% ($SE = 2.2\%$), with a mean RT of 571 ms ($SE = 14$ ms) and a false alarm rate of 6.4% ($SE = 1.1\%$). A one-way ANOVA carried out on the performance data from the RSVP task in Experiments 1-5 revealed no significant difference in performance on this concurrent primary task across all the five experiments for either the percentages of correct responses, $F(4,59) = 2.1$, $MSE = 133.3$, $p = .09$, or the RT data, $F(4,59) < 1$, *n.s.* This suggests that the extent to which participants engaged in

the primary task was similar across all five of the experiments reported here (see Chapter 2.7 for an analysis of the RSVP performance as a function of the four critical conditions in the driving task).

2.6.3 Discussion

The results of Experiment 5 demonstrate the potential effectiveness of using informative spatial verbal cues to direct a driver's visual attention. In order to assess the consequences of combining spatial cues with verbal cues (i.e., of using redundant spatial cuing), a three-way mixed ANOVA was performed on the RT data with the between-participants factor of cue type (spatial-nonverbal in Experiment 3, nonspatial-verbal in Experiment 4, or spatial-verbal in Experiment 5), and the within-participants factors of auditory cue direction (front vs. back) and visual stimulus location (front vs. back). This analysis revealed a significant main effect of cue type, $F(2,37) = 4.8$, $MSE = 59544.0$, $p = .014$, with the fastest overall performance being reported when the auditory cues were spatial-verbal (Experiment 5; overall mean response latency of 868 ms) than when they were nonspatial-verbal (Experiment 4; $M = 895$ ms) or spatial-nonverbal car horn sound cues (Experiment 3; $M = 1008$ ms). Post-hoc multiple comparison (LSD) showed a significant difference between spatial-nonverbal and spatial-verbal cuing, $p = .005$, and between spatial-nonverbal and nonspatial-verbal cuing, $p = .030$, but not between nonspatial-verbal and spatial-verbal cuing, $p = .57$.

A subsequent one-way ANOVA on the mean cuing effects with the factor of cue type revealed a significant main effect, $F(2,37) = 7.8$, $MSE = 4916.4$, $p = .001$. Post-hoc multiple comparison (LSD) showed that the mean cuing effects were significantly larger with spatial-verbal cuing ($M = 180$ ms, $SE = 20$ ms) than with the

nonspatial-verbal cuing (M = 75 ms, SE = 20 ms), $p < .001$, and also significantly larger with spatial-verbal over spatial-nonverbal (M = 124 ms, SE = 15 ms) cuing, $p = .041$, but not for the difference between spatial-nonverbal and nonspatial-verbal cuing, $p = .10$. A similar analysis of the error data revealed no significant main effect of cue type, $F(2,37) = 1.4$, $MSE = 339.7$, $p = .25$, nor any significant three-way interaction, $F(2,37) = 2.2$, $MSE = 193.0$, $p = .13$.

2.7 RSVP performance in Experiments 1-5

Performance in the RSVP task (i.e., the probability of correctly detecting the RSVP targets) was analysed for each participant in each of the five experiments reported in this chapter as a function of the four critical driving conditions in the driving task. Target stimuli in the RSVP task presented after the onset of one auditory cue and before the onset of the next auditory cue were classified as belonging to the driving condition associated with the first auditory cue. Given that there were only eight trials for each of the four noncritical driving conditions, the data from these conditions were not included in the analyses.

Paired comparison t-tests performed on the data from Experiment 1 (nonspatial-nonpredictive car horn sounds) revealed no significant difference in participants' performance in the RSVP task as a function of whether the critical visual driving trials occurred at the front or back, $t(11) = -1.3$, $p = .22$.

Separate ANOVAs were performed on the data from Experiments 2-5 to assess whether the spatial location from which the auditory cues and critical visual scenes were presented had any effect on participants' ability to respond to the RSVP targets. The two factors in the within-participants design were auditory cue direction

(front vs. back) and visual stimulus location (front vs. back). The analyses of the probability data from Experiments 2 (spatially-nonpredictive car horn sounds) and 3 (spatially-predictive car horn sounds) revealed no significant main effects or interactions on the RSVP task as a function of the critical driving conditions, all Fs < 1, *n.s.* (except for the insignificant main effect of auditory cue direction for Experiment 2, $F(1,11) = 2.6$, $MSE = 0.0029$, $p = .13$). Interestingly, the analysis of the data from Experiment 4 (predictive verbal cues) showed a significant interaction between auditory cue direction and visual stimulus location, $F(1,11) = 12.6$, $MSE = 0.0024$, $p = .005$. In particular, participants detected more RSVP targets when the critical visual driving event was validly cued by the verbal cue (mean probability of correct detection = 0.69, $SE = 0.04$) instead of invalidly cued ($M = 0.64$, $SE = 0.04$). There was no significant main effect of either auditory cue direction or visual stimulus location, both $F(1,11) < 1$, *n.s.*

The analysis of the probability data from Experiment 5 (spatially-presented verbal cues) again revealed a significant interaction between the auditory cue direction and visual stimulus location, $F(1,15) = 38.6$, $MSE = 0.0012$, $p < .001$, with participants detecting more RSVP targets correctly when the driving cue and target were presented from the valid ($M = 0.79$, $SE = 0.02$) rather than from the invalid ($M = 0.74$, $SE = 0.02$) directions. The main effects of auditory cue direction and visual stimulus location were also significant, $F(1,15) = 10.6$, $MSE = 0.0037$, $p = .005$, and $F(1,15) = 83.7$, $MSE = 0.0016$, $p < .001$, respectively, with participants detecting more RSVP targets when the driving trials contained a 'back' auditory cue and/or a visual critical target from in front.

Taken together, these analyses of the RSVP monitoring task performance data as a function of the conditions in the driving task seem to suggest that participants

were more distracted by the spatial elements inherent in the driving trials when verbal rather than nonverbal spatial auditory cues were used. These observations also coincide with the higher error rates in the verbal than in the nonverbal spatial cuing conditions.

2.8 General discussion of auditory spatial cuing

Taken together, the results of Experiments 1-5 help to elucidate some of the potential implications of the existence of crossmodal links in spatial attention between audition and vision for interface design. The results documented so far reveal that a spatially-nonpredictive auditory cue coming from an appropriate (or valid) spatial direction can be used to facilitate the overt orientation of visual attention in that direction. The results of Experiments 2-5 show a significant performance advantage in the detection of potential emergency visual driving events (requiring either an acceleration or braking response) when participants were cued by an auditory cue coming from the relevant direction, or else when their attention was directed in the appropriate direction by means of a semantically-meaningful verbal cue. Such an effect of a valid auditory spatial cue was enhanced by making the cues spatially-predictive (as shown by the comparison of the data from Experiments 2 and 3). These results are consistent with Begault's (1993) previous findings that spatial auditory cues can be used to facilitate the visual search performance of pilots, and extend the potential facilitatory effect of the use of spatial auditory warning signals on visual information detection (and subsequent reactions) into a simulated driving set-up.

Previous laboratory-based studies have demonstrated that the *covert* orienting of visual and auditory attention influence one another at both the endogenous and

exogenous levels (see Driver & Spence, 2004; Spence et al., 2004, for reviews). According to conventional thinking, the spatial cuing effects reported in Experiment 2 would be regarded as purely exogenous (given the spatially-nonpredictive nature of the cues), while the cuing effects reported in Experiments 3 and 5 would be considered to reflect some combination of both exogenous and endogenous orienting (given that the location of the cue predicted the likely target location on 80% of the trials). By contrast, the cuing effects reported in Experiment 4 would be considered as purely endogenous (since the location of the symbolic verbal cue carried no information in-and-of-itself). Crossmodal links in spatial attention between audition and vision have been shown in this series of experiments to draw a participant's (i.e., driver's) visual attention more readily to the validly cued than the invalidly cued spatial direction by the auditory signals, thus an *overt* orienting of visual attention by audition. Overall, the results suggest that the combined use of exogenous and endogenous orienting provides the most effective means of capturing a driver's attention.

On the theoretical side, the successful demonstration of crossmodal links in spatial attention between audition and vision, and the varying effects of the various auditory cues on performance on the same visual task, together argue against traditional modality-specific accounts of independent channels for auditory and visual information processing (see Wickens, 1980, 1991). The results reported in this chapter instead support recent claims that the mechanisms controlling spatial attention in different sensory modalities can interact and thereby influence one another (e.g., Spence & Driver, 2004). Given that the facilitation of responses was measured at the behavioural level, it will be important in future experiments to investigate whether the performance improvement reported in Experiments 2-5 reflects the consequences of a

perceptual enhancement attributable to the spatial aspect of the cues coinciding with that of the targets, a priming of the appropriate responses by the cues (which can be generated by cues regardless of their location relative to the critical driving events), or some unknown combination of the two effects (see Chapter 5 for further experiments precisely on this topic). No matter what the underlying cause(s) of the facilitatory effects reported in this chapter turn(s) out to be, it is important for the applied domain to combine the perceptual and response compatibility aspects of cuing in the design of the most effective multisensory interfaces.

2.8.1 Meaningful auditory warnings

Previous studies of crossmodal links in exogenous spatial attention have always used cues of questionable (or no) ecological validity, such as pure tones or white noise bursts in the case of auditory cuing experiments (see Spence et al., 2004). It is therefore possible that the use of a semantically-meaningful sound, such as the car horn used in Experiments 1-3, might engage attention more effectively than these other arbitrary sounds (cf. Oyer & Hardick, 1963). It remains an interesting question for future research to determine whether the use of a car horn or other semantically-meaningful spatial auditory cue is more effective at capturing an interface operator's attention than, say, a white noise burst or pure tone of equivalent intensity and localizability. Note that the semantic meaning conveyed by the car horn sound used in Experiments 1-3 might also have activated other attentional mechanisms than those typically thought to control spatial attentional orienting (cf. Langton et al., 2000). For instance, research has shown that the physiological state of arousal of drivers can sometimes determine their driving behaviours, such as modifying their responses to critical emergency driving situations (see Collet, Petit, Priez, & Dittmar, 2005).

Gregory (1998), in his extended analysis of mirrors and perception, mentioned the visual ambiguity in certain images perceived via mirror reflection. In particular, he hints that in an emergency situation, drivers may need to spend time processing what they perceive in the rearview or side mirrors (Gregory, pp. 208-9). In fact, drivers may not encounter an emergency situation for several years, but when they do, the warning signal needs to alert the driver and convey sufficient information for him/her to make the necessary reaction in a cognitively demanding and short time frame (cf. Belz, Robinson, & Casali, 1999). Note that the cuing of spatial attention to the rear in the results reported in this chapter seems to be automatic and quick. This is perhaps the first empirical study to have investigated the cuing of attention into the space seen only indirectly via a mirror reflection, an area of growing interest in cognitive neuroscience (e.g., Binkofski et al., 1999; Gregory, 1998; Maravita et al., 2002).

It should be pointed out that it is somewhat unclear whether a spatial auditory cue presented from behind a driver draws his/her attention to the actual space behind him/her (i.e., to the rear) or to the rearview mirror (which in some sense constitutes a visual event seen in front). If the former account were to be correct, then the spatial cues are effective in shifting attention to the relevant locations of the visual elements that represent a certain well-learnt spatial location. The learning of the special property of a mirror and how people accommodate that spatial information with other spatial elements in their representation of the environment is certainly a topic deserving of further investigation (e.g., Gregory, 1998; Ramachandran, Altschuler, & Hillyer, 1997).

2.8.2 Reliability of warning signals

The issue of warning signal reliability has been investigated in both the aviation and driving literature (e.g., Bliss, 2003; Parasuraman et al., 1997). One key point to have emerged from this research is that false alarms can potentially be very distracting to an operator in diverting their attention from their primary task. Additionally, the available evidence suggests that an operator may choose to ignore a warning signal if it proves to be inconsistent and/or unreliable, thus potentially negating its value (e.g., Parasuraman & Riley, 1997; Sorkin, 1988). In a recent study, Bliss and Acton (2003) examined the effect of varying the reliability of collision alarms on performance in a driving simulator. Participants in the study were instructed to drive and to swerve to the left or right depending on the side from which cars approached randomly in the rearview mirror. Bliss and Acton reported that performance improved (i.e., in terms of the frequency of appropriate reactions to the alarm signals) as the reliability of the cue increased (from 50% through 75% to 100% valid). Consistent with Bliss and Acton's findings, responses were both faster and more accurate when the reliability of the auditory cues increased from 50% valid (Experiment 2) to 80% valid (Experiment 3).

2.8.3 Speech vs. non-speech signals in driving

Responses to speech warnings in an emergency situation may also be slower than under normal circumstances, particularly if an operator does not understand the meaning of a speech message until it is finished (e.g., Simpson & Marchionda-Frost, 1984). Since Experiments 4 and 5 used only two single-syllable verbal cues ('front' and 'back'), the results were probably not influenced by any potential problems

associated with disambiguating multiple possible speech warnings that may be present in applied settings incorporating multiple verbal warning signals (cf. Chan, Merrifield, & Spence, 2005).

Given that drivers are typically engaged in other tasks involving linguistic elements, such as, for example, listening to the radio, perhaps having a conversation with a passenger or over the mobile phone, or else possibly taking in speech instructions from an in-car navigation system (e.g., Kames, 1978; Streeter, Vitello, & Wonsiewicz, 1985), the additional verbal cues from the warning systems may inevitably lead to some confusion, misunderstanding, and/or masking (either energetic or informational; see Oh & Lutfi, 1999). Thus, although drivers can easily acquire and react to a verbal instruction presented in isolation (as in Experiments 4 and 5), some caution may be needed before implementing verbal cues in a real warning system. In a real driving situation, it might actually be better to implement nonverbal warning signals, as they are less susceptible to the influence of other concurrent linguistic elements in the environment.

Some recent research has been designed to investigate the most effective audible icons that can convey the 'right degree of urgency' and have a 'commonly-understood meaning' for in-car systems (e.g., Catchpole, McKeown, & Withington, 1999a, b; McKeown & Isherwood, in press). Indeed, there is a long history of research on the idea of ecologically-valid auditory icons in interface design (see Catchpole et al., 2004; Gaver, 1993a, b; Oyer & Hardick, 1963), though that has not been widely implemented in in-car systems to date. Spatial cues may therefore be better than verbal cues or arbitrary nonspatial auditory icons in that they utilize an orienting response that should be common to everyone, whereas there may be distinct cultural interpretations of the meanings inherent in different auditory icons. A

successful warning signal needs to be representational in the sense that any likely operator can intuitively recognize its meaning and be informed of the required actions.

CHAPTER 3

VERBAL DIRECTIONAL CUING

3.1 Experiment 6

Although the last few years have seen a rapid growth of interest in the use of verbal information displays in many applied interface settings (see earlier discussion), it is unclear what effect the presentation of verbal directional/spatial cues, such as the words 'front', 'back', left', or 'right', has on the spatial distribution of an interface operator's attention. Experiment 6 was therefore designed to address this issue by investigating whether centrally-presented spatially-nonpredictive verbal directional cues elicit an automatic shift of visual spatial attention in the direction indicated by the cue, in a manner similar to that typically found in studies using centrally-presented uninformative symbolic cues (e.g., Friesen, Ristic, & Kingstone, 2004).

3.1.1 Introduction

Laboratory-based research has demonstrated that informative and uninformative cues have differential effects on the distribution of spatial attention (e.g., Jonides, 1981; Müller & Rabbitt, 1989; Ristic, Friesen, & Kingstone, 2002). Participants in these previous studies usually had to make speeded detection or

discrimination responses to targets presented either alone, or else amongst distractors (Friesen et al., 2004; Hommel et al., 2001; Jonides, 1981). These studies have typically shown that participants respond more rapidly, and somewhat more accurately, to targets on validly cued trials (where the cue correctly indicated the location of the upcoming target) than on invalidly cued trials (where the target appeared at the uncued location) at short stimulus onset asynchronies (SOAs; typically in the range of 100-400 ms). The cues used in these previous studies have included peripheral cues such as the sudden onset of a visual, auditory, or tactile stimulus on either the left or right side (see Spence et al., 2004, for a recent review), and/or central symbolic cues such as centrally-presented uninformative arrow cues (Friesen et al., 2004; Müller & Findlay, 1987; Schneider & Bavelier, 2003; Shepherd, Findlay, & Hockey, 1986), eye gaze cues (Friesen & Kingstone, 2002; Friesen et al., 2004; Hood, Willen, & Driver, 1998; Schneider & Bavelier, 2003; Senju & Hasegawa, 2005), head orientation cues (Langton & Bruce, 2000), and even word cues (Baldo, Shimamura, & Prinzmetal, 1998; Hunt & Kingstone, 2003; Vecera & Rizzo, 2004; see also McCarthy & Beaumont, 1996).

However, to date, few studies have attempted to examine the effect of the presentation of word cues on the distribution of spatial attention in a multisensory setting. In fact, the majority of studies have only presented visual directional word cues prior to visual targets (e.g., Gibson & Kingstone, 2006). For instance, in Hommel et al.'s (2001) intramodal visual cuing study, the attentional orienting effects of nonpredictive visual cues (nonpredictive in the sense that they were no more likely to coincide with the target position than with the non-target position; see Jonides, 1981, for a discussion of cue expectancy) were examined using both centrally-presented symbolic arrow cues (pointing to the left, right, top, or bottom), and

centrally-presented visual word cues corresponding to the four directions in German ('LINKS', 'RECHTS', 'OBEN', or 'UNTEN'). Hommel and colleagues compared participants' responses to validly cued versus invalidly cued trials using three different tasks: A simple speeded detection task in which the participants had to detect the target letter 'X' presented amongst the distractor letters 'A', 'E', 'L', and 'M', four of which were presented in each of the four boxes situated to the left, right, top, or bottom of a central fixation point on each trial; A speeded detection task in which participants had to detect a target circle upon the presentation of both a peripheral cue (on either the left or right) and a centrally-presented arrow or word cue indicating either the left, right, or centre (i.e., a neutral cue); And lastly, a colour discrimination task in which the participants had to discriminate whether a red or blue target had been presented (either on the left or right) following the central presentation of the left or right arrow or word cues. The major finding to emerge from all three experiments was that the presentation of both spatially-nonpredictive symbolic arrow and directional word cues (which Hommel et al. considered to be 'conventional, over-learned communicative signals', p. 360) facilitated subsequent responses to stimuli presented in the cued direction. That is, the presentation of spatially-nonpredictive symbolic visual cues led to an automatic orienting of visual attention in the direction indicated by the cues in a unimodal visual setting. Given the rapid recent increase of interest in the use of speech commands for both input and output in many interfaces (such as verbal instructions for geographical information systems, car navigation systems, and air traffic controls; e.g., Oviatt, 1999, 2002; Oviatt, Coulston, & Lunsford, 2004; Schneider, Healy, & Barshi, 2004), the examination of the possible orienting properties of verbal directional cues is clearly of importance to applied research. To date, however, only limited research has examined whether verbal

directional cues are as effective as peripheral spatial cues in orienting attention. These cues may encompass both exogenous (i.e., stimulus-driven) and endogenous (i.e., voluntary) components (see Klein, 2004; Posner, 1980).

In one of the few previous studies in this area, Selcon et al. (1995) examined the effectiveness of various different auditorily-and/or visually-presented verbal and/or spatial missile approach warning signals on participants' ability to respond to the direction indicated by the warnings. The verbal warnings consisted of the vocal command words 'left' or 'right', while the spatial (i.e., peripheral) auditory warnings consisted of a pure tone cue presented from either the left or right. The corresponding visual warning signals consisted of the words 'left' or 'right' presented on a monitor, and a row of 'X's presented from either side of the visual display. These warning signals were either presented individually or else in one of a number of different redundant combinations (such as the word 'left' written on the left side of the display, together with the spoken word 'left' presented to the left ear). While the nature of the task used in Selcon et al.'s experiment, which involved responding to the direction indicated by the warning signal by pressing the left or right button, is susceptible to response priming artifacts (e.g., see Spence, 2001; Spence & Driver, 1999; though see also Proctor et al., 2005), a significant performance advantage (of up to a 30% reduction in response latencies) was reported under conditions where the warning signal was multiply redundant rather than being non-redundant (i.e., when it came from a single source, such as the word 'left' written in the centre of the display). Although Selcon et al. did not compare the efficiency of the four different types of information presentation directly, their study does at least suggest that spatial warning signal information can be conveyed either by presenting the information from a

relevant spatial position, or by means of presenting linguistically-meaningful spatial directional cues.

Experiment 6 was therefore designed to investigate whether verbal (i.e., auditorily presented) directional word cues elicit an orienting effect similar to that shown previously in unimodal visual studies that have used either uninformative (i.e., spatially-nonpredictive) central arrow or social cues (e.g., eye gaze and/or head orientation). The prediction was that any such automatic spatial cuing effect should reveal itself as a speeding-up of responses, and/or an improvement in the accuracy of responses, on validly cued trials (when the verbal cue happened to correctly indicate the side of the upcoming target) as compared to invalidly cued trials (when the verbal cue indicated the side opposite to that of the upcoming target). It was hypothesized that people might find it impossible to voluntarily suppress the learned semantic meaning associated with directional word cues (even when the word cue was spatially-nonpredictive with regard to the likely target location). It was also hypothesized that directional words might act in a manner similar to symbolic central cues, whose meaning must be decoded, and at the same time, act like peripheral cues that communicate spatial information directly. Alternatively, however, it also seemed possible that people might be able to ignore the verbal (i.e., auditory) cues entirely when performing a purely visual task.

On the basis of previous research, the biggest spatial cuing effect was expected at the shortest SOA, with the magnitude of the cuing effect falling off as the SOA increased, and possibly (but by no means necessarily) reversing at the longest interval. Such a reversal is known as inhibition of return (IOR), a phenomenon whereby responses to targets on the validly cued side tend to be slower than to those in the invalidly cued side at cue-target SOAs exceeding approximately 200-300 ms

(e.g., Klein, 2000; Posner & Cohen, 1984). The results of Experiment 6 should therefore inform our understanding of the consequences of the presentation of linguistic cues on the distribution of spatial attention.

The spatial cuing effect of linguistic directional cues was examined in both crossmodal (auditory cues and visual targets) and unimodal (visual cues and visual targets) conditions. A masked crossmodal condition was also included in which a target was presented briefly and then overlaid by a mask. Varying the duration of the mask relative to the target provides a conventional means of moving performance off ceiling, and hence allowing one to perform signal detection theory analyses on the results. In particular, such analyses were performed to examine whether the presentation of the verbal cues would lead to a change in detection sensitivity for the targets (see Green & Swets, 1966; Macmillan & Creelman, 1991, for a detailed explanation of the principles behind signal detection theory). The present investigation of any automatic (i.e., exogenous) orienting of spatial attention following the presentation of spatially-nonpredictive verbal directional cues should also have important implications for the design of warning signals, as well as being of theoretical interest. For instance, one could imagine a situation in which the presentation of the directional cue 'left' by an in-car navigation system might lead a driver to fail to detect (and hence respond to) a sudden event occurring on the right of the car.

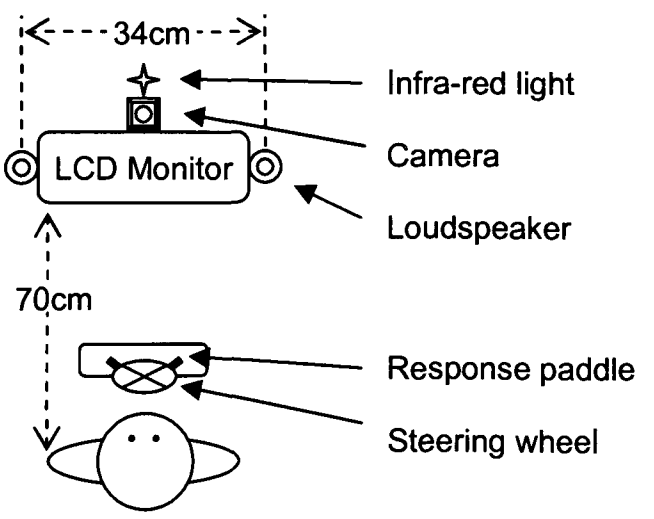


Figure 3.1 Schematic bird's-eye view of the experimental set-up in Experiment 6.

3.1.2 Methods

3.1.2.1 Participants

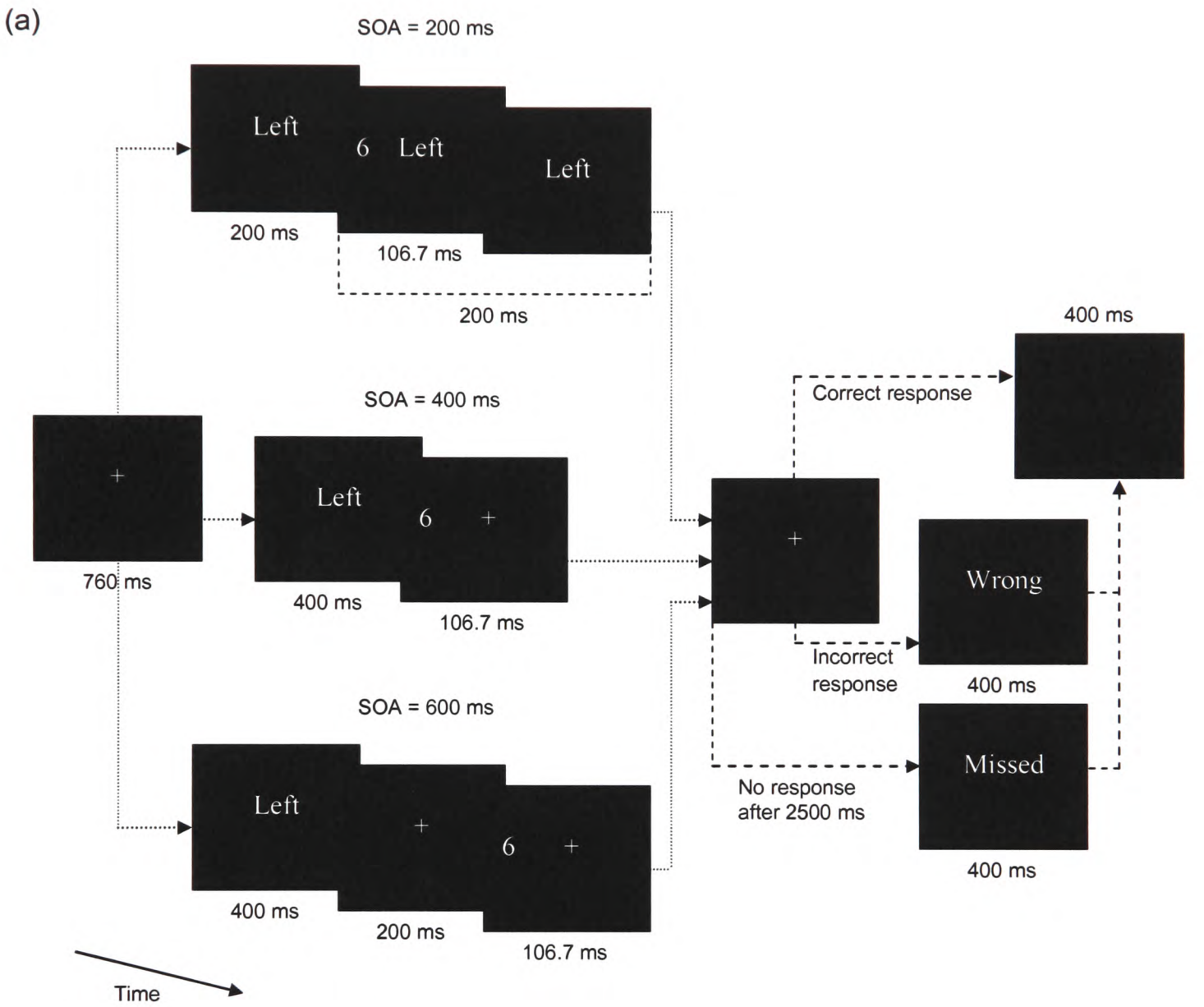
Thirty native English speakers (mean age of 25 years, age range from 19-37 years; 14 males and 16 females) took part in Experiment 6. All of the participants had normal hearing and normal, or corrected-to-normal, vision. Twenty-seven of the participants were right-handed, and three were left-handed by self-report. The experiment lasted for approximately 40 min. The participants received a £5 UK sterling gift voucher in return for taking part. The experiments were conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford.

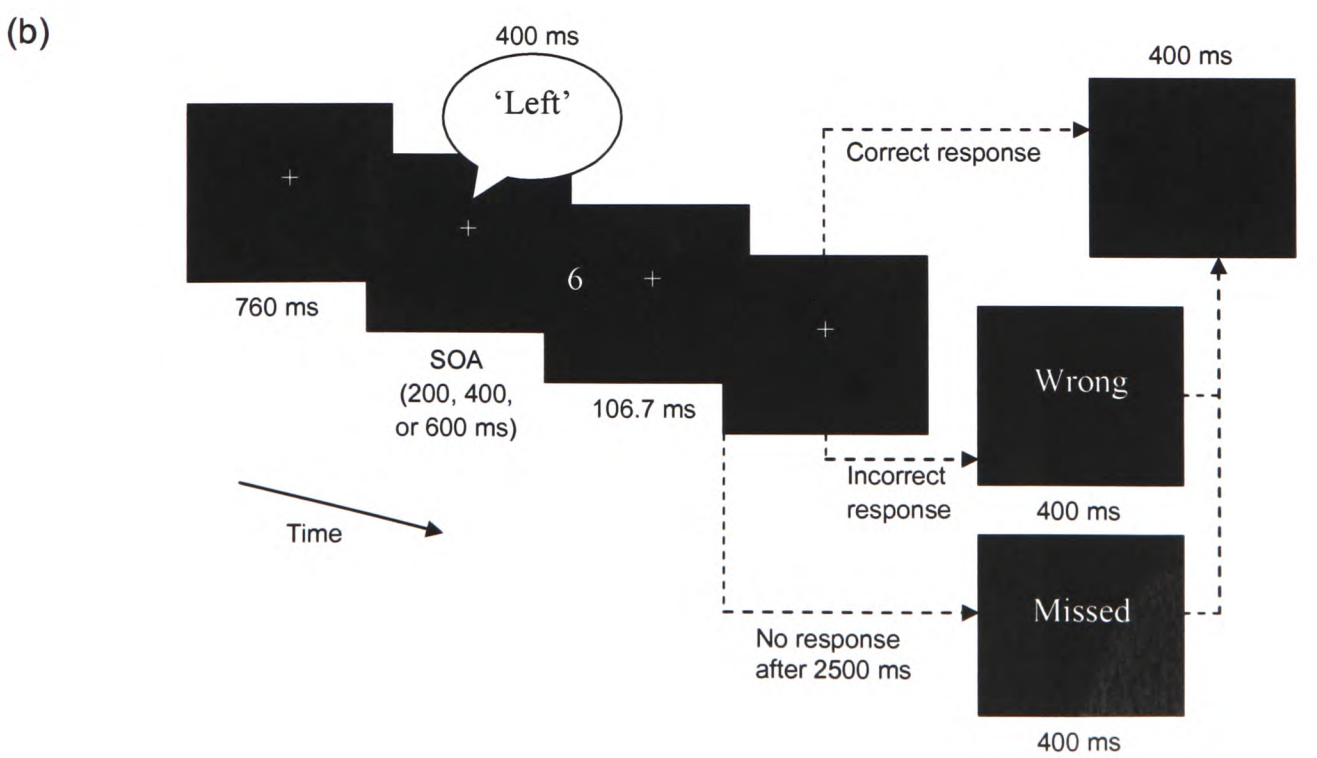
3.1.2.2 Apparatus

The participants were seated in the middle of a darkened experimental booth and were instructed to give their responses by pressing one of two paddle levers on a Logitech® MOMO® Racing Force Feedback Wheel (Logitech Inc., Fermont, CA) mounted on a desk situated directly in front of them. These two paddle levers were connected to response keys placed behind the paddle levers in order to ensure millisecond accuracy when recording response latencies. The visual stimuli were presented on a 43.2 cm (17 inch) LCD monitor (screen refresh rate of 75 Hz) positioned 70 cm directly in front of the participants (see Figure 3.1). Two loudspeaker cones, aligned vertically with the middle of the monitor, were placed 34 cm apart, one attached to either side of the monitor. A camera (CL600, FVS, England) and an infra-red light (Mini 50 W Infrared IP66 Flood Lamp, Molynx Ltd., Newport,

England) were mounted above the monitor in order to enable the experimenter to ensure that the participants maintained central fixation throughout the experiment.

3.1.2.3 Stimuli





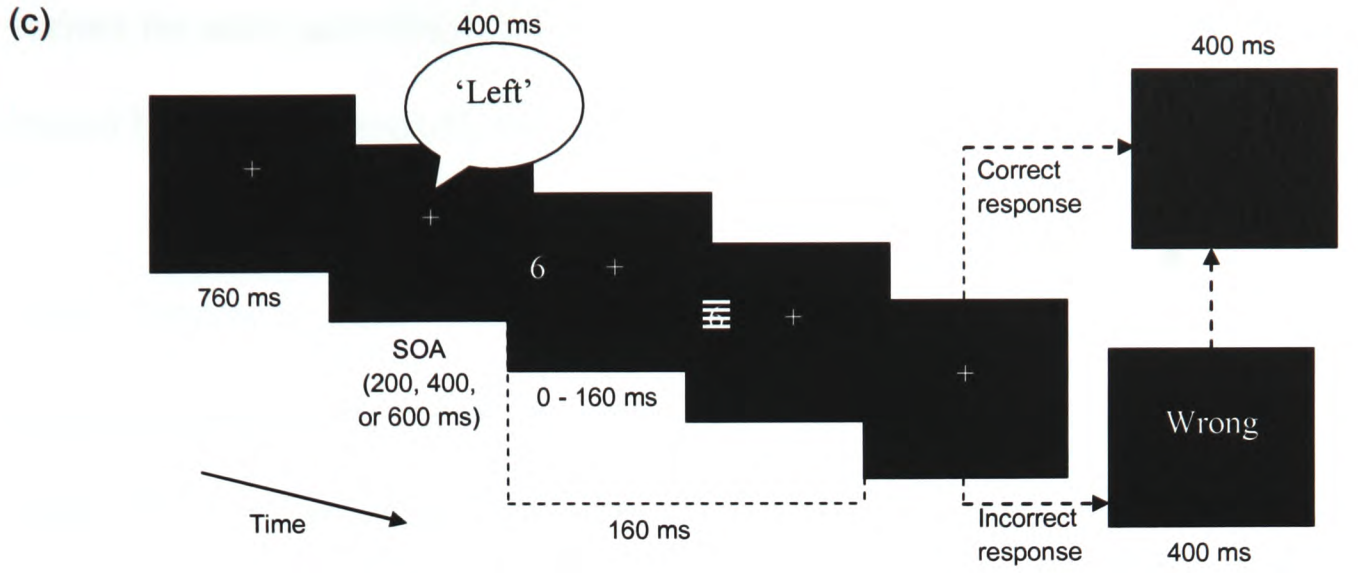


Figure 3.2 Illustration of the visual stimuli and the trial sequences for the (a) unmasked visual, (b) unmasked auditory, and (c) masked auditory conditions of Experiment 6.

An 8 mm x 8 mm cross presented at the centre of the screen served as the central fixation point. The visual cues consisted of the words 'right' (32 mm x 11 mm) and 'left' (23 mm x 11 mm) presented from the centre of the screen ('Times New Roman' font; font size 48). The target digits '6' and '9' (8 mm x 12 mm; 'Times New Roman' font; font size 48) were presented 142 mm to the left or right of the fixation cross. The feedback cues 'wrong' and 'missed' were also presented from the centre of the screen. All of the characters were presented in white on a black background.

The visual masking stimulus consisted of a 19 mm x 19 mm black and white cosine grating (oriented horizontally) superimposed directly over the target digit (see Figure 3.2). Specifically, the total digit plus mask presentation time was always fixed at 160 ms. In the first 10 trials in the masked auditory practice block, the target digit was presented for 106.7 ms, followed by a mask superimposed on the target digit for 53.3 ms. Thereafter, the target presentation duration was reduced by one frame (i.e., by 13.3 ms) if the average hit rate for the last 10 trials (regardless of condition) exceeded 70% correct, or increased by one frame if the hit rate dropped below 60% correct responses. The aim was to maintain the overall hit rate in the range of 60-70%

correct for each participant. The target and mask durations were carried forward over breaks between the practice and experimental trials.

The verbal cues consisted of the words 'left' and 'right' as pronounced by a male voice in the MSN Encarta® Online Dictionary (retrieved from http://images.encarta.msn.com/xrefmedia/sharemed/targets/audio/pron/a30/A3029200.wav and http://images.encarta.msn.com/xrefmedia/sharemed/targets/audio/pron/a45/A4547200.wav; downloaded on 08-07-2004) presented at 57-58 dB(A) as measured from the participant's ear position. The audio files were edited with Any Sound Recorder version 1.00 (retrieved from http://www.any-sound-recorder.com/download.html; downloaded on 08-07-2004) to ensure that the duration of the two verbal cues was matched at 400 ms. The verbal cues were always presented simultaneously from both loudspeaker cones to create the subjective impression of a verbal cue originating from the centre of the display.

3.1.2.4 Design

The experimental session consisted of one block of 12 unmasked auditory practice trials, two blocks of 120 unmasked auditory experimental trials, one block of 40 masked auditory practice trials, two blocks of 120 masked auditory experimental trials, and lastly, one block of 120 unmasked visual experimental trials. All of the participants completed the experimental blocks in the same order. The cue-target SOA (200, 400, or 600 ms), cue direction (left or right), target position (left or right), and target digit (6 or 9) factors were crossed and each condition was randomly chosen and equiprobable within each block of experimental trials. The directional cues used in the experiment were nonpredictive of the target position, meaning that the cues indicated

the side of the target on 50% of trials (and the non-target side on the remaining 50% of trials).

3.1.2.5 Procedure

The participants were instructed to fixate on the central cross throughout each block of experimental trials, and to maintain their fixation on the centre of the screen in the unmasked visual condition when the visual cue words were presented. Prior to the start of each block of experimental trials, the participants were told whether the speed (for the unmasked auditory and visual blocks) or accuracy (for the masked auditory blocks) of their responses was more important. The response paddle (left or right) associated with each target stimulus (6 or 9) was counterbalanced across participants.

Each trial began with the presentation of the central fixation cross which remained on the screen for the duration of the trial (except in the unmasked visual condition where the visual cues were presented centrally). After 760 ms, the cue (either auditory or visual) was presented for 400 ms (see Figure 3.2). The target digit (6 or 9) appeared on either the left or the right, 200, 400, or 600 ms after the onset of the cue. In the unmasked auditory and unmasked visual blocks, the target digit remained on the screen for 106.7 ms. In the masked auditory blocks, the target digit was overlaid by a mask after a specific delay (calculated on the basis of a participant's average hit rate for the last 10 trials; see Chapter 3.1.2.3). The total target digit plus mask presentation time was 160 ms, after which time the target and any mask was removed until a response was given.

The word 'Wrong' was displayed on the screen for 400 ms after an incorrect response. The word 'Missed' was displayed on the monitor for 400 ms if no response

had been recorded within 2500 ms of target onset in the unmasked auditory and unmasked visual blocks (but not in the masked auditory condition as it was an unspeeded condition, meaning that participants must give a response before moving on to the next trial). The inter-trial interval was 400 ms, during which time the screen remained blank until the onset of the fixation cross at the start of the next trial.

3.1.3 Results

Separate ANOVAs were performed on the RT and error data from each of the experimental conditions (i.e., unmasked visual, unmasked auditory, and masked auditory) to assess what effect the directional cues had on target discrimination performance. The two factors in each within-participants design were SOA (200, 400, or 600 ms) and cue validity (valid vs. invalid). Table 3.1 shows the mean RTs, percentages of errors, and IE scores for the three experimental conditions.

3.1.3.1 Unmasked visual condition

Analysis of the RT data revealed a significant main effect of SOA, $F(2,58) = 56.8$, $MSE = 994.3$, $p < .001$, with response latencies decreasing as the SOA increased (618 ms at the 200 ms SOA; 574 ms at the 400 ms SOA; and 560 ms at the 600 ms SOA). This presumably reflects the well-known alerting effect (e.g., Posner, 1978; Spence & Driver, 1997a; Zeigler et al., 2001). There was no significant main effect of cue validity, $F(1,29) = 1.0$, $MSE = 1044.5$, $p = .32$, but the interaction between SOA and cue validity was highly significant, $F(2,58) = 5.2$, $MSE = 747.5$, $p = .008$ (see Figure 3.3a). Subsequent paired comparison t-tests revealed that the intramodal visual cuing effect was significant at the 200 ms SOA ($M = 20$ ms), $t(29) = 2.2$, $p = .033$, but

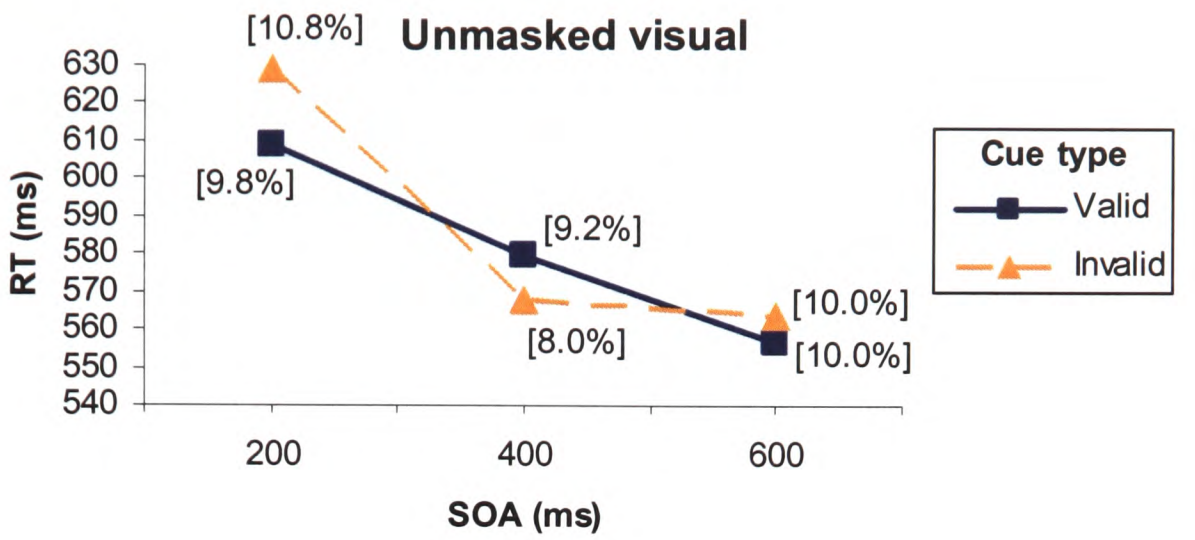
not at the 400 ms SOA (M = -12 ms), $t(29)$ = -1.9, p = .07, nor at the 600 ms SOA (M = 7 ms), $t(29)$ = 1.0, p = .33.

Table 3.1 Mean RTs (ms), percentages of errors (%), IE scores (ms), and their standard errors (in parentheses), as a function of SOA (ms) and Cue Validity, together with the Mean Cuing Effects.

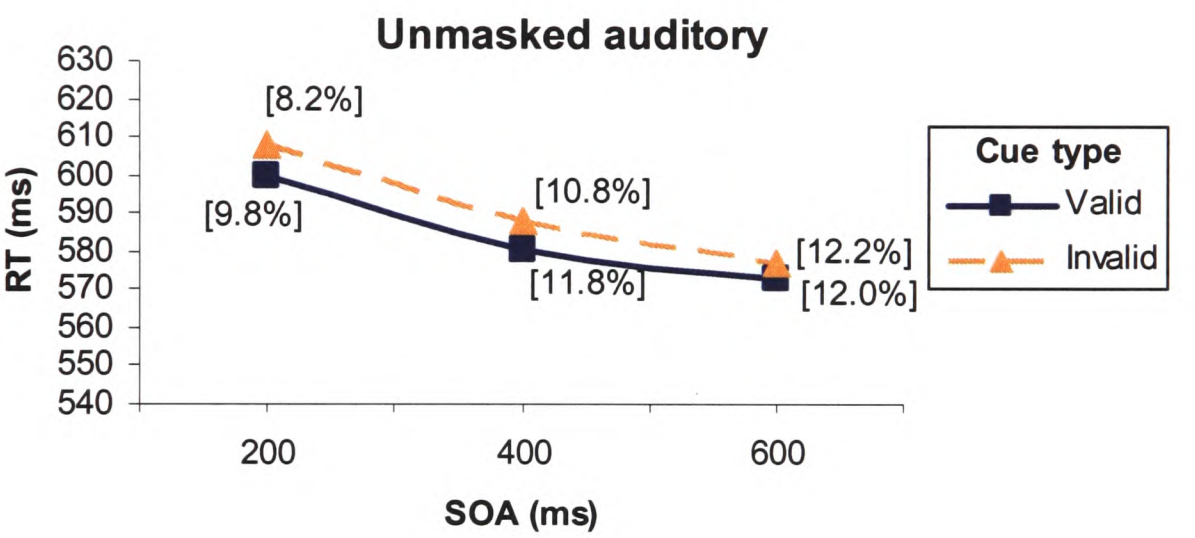
			Cue Validity								
			Valid			Invalid			Mean Cuing Effect		
Cue Type	Target Masking	SOA	RT	% error	IE*	RT	% error	IE	RT	% error	IE
Visual	No mask	200	608 (18)	9.8 (1.6)	682 (25)	628 (18)	10.8 (1.6)	718 (30)	20	1.0	36
		400	580 (16)	9.2 (1.3)	641 (20)	568 (15)	8.0 (1.6)	623 (22)	-12	-1.2	-18
		600	556 (18)	10.0 (1.7)	624 (23)	563 (16)	10.0 (1.6)	630 (20)	7	0.0	6
Auditory	No mask	200	600 (17)	9.8 (1.9)	681 (31)	608 (19)	8.2 (1.4)	672 (29)	8	-1.6	-9
		400	581 (17)	11.8 (1.8)	669 (27)	588 (20)	10.8 (1.8)	672 (32)	7	-1.0	3
		600	573 (19)	12.0 (2.0)	665 (32)	577 (17)	12.2 (2.2)	671 (30)	4	0.2	6
Auditory	Masked target	200	758 (27)	31.3 (1.5)	1129 (55)	800 (33)	35.9 (1.7)	1280 (64)	42	4.6	151
		400	745 (30)	32.2 (1.3)	1108 (48)	759 (35)	34.6 (1.2)	1172 (61)	14	2.4	64
		600	759 (36)	32.2 (1.4)	1132 (60)	755 (33)	33.9 (1.5)	1145 (44)	-4	1.7	13

*** IE scores were calculated by dividing the mean RT by the proportion of correct responses for each condition for each participant (see Townsend & Ashby, 1983).**

(a)



(b)



(c)

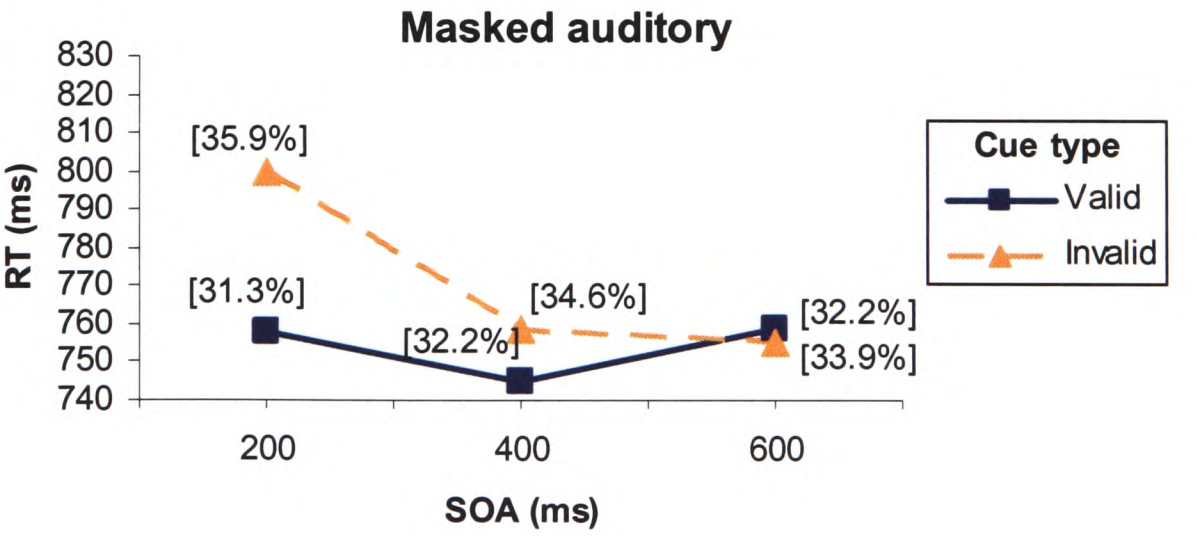


Figure 3.3 Graphs highlighting the mean cuing effects reported in (a) unmasked visual, (b) unmasked auditory, and (c) masked auditory conditions. The numbers in parentheses indicate the percentages of errors associated with the chosen RT point.

Analysis of the error data revealed no significant main effect of SOA, $F(2,58) = 1.4$, $MSE = 38.0$, $p = .26$, or cue validity, $F(1,29) < 1$, *n.s.*, nor any interaction between these two factors, $F(2,58) < 1$, *n.s.* Importantly, however, participants responded more accurately on valid trials than on invalid trials at the shortest interval, thus allowing one to rule out a speed-accuracy trade-off account of the RT cuing effect reported at this interval (see Müller & Findlay, 1987). By contrast, the data revealed a trend toward a speed-accuracy trade-off at the 400 ms SOA, thus negating the trend in the RT data toward an IOR effect (see Klein, 2000; Posner & Cohen, 1984) at this interval.

3.1.3.2 Unmasked auditory condition

Analysis of the RT data revealed a significant main effect of SOA, $F(2,58) = 11.9$, $MSE = 1100.8$, $p < .001$, with response latencies decreasing as the SOA increased (mean RT of 604 ms at the 200 ms SOA; 584 ms at the 400 ms SOA; and 575 ms at the 600 ms SOA), just as in the unmasked visual condition (see Figure 3.3b). There was, however, no significant main effect of cue validity, $F(1,29) = 1.8$, $MSE = 993.7$, $p = .19$, nor (in contrast to the unmasked visual condition) any interaction between SOA and cue validity, $F(2,58) < 1$, *n.s.*, suggesting the absence of any crossmodal cuing effect on discrimination latencies in response to the unmasked visual targets following the presentation of the verbal cues.

Analysis of the error data also revealed a significant main effect of SOA, $F(2,58) = 4.5$, $MSE = 33.3$, $p = .015$, with response accuracy declining as the SOA increased (mean error rates = 9.0%, 11.3%, and 12.1%, at the 200, 400, and 600 ms SOAs, respectively). However, the main effect of cue validity was not significant, $F(1,29) = 1.3$, $MSE = 21.9$, $p = .26$, nor was the interaction between cue validity and

SOA, $F(2,58) < 1$, *n.s.* It is worth noting that although participants responded somewhat more rapidly on validly-cued trials (M = 585 ms) than on invalidly-cued trials (M = 591 ms) overall, this trend was offset by a reverse trend in the error data, with participants making lightly more mistakes on validly-cued trials (M = 11.2%) than on the invalidly-cued trials (M = 10.4%). Taken together, these results therefore suggest the presence of a speed-accuracy trade-off in the performance data in this speeded crossmodal cuing condition. Overall, the results suggest that while visually-presented linguistic cues lead to an exogenous shift of spatial attention in the cued direction, auditorily-presented verbal cues do not.

3.1.3.3 Masked auditory condition

Analysis of the error data revealed a significant main effect of cue validity, $F(1,29) = 5.8$, $MSE = 65.8$, $p = .022$, with participants making significantly fewer mistakes on validly-cued trials (M = 31.9%) than on invalidly-cued trials (M = 34.8%) overall. The main effect of SOA was, however, not significant, $F(2,58) < 1$, *n.s.*, nor was the interaction between SOA and cue validity, $F(2,58) < 1$, *n.s.* The fact that participants tended to respond somewhat more rapidly on validly-cued trials than on invalidly-cued trials (at all three SOAs; see Figure 3.3c) allows one to rule out of a speed-accuracy trade-off account of the cuing effects reported in these data. The data from the masked auditory condition therefore support the existence of a crossmodal facilitatory cuing effect. That is, the presentation of directional word cues really does appear to lead to an automatic shift of visual spatial attention in the direction indicated by the cue.

The manipulation of target duration ensured that performance was in the range of 60-70% correct, thus meaning that a signal detection analysis (e.g., Green & Swets,

1966) of the accuracy (error) data from the masked auditory condition could be performed. The detection sensitivity (*d'*) and response criterion (*ß*) values of the masked auditory condition were analysed using separate ANOVAs, with the within-participants factors of SOA and cue validity. The analysis of the *d'* data revealed a significant main effect of cue validity, $F(1,29) = 6.3$, $MSE = 0.2$, $p = .018$, but no main effect of SOA, $F(2,58) < 1$, *n.s.*, nor any interaction between these two factors, $F(2,58) = 1.0$, $MSE = 0.3$, $p = .37$. These results therefore show that participants were better able to detect targets (i.e., the perceptual representation of the masked visual targets was better) when they were validly cued than when they were invalidly cued across all three SOAs. The analysis of *ß* revealed no significant main effect of either SOA, $F(2,58) = 1.9$, $MSE = 0.1$, $p = .16$, or cue validity, $F(1,29) < 1$, *n.s.*, nor any interaction between these two factors, $F(2,58) < 1$, *n.s.* These results therefore suggest that while verbal directional cues may not facilitate speeded responses to unmasked visual targets presented on the cued side, they can enhance the acuity of the perceptual representation of masked visual stimuli subsequently presented there (cf. Schneider & Bavelier, 2003).

3.1.4 Discussion

The results of Experiment 6 show that the central visual presentation of the directional words 'left' and 'right' (even when they are spatially-nonpredictive with regard to the likely location of a subsequently-presented visual target) leads to an automatic and involuntary shift of spatial attention to the side indicated by the cue (cf. McCarthy & Beaumont, 1996). This short-lasting intramodal visual cuing effect (elicited by the presentation of the visual cue) was maximal at the shortest SOA (200 ms) as predicted, and dissipated at the longer intervals. This pattern of intramodal

visual cuing effects is consistent with previous studies that have shown maximal cuing effects from spatially-nonpredictive centrally-presented visual directional cues (such as arrows and eye-gaze cues) at short SOAs (e.g., 100-150 ms; Friesen & Kingstone, 2002; Hommel et al., 2001; Langton & Bruce, 1999).

Spatial cuing effects were demonstrated following the presentation of visual cues (unmasked visual condition), but not following auditory cues in the unmasked auditory condition. Contrary to the hypothesis outlined earlier, Experiment 6 failed to obtain any attentional orienting effect in the unmasked crossmodal condition (i.e., no visual attentional orienting was observed in response to the presentation of the auditory cue) when participants had to make a speeded response to unmasked visual targets, despite there being clear evidence that the auditory cue elicited a robust crossmodal alerting effect. This study perhaps provides the first empirical evidence demonstrating a null effect of verbal directional cues on the spatial distribution of visual attention under conditions where visual cues were shown to be effective (cf. Frick, 1995).

The fact that the trend in the RT data toward a crossmodal cuing effect in the unmasked auditory condition failed to reach statistical significance may have been caused by the demands of the task. In particular, the participants might have found it too easy to ignore the verbal cues while focusing on the unmasked visual targets (see Miller, Heise, & Lichten, 1951). By contrast, in the masked auditory condition, the discrimination task was much more attention-demanding (i.e., one could argue that the perceptual load was higher; cf. Lavie, 2005; Rees & Lavie, 2001), and so participants might have been less able to suppress any automatic influence of the verbal cues (cf. Spence et al., 2000c). Consequently, crossmodal cuing effects, such as the improved visual sensitivity reported in the validly cued than in the invalidly cued

trials, may become more evident as the perceptual load of the task increases (though see also Weissman, Warner, & Woldorff, 2004).

The results of the signal detection analyses on the data from the masked auditory condition converge with the results of a study of peripheral auditory cuing reported by McDonald, Teder-Salejarvi, and Hillyard (2000). They showed that the presentation of a nonpredictive pink noise burst could orient spatial attention, and improve the perceptibility of a subsequently-presented peripheral visual target (a green light) presented at the same side, as opposed to the opposite side (cf. Kato & Kashino, 2001; Mondor & Breau, 1999). As pointed out by McDonald et al., the use of signal detection measures enables researchers to isolate the purely perceptual consequences of biased attentional processing from the post-perceptual decisional and response-related processes that may also influence performance under many conditions (such as under conditions of speeded discrimination performance; cf. Spence et al., 2004; Watt, 1991, pp. 205-6). According to this logic, the facilitation of response latencies reported in many other previous crossmodal spatial cuing studies may merely reflect facilitated motor responses rather than an enhancement in the perceptual salience of spatially-relevant stimuli presented in a different sensory modality to the cue. While both types of facilitation may be of interest in an applied setting (given the need to facilitate behavioural responses to potential emergency situations), it is the perceptual aspect of attentional facilitation that has been of most interest theoretically.

Given the simplicity of the experimental design used in Experiment 6, and the fact that only spatially-nonpredictive cues were used, it should not have been difficult for participants to ignore the cues while focusing on the peripheral visual discrimination task. Indeed, one might have expected that it would be easier to ignore

the auditory cues than to ignore the visual cues because the participants could presumably have performed the task by selectively attending just to the visual modality. Note though that research has shown that participants may find it somewhat harder to ignore sounds presented at fixation than sounds from other (non-visually fixated) directions (Spence et al., 2000c).

One of the motivations for conducting Experiment 6 was to examine whether the presentation of verbal directional cues would automatically orient an interface operator's spatial attention, in a manner similar to that found using nonverbal auditory directional spatial cues (e.g., see Spence et al., 2004, for a recent review). The results would appear to suggest that participants could not voluntarily suppress the learned semantic meaning of directional word cues (as evidenced in the visual and masked auditory conditions). Previous crossmodal cuing studies that have used nonverbal directional spatial cues, such as white noise or pure tone bursts, have demonstrated robust automatic crossmodal cuing effects between audition and vision (see Spence et al., 2004). Thus, it could be argued that it would be more effective to use nonverbal spatial directional cues than to use verbal directional cues (which, after all, will not be universally effective, but instead restricted only to those who understand the language in which the message is spoken) in order to direct an interface operator's attention rapidly and automatically in a particular direction. On the other hand, any such benefits must be weighed against the problems that have been identified with people correctly localizing auditory spatial warning signals that have been reported in certain previous studies (cf. Catchpole et al., 2004; Geissler, 1915).

None of the studies published to date that have examined the consequences of the central presentation of word cues have demonstrated IOR. Previous laboratory-based studies that have managed to demonstrate IOR in a discrimination task setting

have typically only shown it at relatively long SOAs (i.e., in the range of 700-1000 ms in intramodal visual cuing studies; see Lupianez, Milan, Tornay, Madrid, & Tudela, 1997; cf. Pratt, Kingstone, & Khoe, 1997). Peripheral uninformative cues (i.e., cues that may occur at the target location though do not necessarily predict it) have been shown to elicit IOR, whereas centrally-presented uninformative symbolic cues have not (e.g., Jonides, 1981; Kingstone & Pratt, 1999; Müller & Rabbitt, 1989). The failure to observe any IOR effect in Experiment 6, or for that matter in any other previous symbolic central cuing study, therefore suggests that the mechanism governing the facilitatory spatial cuing effect evidenced in studies using central nonpredictive cues may be qualitatively different from those that are typically elicited in studies in which peripheral nonpredictive cues have been used (see Rafal, Calabresi, Brennan, & Sciolto, 1989). Taken together, the results of the cuing studies that have been published to date argue for the existence of at least two distinct mechanisms governing the differential cuing effects in spatial attention.

What then is the nature of the attentional orienting triggered by linguistic directional cues? Do linguistic directional cues trigger an exogenous (reflexive) shift of spatial attention and/or an endogenous (voluntary) one? Tipples (2002) has argued that linguistic directional cues, such as a central arrow cue, act to 'push' attention away from the centre of the display in the direction indicated by the cue. By contrast, other researchers have argued that the learnt meanings conveyed by directional words may prime some arbitrary representation of 'space' that acts to 'pull' (or attract) attention in the cued direction, just as the presentation of a peripheral visual cue will also automatically capture attention (e.g., Langton et al., 2000; Posner & Cohen, 1984; see Logan, 1995, for a review). Note also the notion of 'projective relations' and 'deictic relations' of spatial language (see Gibson & Kingstone, 2006; Logan, 1995):

While 'projective relations' refers to specifying a spatial location with respect to a frame of reference, 'deictic relations' relates to the varying semantic meanings of a linguistic term that is dependent on the context in which the term is spoken.

Cognitive science researchers have also used verbal directional cues to study various other aspects of human information processing. For example, Dyer (1972) investigated the potential processing advantage of moving directional stimuli in a Stroop-like task using congruent and incongruent word stimuli. Dyer assessed naming latencies to report the direction of movement of the directional words ('up', 'down', 'right', 'left', and 'XXXX') that could either move in a direction that was congruent or else incongruent with the word itself, after variable pre-exposure intervals. A significant Stroop interference effect was evidenced in the incongruent conditions (see also Seymour, 1973; Shor, 1970; Stroop, 1935; Virzi & Egeth, 1985, for similar results). Moreover, naming directional words has been shown to be less susceptible to interference by the direction of movement of those words than vice versa. In sum, research suggests that the relevance of information that is incongruent with a person's task will determine whether that information impairs or, in certain cases, facilitates information processing (cf. Logan & Zbrodoff, 1979).

The findings from laboratory-based studies of verbal cuing are not, however, only of theoretical interest, but may also be of relevance in applied domains (e.g., Selcon et al., 1995). With respect to the semantic element embedded in visual and auditory cues, Laurienti, Kraft, Maldjian, Burdette, and Wallace (2004) reported that the semantic congruency of redundant cues (e.g., a blue circle presented together with the word cue 'blue' presented visually or auditorily) are important for multisensory, but not unimodal, tasks. If the auditory or visual presentation of word cues can lead to an effortless and automatic shift of spatial attention in a particular direction even

when they are spatially-nonpredictive with regard to the likely target location, it may have potential value in applied interface design. The implication may be particularly valuable for systems where a large amount of spatial information has to be presented, such as for in-car navigation systems (e.g., Cnossen et al., 2004). Note though that the meaning of directional words when presented alone (as in Experiment 6) will probably be dependent on the particular frame of reference in which they are interpreted (cf. Driver, 1999). Indeed, the referent of directional word cues can only be understood unambiguously by an interface operator if they know the speaker's frame of reference. Given the prevailing idea of user-centred design, designers should consider potential confusions caused by the use of ambiguous directional words, particularly in applications where a user's perspective may be constantly changing.

One question for future research will be to examine the effect of the extent of language mastery on semantic spatial cuing effects. Developmental studies have already shown that the attention of infants as young as two months is more attracted to speech sounds than to other sounds (Vouloumanos & Werker, 2004). It would therefore be interesting to examine the age at which the orienting or spatial cuing effect emerges in native English speakers, and the extent to which verbal directional cues affect the spatial distribution of attention in adults for whom English is not their native language. Future studies can introduce extra components that require participants to process language actively in the verbal cuing and/or target discrimination stages to examine how the magnitude of any spatial cuing effects are affected when language is processed actively. It would also be interesting to investigate whether increasing the perceptual load of the task (e.g., Lavie, 2005; Rees & Lavie, 2001) reduces the symbolic cuing effects elicited by the presentation of word cues.

CHAPTER 4

VIBROTACTILE SPATIAL CUING IN DRIVING

The one human sense that could potentially be utilized far more in driving is the sense of touch. In fact, 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, 2000a; Sklar & Sarter, 1999; Triggs, Lewison, & Sanneman, 1974; van Erp et al., 2004; Zlotnik, 1988). Part of the reason for this growth of interest is related to 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 (e.g., 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, Spape, & van Erp, 2004); to facilitate orientation awareness in microgravity or deep-sea diving environments (Bhargava et al., 2005; Rochlis & Newman, 2000; Rupert, 2000a; 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 an

interface operator's spatial attention (Gilliland & Schlegel, 1994; Sklar & Sarter, 1999; Tan et al., 2003).

The integration of touch into the traditional focus on vision and audition in automobile design can now be supported by robust neuropsychological research on the multisensory integration of sensory information (see Calvert et al., 2004; Spence & Driver, 2004). Given the high utilization of vision in driving (e.g., Sivak, 1996), it seems plausible to present certain information to the tactile sense when the visual channel is heavily loaded (or perhaps even overloaded). The tactile sense has been demonstrated to be automatically alerting, inherently directional, private to the driver, and that unlike vision, it cannot be 'shut out' voluntarily (see Gilmer, 1960, 1961; see also Burnett & Porter, 2001; Campbell et al., 1996; Hennessy, 1966; Lee et al., 2004).

The experiments reported in this chapter were therefore designed to investigate the possibility of using spatially-distributed vibrotactile warning signals to direct a person's attention to the front versus rear in a simulated car driving task (cf. Enriquez & MacLean, 2004; Fenton, 1966; van Erp & van Veen, 2001). The motivation for this series of experiments 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, 2000b).

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 with regards to 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 (or hand; see Spence et al., 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 et al., 1978; Spence et al., 2000b), 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., 2000b, 2001c). 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, 2000b, studies). Thus, while such results may be able to 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), one 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 itself.

Two laboratory-based experiments were thus designed to assess the possibility of using spatially-distributed vibrotactile warning signals to direct a person's attention to the front or rear. Vibrotactile stimuli were presented via a belt worn around a participant's waist. Experiment 7 examined performance under conditions where these vibrotactile stimuli were predictive (i.e., 80% valid) with regard to the direction of a potential critical visual driving event, while Experiment 8 looked at the potential utility of nonpredictive vibrotactile cues (i.e., 50% valid). Further, a driving simulator study (Experiment 10) was also conducted to examine the potential use of vibrotactile cuing in driving in a more realistic testing environment.

4.1 Experiment 7

4.1.1 Methods

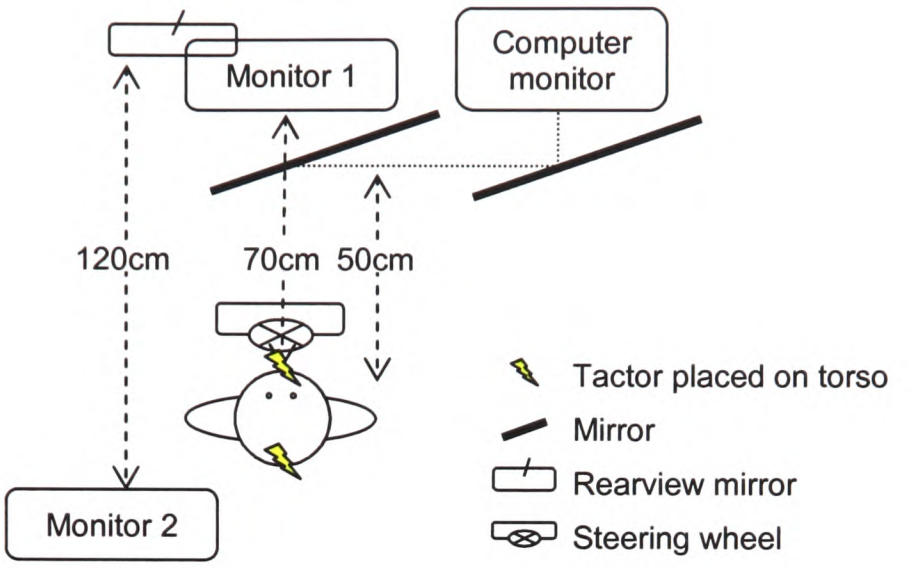
4.1.1.1 Participants

Sixteen participants (mean age of 23 years, age range from 19-35 years; 7 males and 9 females) took part in Experiment 7. All of the participants had a valid UK driving licence, and had, on average, been driving for 4.8 years (range from 6 months to 12 years). 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. None of the participants had taken part in any of the preceding auditory cuing experiments. Ten participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation. The experiment lasted for 60 min. The experiments were conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford.

4.1.1.2 Apparatus and materials

The participants were seated in the middle of an experimental booth and were instructed to hold a Logitech® MOMO® Racing Force Feedback Wheel (Logitech Inc., Fermont, CA) 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

(a)



(b)

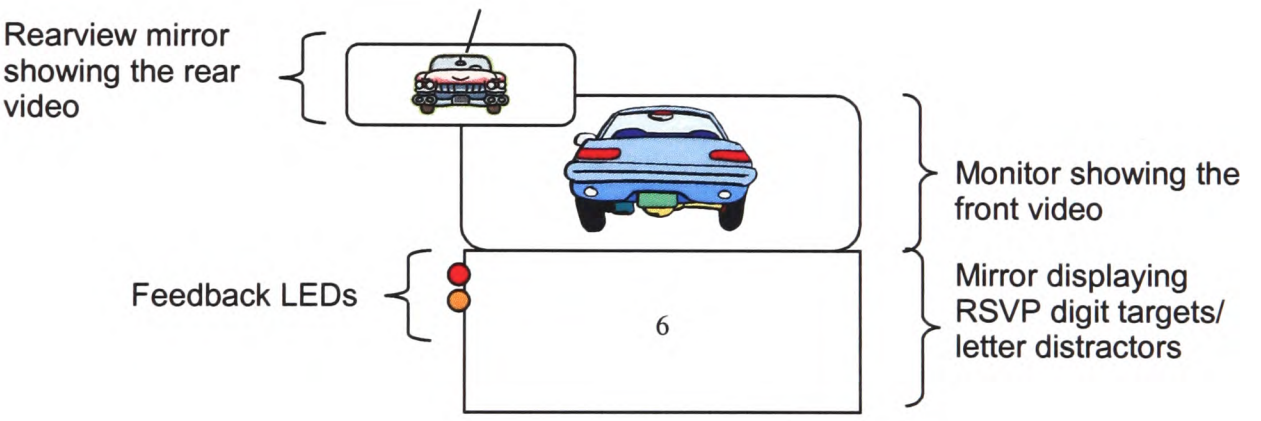


Figure 4.1 (a) Schematic bird's-eye view and (b) participant's-eye view of the experimental set-up used in Experiments 7 and 8.

participants (at a distance of 50 cm) was used to display the RSVP stimuli (see Figure 4.1). 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 x 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 x 1.85 x 1.07 cm, VBW32, Audiological Engineering Corp., Somerville, MA) 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 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 Figure 4.1). The RSVP characters were 8.3 x 8.5 mm in size in the mirror.

The video clips were the same clips used previously in Experiments 1-5 (see Chapter 2.2.1.2; Figure 2.2).

4.1.1.3 Design & Procedure

The design and procedure were exactly the same as that used previously in the Experiments 1-5, with the sole exception that vibrotactile cues that correctly predicted the direction of the visual driving event on 80% of the trials were used instead of auditory cues (see Figure 4.2).

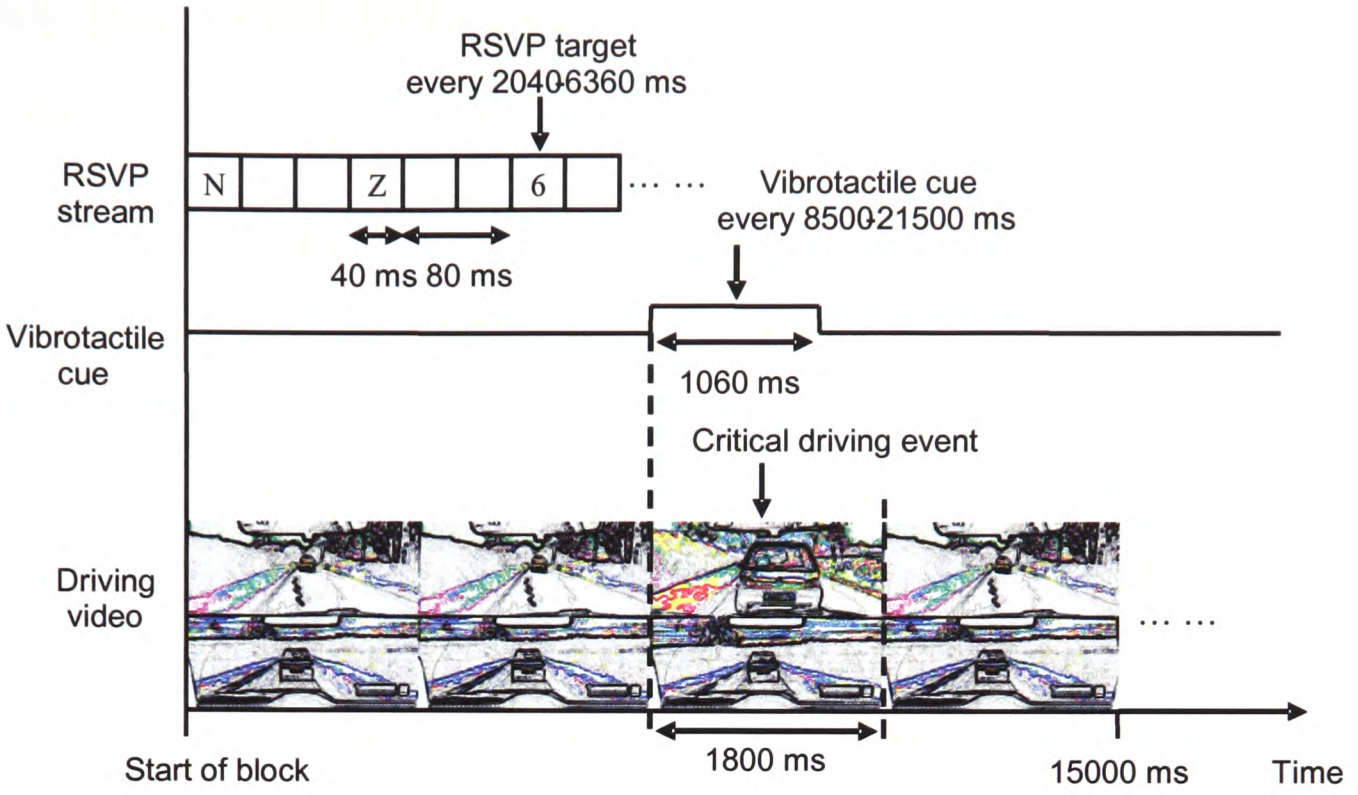


Figure 4.2 A schematic timeline showing the temporal sequence of events in Experiments 7 and 8.

4.1.2 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. Trials with an incorrect response were discarded from the RT analysis. An 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 significant 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, $F(1,15) = 16.5$, $MSE = 4208.7$, $p = .001$, with faster responses to critical visual driving events being reported when validly spatially-cued by the vibrotactile stimuli than when invalidly spatially-cued (see Figure 4.3). 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, $t(15) = -3.4$, $p = .004$, and when they occurred at the rear, $t(15) = 3.3$, $p = .005$.

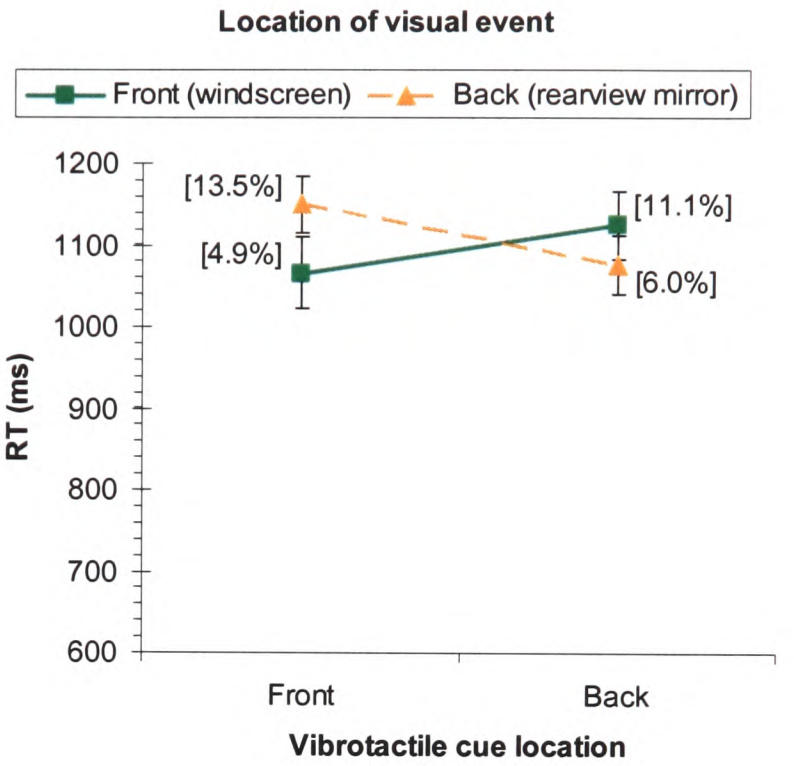


Figure 4.3 Interaction between the location of the spatially-predictive vibrotactile cue and the location of the critical visual events in the driving task in Experiment 7. Percentages of errors are indicated by numerical values in parentheses. Error bar indicate the standard errors of the RTs.

Analysis of the error data (where participants made an incorrect response on the driving task) again revealed no significant main effect of vibrotactile cue location or visual stimulus location, both $F(1,15) < 1$, *n.s.* The interaction between these two factors also failed to reach significance, $F(1,15) = 4.3$, $MSE = 173.5$, $p = .06$. Given that the trend was for participants to make fewer errors in the validly cued than in the invalidly cued trials, a speed-accuracy trade-off account of the spatial cuing effects in the RT data could be ruled out (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 as 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 10500 ms prior to the onset of the next target.

4.1.3 Discussion

The results of Experiment 7 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. These 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. These 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, 2000b, 2001c), in showing that attention can also be cued to the front versus rear. These results are noteworthy because 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. Alternatively, however, participants might have used the informational content of the vibrotactile cues to direct their attention endogenously (rather than exogenously), and hence it may have been 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 used in Experiment 7, it is unclear whether the attentional cuing effects reported in Experiment 7 reflect endogenous orienting, exogenous orienting, or a combination of these two effects (Spence et al., 2000b).

4.2 Experiment 8

Experiment 8 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 Experiment 8 remained unchanged (despite the fact that the cue was no longer spatially-predictive with regard to the likely target location), 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.

4.2.1 Methods

Sixteen new participants (mean age of 24 years, age range from 18-30; 8 males and 8 females) took part in Experiment 8. 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 of the participants. All of the participants had a valid UK driving licence, and had, on average, been driving for 5.7 years (range from 6 months to 11 years). 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. None of the participants had taken part in any of the preceding

experiments. Four participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation.

The apparatus, materials, design, and procedure were exactly the same as in Experiment 7, 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.

4.2.2 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 and visual stimulus location. The analysis revealed no significant main effect of vibrotactile cue location, $F(1,15) < 1$, *n.s.* The main effect of visual stimulus location was, however, significant, $F(1,15) = 10.6$, $MSE = 15554.8$, $p = .005$, 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 also significant, $F(1,15) = 16.7$, $MSE = 1605.2$, $p < .001$. 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 Figure 4.4). Subsequent paired comparison *t*-tests revealed significant spatial cuing effects for visual targets presented both from the front, $t(15) = -4.3$, $p < .001$, and from the rear, $t(15) = 2.4$, $p = .028$.

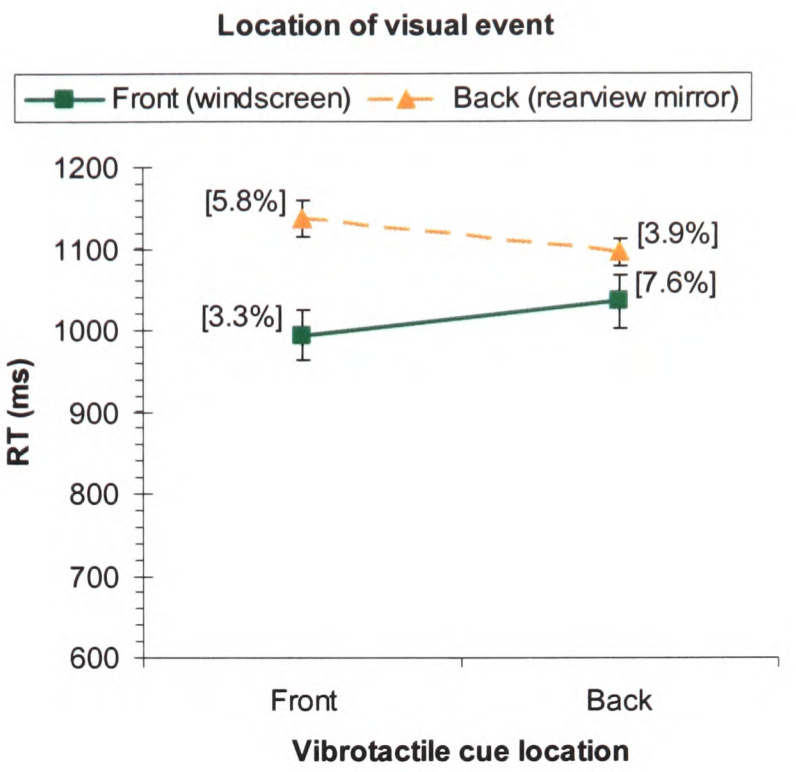


Figure 4.4 Interaction between the location of the spatially-nonpredictive vibrotactile cue and the location of the critical visual events in the driving task in Experiment 8. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs

A similar analysis of the error data showed no significant 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, however, significant, $F(1,15) = 6.1$, $MSE = 25.2$, $p = .027$ (see Figure 4.4). 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, $t(15) = 2.1$, $p = .050$. The participants also made fewer mistakes on validly cued trials than on invalidly cued trials for visual events presented from the rear, $t(15) = -2.1$, $p = .049$, once again ruling out a speed-accuracy trade-off account of the spatial cuing effects in the RT data (Müller & Findlay, 1987).

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 onset of the next target. These results, which are comparable to those obtained in Experiment 7, 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[4.1] (Soto-Faraco, Spence, Fairbank, Kingstone, Hillstrom, & Shapiro, 2002).

4.2.3 Discussion

The participants in Experiment 8 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 Experiment 8 resulted in an exogenous shift of visual attention in the cued direction. Interestingly, although the magnitude of the crossmodal cuing effects reported in Experiment 8 (mean cuing effect of 41 ms and 3.1% in terms of RT and errors, respectively) were numerically somewhat smaller than those reported in Experiment 7 (66 ms, 6.8%), between-experiments analyses of the mean cuing effect revealed that the advantage of spatially-predictive over spatially-nonpredictive cues failed to reach statistical significance in either the RT or error data, $t(30) = 1.3$, p

[4.1] The attentional blink (AB) refers to people's inability to detect the second of two targets presented in close succession, typically in a RSVP stream. The duration of the AB has been shown to vary between individuals, but typically lasts for approximately 400 ms in normal participants (e.g., Raymond, Shapiro, & Arnell, 1992; Soto-Faraco & Spence, 2002; though see Husain, Shapiro, Martin, & Kennard, 1997, for evidence that the AB can last for much longer in certain neuropsychological patients). The AB has been widely studied and the results of numerous studies now show that it provides a reliable measure of the temporal dynamics of attention (e.g., see Arnell & Jolicœur, 1999; Hommel et al., in press; Shapiro, Raymond, & Arnell, 1994).

= .20, and $t(30) = 1.1$, $p = .30$, respectively. There are several possible explanations for this result: First, it may be that the benefits of voluntarily orienting spatial attention to the direction of the predictive cues in Experiment 7 were of a similar magnitude to those resulting from the exogenous orienting of attention to the cued direction in Experiment 8. Alternatively, however, it is also possible that the participants in Experiment 7 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 7), 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 8 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.

Once again, just as in the case of the auditory cuing experiments reported in Chapter 2, the facilitation of responses reported in this chapter was measured at the behavioural level. It will be important from a theoretical perspective to investigate whether this 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 Chapter 5). 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.

4.3 Experiment 9

Finally, in order to assess the effectiveness of the vibrotactile cuing of visual attention per se, a control experiment was conducted. It involved 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 7 and 8). 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 make any such comparison between this control experiment and the other two experiments somewhat problematic. For instance, participants in the no-cue control experiment had to allocate their attention to both tasks, while participants in Experiments 7 and 8 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 7 and 8 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).

Twelve new participants (mean age of 20 years, age range from 18-26 years; 2 males and 10 females) took part in Experiment 9. All reported normal, or corrected-to-normal, vision. Their average driving experience was 2 years (range from 6 months to 8 years). All of the participants were right-handed by self-report. They were naïve

as to the purpose of the experiment, and all received course credit in return for their participation. The apparatus, materials, design, and procedure were exactly the same as those used in Experiments 7 and 8, with the exception that no vibrotactile cues were presented in the driving task.

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 percentage of correct responses in the RSVP task was 57.5% (SE = 4.4%), which is significantly lower than that reported in Experiment 7, M = 70.1%, $t(26)$ = -2.3, p = .028, and Experiment 8, M = 75.4%, $t(26)$ = -3.7, p = .001. The comparison of performance in the no-cue control experiment with that reported in Experiments 7 and 8 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 (for whatever reason) they are sometimes invalid with respect to the direction of the critical driving event than to have no warning signal at all.

4.4 Interim discussion of vibrotactile spatial cuing

Taken together, the results of Experiments 7 and 8 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). These 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.

The findings reported in Experiments 7 and 8 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). Experiments 7 and 8 extend 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 the sense of touch (see Gallace, Tan, & Spence, 2006). Such information transfer can be supported by varying the intensity of the tactile stimuli, and/or perhaps 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 torsos (van Erp, 2005), a recent study shows that participants who have little prior experience of vibrotactile displays cannot correctly count (i.e., at above chance level) the number of stimuli presented when more than four vibrotactile stimuli were presented at any one time (Gallace et al., 2006).

One can interpret the driving task outlined in this chapter as being similar to 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 from the car behind. Even though

the participants in Experiments 7 and 8 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 have to 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 in 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, however, 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 short, the results of Experiments 7 and 8 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. These findings add to the recent growing body of research that has documented the feasibility of presenting directional information to drivers via vibrotactile displays embedded in the driver's seat (e.g., van Erp & van Veen, 2004) or worn around their waist (see Experiments 7 and 8). Consistent evidence from studies on pilots and astronauts has also demonstrated the effectiveness of tactile cues for spatial orientation, navigation, and situational awareness (e.g., Gilson & Fenton, 1974; Rochlis & Newman, 2000; Rupert, 2000b; Traylor & Tan, 2002; Triggs et al.,

1974). However, more research on the specific limitations of tactile communication is needed before its widespread application in areas where either no training or else minimal training is offered to users who need to operate an interface (hence the importance of the notion of 'intuitiveness' to warning signal design; see Rupert, 2000b).

4.5 *Ecological validity*

In the laboratory-based computer driving simulation experiments reported above (Experiments 1-5 and 7-9), the RSVP task 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). However, in theory, this task might not have generated the same kind of attentional demand as that in actual driving. Moreover, the driving stimulation was restricted to the visual, auditory and vibrotactile stimuli provided in the experiments, which might not be comparable to a realistic driving environment. Therefore, it would be interesting to examine if the effects found previously could be reliably obtained in a more realistic testing environment, such as in a high-fidelity driving simulator (cf. Haigney & Westerman, 2001). Note though the significant effects reported in these laboratory-based experiments provide a strong basis for further investigation in a more applied setting.

Therefore, Experiment 10 was designed to investigate the possibility that driver responses to potential front-to-rear-end collision situations could be facilitated by implementing vibrotactile warning signals that indicate the likely direction of the potential collision. If Experiment 10 were able to replicate the effects found previously, it would suggest that the implementation of vibrotactile in-car displays for directional information presentation be practical and useful in preventing front-to-rear-end accidents. Experiment 10 was also conducted to examine whether there could be any 'intuitive' mapping of certain driving actions to a new class of vibrotactile warning signals.

4.6 Experiment 10

4.6.1 Methods

4.6.1.1 Participants

Eleven participants (mean age of 30 years, age range from 20-39 years; 6 men and 5 women) took part in Experiment 10. One additional participant was excluded because she was unable to follow the instruction to drive at the appropriate time headway, resulting in less than 35% of her data being usable (see below for details). All of the participants had a valid UK driving licence and had, on average, been driving for 11.7 years (range 3.5-22 years). The participants reported having driven, on average, 19970 km (12409 miles) in the preceding year (range 4023-80467 km; i.e., 2500-50000 miles). The participants were recruited from the Transport Research Laboratory (TRL) database consisting of over 1000 members of the public. All TRL

participants were required to complete a familiarization training of at least 10 min (or as long as required) driving the simulator vehicle. The experiment lasted for about 60 min in total and the participants received £15 for their participation.

4.6.1.2 Apparatus and materials

The advanced TRL driving simulator at Crowthorne, England comprised a Honda Civic family hatchback car with a five-speed manual gearbox. A sophisticated electronic motion system provided realistic vehicle dynamics such as the vibrations that would be experienced when driving an actual vehicle on the road. The driving environment was projected at a resolution of 1280 x 1024 pixels onto three forward screens giving a 210 degree horizontal forward field of view and a rear screen providing a 60 degree rear field of view, thus permitting the normal use of the rearview and two side mirrors. A stereo sound system provided simulated engine, road, and traffic sounds. The driving simulation was generated by the SCANeR II software (OKTAL, France) and driving performance data were recorded at a frequency of 20 Hz throughout each participant's drive (see Table 4.1 for details).

Table 4.1 A summary list of the driving performance variables sampled at a frequency of 20 Hz throughout each participant's drive in Experiment 10.

Driving Performance Variables Recorded
1. Speed
2. Lateral distance from the centre of the road
3. Distance headway
4. Distance to the following vehicle
5. Accelerator pedal force
6. Brake pedal force
7. Steering wheel angle
8. Gear position engaged

(a)



(b)

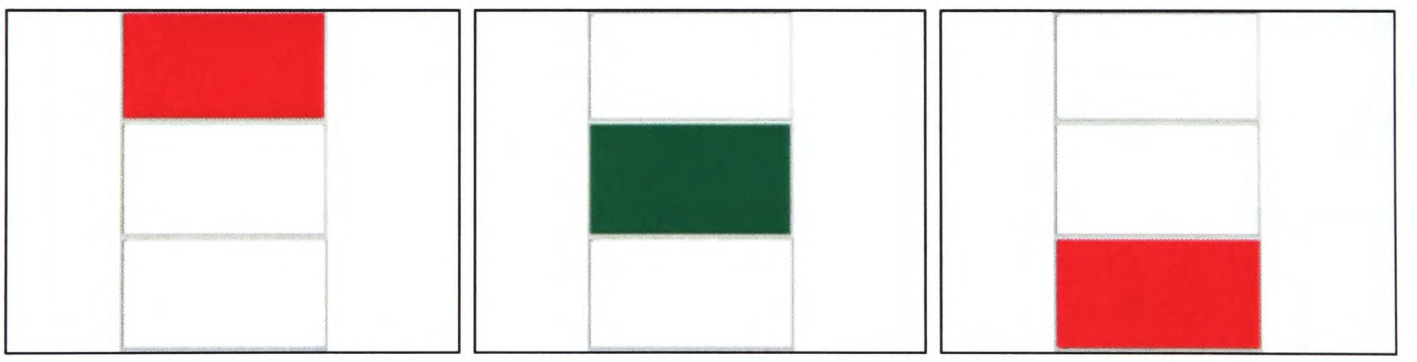


Figure 4.5 (a) Sample still frame of one of the driving scenes in the experiment taken from behind the driver's seat, showing the tri-box headway distance indicator on the lower-left of the frame. (b) The tri-box indicator displayed on the in-car navigation screen showing the status when the headway distance was too close, appropriate, or too far. Numbers in parentheses indicate the actual time headway (s) of the participant's vehicle to the lead vehicle.

The experimental driving route consisted of a two-way road passing through a rural neighbourhood with traffic passing in the other lane in the opposite direction

(see Figure 4.5). A car-following scenario was modelled such that the driven vehicle was positioned between a lead vehicle in front which had its brake lights disabled and a following vehicle travelling at 2 s time headway behind the driven vehicle. A 14 cm (5.5 inch) in-car navigation screen positioned in the centre of the driving console (i.e., to the left of the steering wheel in the right-hand drive car used) was used to display a tri-box (red-green-red) indicator (see Figure 4.5). The middle green box indicated that the driven vehicle was travelling at the correct distance (i.e., falling within the 1.8-2.2 s time headway limit) from the lead vehicle. If the upper red box was illuminated, it indicated that the driven vehicle was travelling too close to the lead vehicle (i.e., time headway < 1.8 s). If the lower red box was illuminated, it indicated that the driven vehicle was too far from the lead vehicle (i.e., time headway > 2.2 s).

The vibrotactile display was the same tactor belt used previously in Experiments 7 and 8 (see Chapter 4.1.1.2). A questionnaire was used to record participants' subjective ratings of various aspects of their driving experience in this experiment (see Table 4.2 for details). The first thirteen questions listed in the questionnaire were designed to measure participants' acceptability of the vibrotactile display.

4.6.1.3 Design

The experimental session consisted of four driving blocks lasting 12 min each. Each participant completed alternate blocks of trials with and without the vibrotactile display, with the order of presentation of the blocks counterbalanced across participants. Twenty randomized critical events were presented in each block (in the same order across all four blocks), with two additional noncritical (i.e., catch) trials in the blocks with the vibrotactile display. In half of the critical trials, the lead vehicle in

front suddenly braked and came to a complete stop (at a deceleration rate of -6 m/s^2). In the other half of the critical trials, the following vehicle accelerated toward the back of the participant's vehicle (i.e., the time headway decreased from 2.0 s to 0.5 s). In the vibrotactile display blocks, a vibrotactile cue lasting for 500 ms was presented from either one of the two tactors at the onset of the critical event. The vibrotactile cues were spatially-predictive in that they correctly predicted the direction of the critical event on 80% of the trials. The critical event occurred in the direction opposite to that indicated by the cue on the remaining 20% of trials (cf. Experiment 7). Note that in real-world scenarios, warning signals are likely to be highly predictive, therefore informative cues were examined in this experiment. However, in order to evaluate the effects of cue validity, a certain number of invalid trials had to be included. For the catch trials, a vibrotactile cue was presented without any specific driving hazard in either the front or rear view (i.e., both the lead and following vehicles behaved as normal).

Throughout the experimental block, the in-car navigation screen indicated whether the participant was maintaining an appropriate distance to the lead vehicle, which travelled at an average speed of 80 km/h. The indicator displayed the middle green box when the participant's vehicle was travelling within the 1.8-2.2 s time headway limit, and changed to the upper red box if time headway was less than 1.8 s or to the lower red box if time headway exceeded 2.2 s.

4.6.1.4 Dependent variables

In an attempt to assess the participants' performance in avoiding the potential front-to-rear-end collisions with the assistance of the vibrotactile display, the following parameters were measured (for critical events occurring in front, i.e., when

the lead vehicle braked suddenly): 1) *Response time* (RT; ms) – the time after the onset of a frontal critical event at which the participant initiated a braking response by depressing on the brake pedal; 2) *Shortest headway* (m) – the shortest distance headway to the lead vehicle from the onset of a frontal critical event to the first acceleration after the completion of the first braking response; 3) *Braking force index* (a proportion ranging from 0 to 1) – the first maximum braking force applied on the brake pedal divided by the time it took from the initial brake depression to reach the first maximum braking peak after the onset of a frontal critical event; 4) *Percentage of collisions* (%) – the percentage of trials in which the participant collided with the lead vehicle; and 5) *Lateral deviation* (m) – the mean lateral distance from the centre of the road measured from the onset of a frontal critical event to the first acceleration after the completion of the first braking response.

4.6.1.5 Procedure

The participants were instructed to drive as they would normally and to follow the lead vehicle at a safe distance (as specified by the in-car display) even when it might involve breaking the speed limit. The operation of the indicator screen was explained to the participants, and they were instructed that they should endeavour to keep the indicator on the middle green panel during the experiment. The instructions also emphasized that the vibrotactile display would indicate the likely direction of potential driving hazards, and that the participants should check both the front and rear views and make the appropriate driving response. No practice session was given as all TRL participants had attended simulator familiarization training prior to their experimental session. The participants completed the questionnaire at the end of the driving session.

4.6.2 Results

4.6.2.1 Driving performance

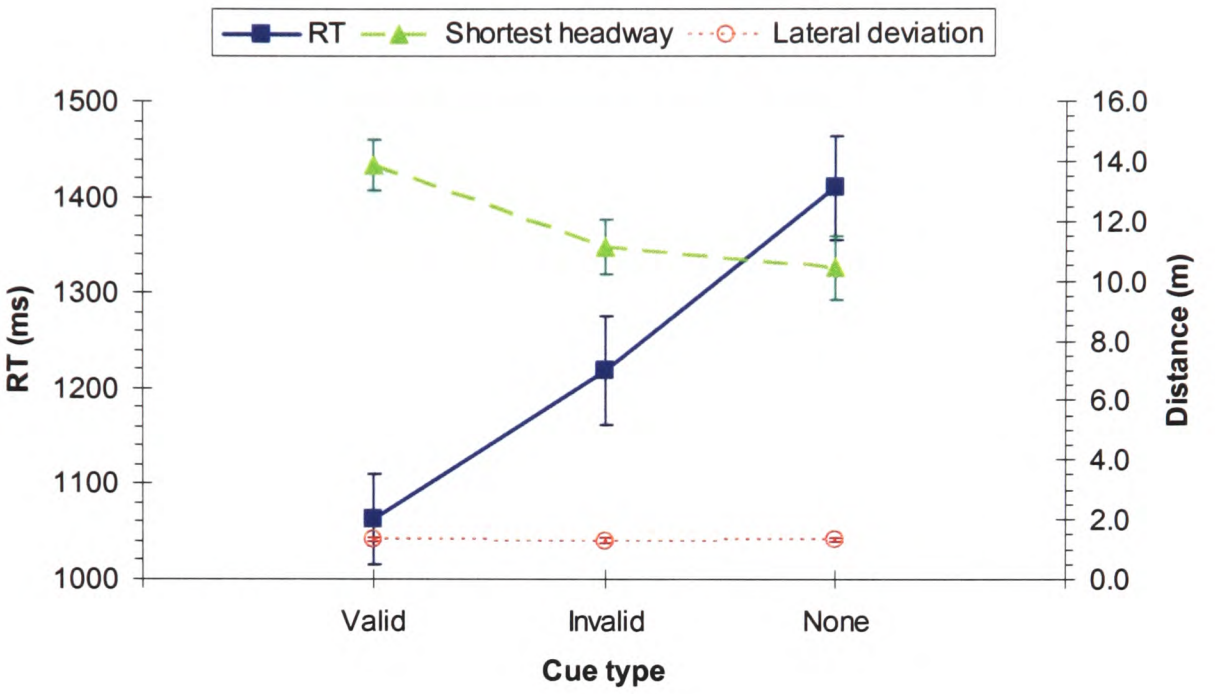


Figure 4.6 Summary graph of mean RT (ms), shortest headway (m), and lateral deviation from the centre of the road (m) results of the experiment as a function of cue type. Error bars indicate the standard errors of the means.

Trials in which participants violated the safe distance rule (i.e., their vehicle was either too close or too far away from the lead vehicle at the start of a critical event) were discarded from the data analysis. As a consequence, 19.8% (*SD* = 7.5%) of the frontal trials were discarded across all participants. For the catch trials, trials in which the participants depressed the brake pedal within 4000 ms of the onset of the vibrotactile cues were considered as false alarm, thus giving a mean false alarm rate of 15.9% (*SE* = 9.1%) with a mean RT of 893 ms (*SE* = 96 ms). Paired comparison *t*-tests were performed on the data to determine whether the vibrotactile display was effective in assisting the participants in making the appropriate collision avoidance response (i.e., a braking response for frontal critical events). Mean scores on the five described parameters (see Chapter 4.6.1.4) were computed for blocks with the

vibrotactile warning signals (i.e., cued) versus without them (i.e., uncued). The results revealed that participants responded significantly more rapidly to frontal critical events in the cued condition (mean RT = 1093 ms) than in the uncued condition (M = 1410 ms), $t(10) = -6.2$, $p < .001$. The shortest headway results also highlighted a significantly larger safety margin with the vibrotactile cuing (M = 13.3 m) as compared to without it (M = 10.4 m), $t(10) = 4.3$, $p = .002$ (i.e., a 27.8% increase in the stopping distance). The braking force index results revealed no significant difference between the two conditions, $t(10) = 1.1$, $p = .32$. Given that there were only four collision incidents in total across all of the participants, no meaningful statistical analysis could be performed on this data. The lateral deviation results showed no significant difference between the two conditions, $t(10) = -0.1$, $p = .93$ (see Figure 4.6).

Taken together, the results of Experiment 10 therefore suggest that the presence of the vibrotactile display enabled the participants to detect and respond to potential front-to-rear-end collisions more rapidly than when no such vibrotactile warning signals were presented, and that this led to an earlier braking response and a larger safety distance relative to the lead vehicle. Having established the potential usefulness of the vibrotactile display, ANOVAs were then performed on the mean RT and shortest headway data to investigate the effect of the spatial validity of the vibrotactile cues. The within-participants factor was cue type (valid, invalid, or none). Analysis of the mean RT data revealed a significant main effect of cue type, $F(2,20) = 22.5$, $MSE = 0.01$, $p < .001$ (see Figure 4.6). Subsequent pairwise comparisons with Bonferroni correction found a significant difference between valid and invalid cues, $p = .004$, and between valid and no cues, $p < .001$, while the difference between invalid and no cues was borderline significant, $p = .057$, with participants responding more

rapidly following valid vibrotactile cues (M = 1062 ms) than following invalid cues (M = 1219 ms) or when no cue was presented (M = 1410 ms).

The analysis of the shortest headway data also revealed a significant main effect of cue type, $F(2,20) = 8.4$, $MSE = 4.3$, $p = .002$ (see Figure 4.6). Subsequent pairwise comparisons (LSD) again revealed a significantly larger safety margin following valid than invalid vibrotactile cues, $p = .011$, and when valid cues were presented as compared to when no cues were presented, $p < .001$. The difference between invalid and no cue trials was not significant, $p = .55$. These results suggest that participants were able to maintain a larger headway distance from the lead vehicle during emergency braking following a valid vibrotactile cue indicating the direction of the critical event (M = 13.9 m) than when the cue came from the opposite direction (M = 11.1 m), or else when no cue was presented (M = 10.4 m). That is, vibrotactile cues originating from the appropriate direction led to a 25.2% and 33.7% increase in stopping distance over invalid spatial cues or no cue trials, respectively.

In an effort to examine the effects of learning and practice, paired comparison t-tests were performed on the mean RT and shortest headway data from the first and second experimental blocks when the vibrotactile display was used. The results revealed that participants responded significantly more rapidly overall (by 162 ms on average) in the second block (M = 1018 ms, SE = 61 ms) than in the first block (M = 1180 ms, SE = 54 ms), $t(10) = 2.6$, $p = .028$. In contrast, the shortest headway data showed no significant difference between the two blocks, $t(10) = -1.2$, $p = .27$. Generally speaking, the participants' overall performance improved over the course of the experiment, while the vibrotactile cues were shown to be equally effective in both halves of the experiment.

4.6.2.2 Questionnaire responses

Table 4.2 Mean scores (and their standard deviations) as rated by the participants along various dimensions regarding the use of vibrotactile warning signals while driving. The percentages were converted from a pen and paper questionnaire on which the participants marked their ratings along a visual analogue scale (e.g., from 0% "Not annoying at all" to 100% "Very annoying" for the Annoyance item).

	Mean* (%)	*SD*
Ratings of the vibrotactile stimuli presented in the present experiment in terms of:		
Annoyance	40.9	29.5
Interference	52.4	24.0
Right timing	54.0	20.8
Appropriateness	51.6	21.5
Trustworthiness / reliability	49.0	16.8
Liked the vibrotactile stimuli	37.9	26.5
Ratings of general applications of vibrotactile in-car interfaces:		
Beneficial as in-car warning signals	38.2	22.3
Likelihood to buy a vibrotactile in-car warning system	22.2	21.7
Likelihood to use a vibrotactile in-car warning system if installed	40.1	32.0
Positive effect on driving safety	53.4	23.9
Confidence in using a vibrotactile in-car warning system on the roads	49.4	23.3
Preference of vibrotactile over auditory warning signals	56.1	35.3
Preference of vibrotactile over visual warning signals	52.6	35.8
Other questions:		
Self-rated confidence in detecting potential collision situations in normal driving	80.2	10.2
Feeling of visual overload while driving	49.8	24.7

***No significant correlation was found between any of these subjective rating scores and the participants' driving performance.**

With reference to Table 4.2, although participants rated themselves as highly confident in being able to detect potential collisions, the objective data indicated performance facilitation with the use of vibrotactile warning signals even for those participants who reported feeling distracted by the vibrotactile stimuli. The *SD* scores (of the first thirteen items) also reflect individual differences in the participants' acceptance of the vibrotactile display. However, no significant correlation was found between participants' age and their acceptability of the vibrotactile display ($p > .15$ for all correlation analyses between age and each of the questionnaire items).

4.6.3 Discussion

The results of Experiment 10 demonstrate the potential utility of providing directional vibrotactile warning signals to alert drivers to potential time-critical events on the road ahead. The findings also demonstrate the efficacy of vibrotactile cues in eliciting a braking response from car drivers. The 24.7% reduction in response latencies, together with the 33.7% increase in stopping distance to a potential collision with a valid vibrotactile warning signal than without, in a car-following scenario may have important safety implications in real driving situations, especially when the road environment may be more complicated (or demanding) than that modelled here, for instance, under poor visibility or severe weather conditions. This speeding-up of emergency braking RTs of a magnitude of over 1/3 s is of significant implication given the common two-second rule advocated in driving (cf. Driving Standards Agency, 2004).

On the whole, braking RTs in car-following situations have been argued to provide a robust measure of the attention and perceptual aspects of driving performance (e.g., see Brookhuis, de Waard, & Mulder, 1994). One potential

weakness of this measure, as noted by Brookhuis et al., is that participants may vary their perceived safe headway distance under different driving conditions. The use of the tri-box headway distance indicator in Experiment 10 was designed to address this issue, as the participants were required to maintain a constant headway across all experimental blocks. Thus, the perception of the lead vehicle's deceleration, which is dependent on the initial headway distance (see Janssen, Michon, & Harvey, 1976; cf. van Winsum & Heino, 1996), was held constant across the different experimental conditions. At the same time, the tri-box headway distance indicator provided an analogue of the visually demanding in-car technology that is becoming evermore available to car drivers and increasingly distracting their attention (e.g., Ashley, 2001; Bruce et al., 2000).

Many researchers have used the term 'intuitive' when describing vibrotactile cues (e.g., see Eves & Novak, 1998; Jeram & Prasad, 2005; Rupert, 2000b; van Erp, 2005; van Erp & van Veen, 2004). Rupert defined 'intuition' as 'the power of attaining direct knowledge or cognition without rational thought and inference' (p. A96; cf. Gregory, 1967). Rupert further proposed intuitive interfaces to be those in which the logical operation of the interface matches the user's mental model of that interface. Consequently, only limited training should be required for a novice user to master the system (see also Logan, 1988). Thus, the intuitiveness of the vibrotactile cues used in Experiment 10 can be defined in terms of the ease with which the cue elicited the desired response from drivers who had had no training in using in-car vibrotactile displays prior to their participation in this study. The results of Experiment 10 clearly suggest that the vibrotactile warning signals could intuitively direct the drivers' attention to the appropriate spatial direction and trigger a rapid (and appropriate) braking response. This can also be taken to reflect one of the strengths of

the tactile system, as compared to the visual system, in terms of its ability to transmit information rapidly to the brain (see Harrar & Harris, 2005; Mowbray & Gebhard, 1961; Robinson, 1934; see also Amlôt & Walker, 2006; Gilmer, 1960, 1961).

The notion of intuitiveness can be contrasted with previous studies showing that the presentation of tactile cues can enhance the perceptual salience of a relevant visual (or auditory) target stimulus occurring in the cued rather than in an uncued spatial location (see Spence et al., 2004). One distinction to be made between the two phenomena would be that while the former is linked to the direct access to cognitive resources, the latter is more concerned with the connection of (or links between) stimuli across various different sensory modalities coming from the same position in external space. Both accounts are important in terms of analysing the attributes (or factors) that influence human information processing and the consequent behavioural performance. So, even if a frontal vibrotactile cue on the body may not necessarily enhance the perception of the vehicle in front (i.e., seen several metres away on the road ahead) since it does not occupy the same spatial location (see Chapter 5 for a detailed discussion of this point), it may rather be particularly effective in eliciting the well-learned action during an unexpected driving event, that is, a braking response (cf. Proctor et al., 2005; see also Bechara, Damasio, Tranel, & Damasio, 1997, on the topic of decision-making).

The subjective data reported in the questionnaire seem to suggest diverse individual differences in terms of user acceptability of the vibrotactile display, even though the objective data indicated performance facilitation with the use of the vibrotactile display for all of the participants tested here. One possible explanation for the poor acceptability ratings given by some of the participants was the reliability of the warning signals, which were only 80% valid in the present study. Linking this to

previous research on alarm reliability (e.g., Bliss & Acton, 2003; Lee, McGehee, Brown, & Reyes, 2002), it is possible that drivers would be more willing to accept (and use) the present vibrotactile display if 100% valid signals had been presented instead. It would also be interesting in future research to study whether drivers would deal with tactile signals in a qualitatively different manner than signals in either the visual or auditory modalities. For instance, would the tolerance for false alarms in touch be greater than that seen in, for example, audition (cf. Sorkin, 1988)? It has also been suggested that while tactile stimuli are highly attention-grabbing (i.e., automatically alerting; e.g., Geldard, 1960; Gilmer, 1960), they may be less irritating than many attention-grabbing (or urgent) auditory signals (cf. McKeown & Isherwood, in press).

In addition, even if drivers are highly confident and capable of detecting potential collisions, the poor maintenance of many vehicles may mean that the situation may actually be worse than they anticipate. For example, among the 22.5 million passenger cars tested in 2003-2004 in the United Kingdom under the road vehicle testing scheme, 15.7% were found to have defective lights (Great Britain Department for Transport, 2004). It therefore seems probable that a driver may fail or be slower to recognise a braking action of the lead vehicle because of the general reliance on expecting to see brake light signals. Experiment 10 tested a scenario in which the brake lights of the lead vehicle were disabled, thus the perception and detection of the deceleration of the lead vehicle might be somewhat different than under normal road conditions. One interesting comparison to look at based on the results of Experiment 10 would be to investigate the advantage of providing vibrotactile cuing when the lead car's brake lights were fully functional, versus when

there was uncertainty as to the functionality of the lead car's brake lights (such as if participants were required to follow a variety of different lead cars).

Front-to-rear-end collisions accounted for 29.6% of the police-reported crashes in the United States in 2003 (U.S. Department of Transportation, 2004). It is estimated that a typical driver will be involved in a front-to-rear-end accidents once every 25 years (Horowitz & Dingus, 1992). Thus, it is essential that any potential warning signal can elicit the appropriate reaction from drivers even if they rarely encounter such signals. Furthermore, the warning signal should not be too irritating given that it is likely to constitute a false alarm on the majority of occasions where it is presented. It would therefore be interesting in future research to examine whether the benefits of vibrotactile cuing highlighted in the present study would be sustained if the cues were presented on a much less frequent basis than that tested in the present study (cf. Bliss & Acton, 2003).

It would also be interesting to examine the thresholds for the potential masking of the detection of vibrotactile signals by background vehicle vibrations. From an applied perspective, van Erp et al. (2004) tested tactile navigation information presentation in the operational environments of helicopter flying and controlling a speed boat moving over open water. They reported tactile cuing to be effective despite the substantial background vibrations present in both of these environments. Meanwhile, psychophysical studies have looked at the possible masking of target vibrotactile stimuli by distractor vibrotactile stimuli presented simultaneously on different body parts (e.g., Gallace et al., 2006). Future studies should also compare the delivery of vibrations directly to the body versus via components in the cars (e.g., vibration of the steering wheel or of the driver's seat). In terms of implementation (and user acceptability), it would appear that drivers will be

more reluctant to use tactile displays if they are required to take an extra step to, for instance, wear a vest. Thus, it seems more practical to design vibrotactile safety devices that are in place for use from the moment that a driver gets into the car (cf. Houston & Richardson, 2005). The majority of the studies mentioned above involve the use of the tactile faculty for a single salient task. It would therefore be particularly interesting in future studies to look at tactile dual-task limitations and further examine the capacity for tactile information processing in humans. For example, one could examine whether the concurrent use of a tactile control stick, such as that described by Fenton (1966) to present headway information to drivers (i.e., replacing the visual tri-box display used in the present study), would lead to the same facilitation of braking responses when using vibrotactile directional cues as seen in Experiment 10 using a visual display (see Spence & Driver, 1997b, on this issue; cf. Fenton & Montano, 1968).

In general, one may legitimately question the validity of findings in a driving simulator study in connection with real-world driving as the perception of danger and differential demands in the two environments can lead to discrepancies in performance (e.g., Alm & Nilsson, 1995). However, as a number of researchers have pointed out, driving simulators surpass on-road testing and driving games as being both more cost effective and more ethical (see Haigney & Westerman, 2001; Reed & Green, 1999; cf. Kemeny & Panerai, 2003; McLane & Wierwille, 1975). For instance, Reed and Green reported that the use of a driving simulator provides good absolute validity in terms of measuring speed control. Another important question when thinking about conducting on-road studies regards the responsibility issue if the driver (participant) should happen to crash during an on-road driving experiment (such as when testing the effectiveness of a collision warning system).

4.7 General discussion of vibrotactile spatial cuing

The results of Experiment 10 demonstrate the potential benefits of using 'intuitive' vibrotactile in-car displays as an alternative means to present time-critical information to drivers than the visual and auditory driving aids that are currently widely used. The findings demonstrate the applicability of the theoretical account of crossmodal links in spatial attention between various different sensory modalities in a practical application domain, and provide further support for the significant spatial cuing effects reported in earlier laboratory-based studies reported in this chapter. Taken together, these findings add to a growing body of empirical evidence highlighting the potential benefits of using 'intuitive' vibrotactile in-car displays to alert drivers to potential front-to-rear-end collisions and to provide time-critical directional information. Future studies should investigate the level of efficacy with which tactile information perception is translated into signals for decision-making and subsequent actions in order to have a better understanding of the mechanisms governing the seemingly spontaneous and automatic translation of a vibrotactile stimulus on the stomach to a braking response (see Proctor et al., 2005). The development of vibrotactile warning signals that have been specifically designed to play to the particular strengths of the human information processing system would seem to offer exciting possibilities for future car warning signal design.

CHAPTER 5

PERCEPTUAL VS. DECISIONAL FACILITATION OF MULTISENSORY SPATIAL CUING

The potential use of non-visual warning signals to present spatial information to car drivers has been successfully demonstrated in Chapters 2 and 4 (for auditory and tactile warning signals, respectively). Empirical research suggests that spatial warning signals can improve a person's ability to detect, and subsequently respond to, events occurring in the cued direction. Among the two types of spatial warning signals investigated (namely, auditory and vibrotactile), spatial auditory cues were found to be particularly effective in directing a driver's visual spatial attention to potentially dangerous events on the road. However, given that the spatial cuing effects were measured at the behavioural level, it is unclear what the factors governing the difference in relative effectiveness are. This chapter attempts to understand the level(s) in information processing at which crossmodal cuing effects attributable to the spatial warning signal sets in.

5.1 Experiment 11

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 et al., 2001b). 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, 2005).

A preliminary comparison of the mean RTs from Experiments 2, 3, 7, and 8 would appear to suggest that when people are multi-tasking, they can respond more rapidly to visual events following auditory warning signals than following vibrotactile signals (see Figure 5.1). Experiment 11 was conducted in order to compare the speeded discrimination of the warning signals used in these earlier experiments and so examine the relative speed with which people can respond to auditory, tactile, and visual warning signals. The hope was that the results of Experiment 11 would enable comparison of the relative effectiveness of the various warning signals across different modalities. It seemed possible that the differences in response latency are primarily governed by the speed with which people can respond to warning signals presented in a given modality. Alternatively, the differences could be governed by the

efficacy of the translation from detecting the warning signals to looking at the visual events.

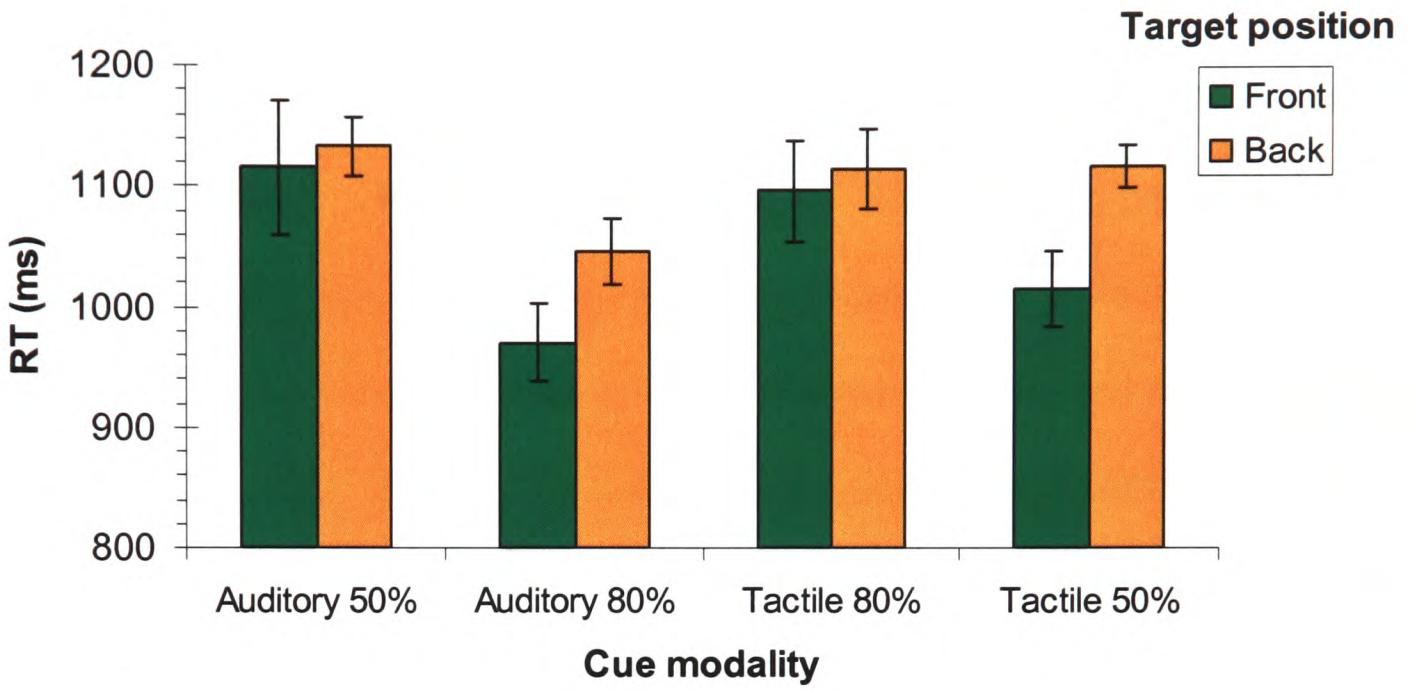


Figure 5.1 Summary graphs highlighting (a) mean RTs (in ms) and (b) percentages of errors as a function of the visual target position (front or back) reported in Experiments 2 (Auditory 50%), 3 (Auditory 80%), 7 (Tactile 80%), and 8 (Tactile 50%), investigating the effectiveness of various warning signals presented from different modalities. Error bars indicate the standard errors of the means.

5.1.1 Methods

5.1.1.1 Participants

Twelve participants (mean age of 26 years, age range from 22-29 years; 8 males and 4 females) took part in Experiment 11. Eleven of the participants were right-handed, and one was left-handed by self-report. The participants reported normal, or corrected-to-normal, vision, a normal sense of touch, and normal hearing. The experiment lasted for 30 min, 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.

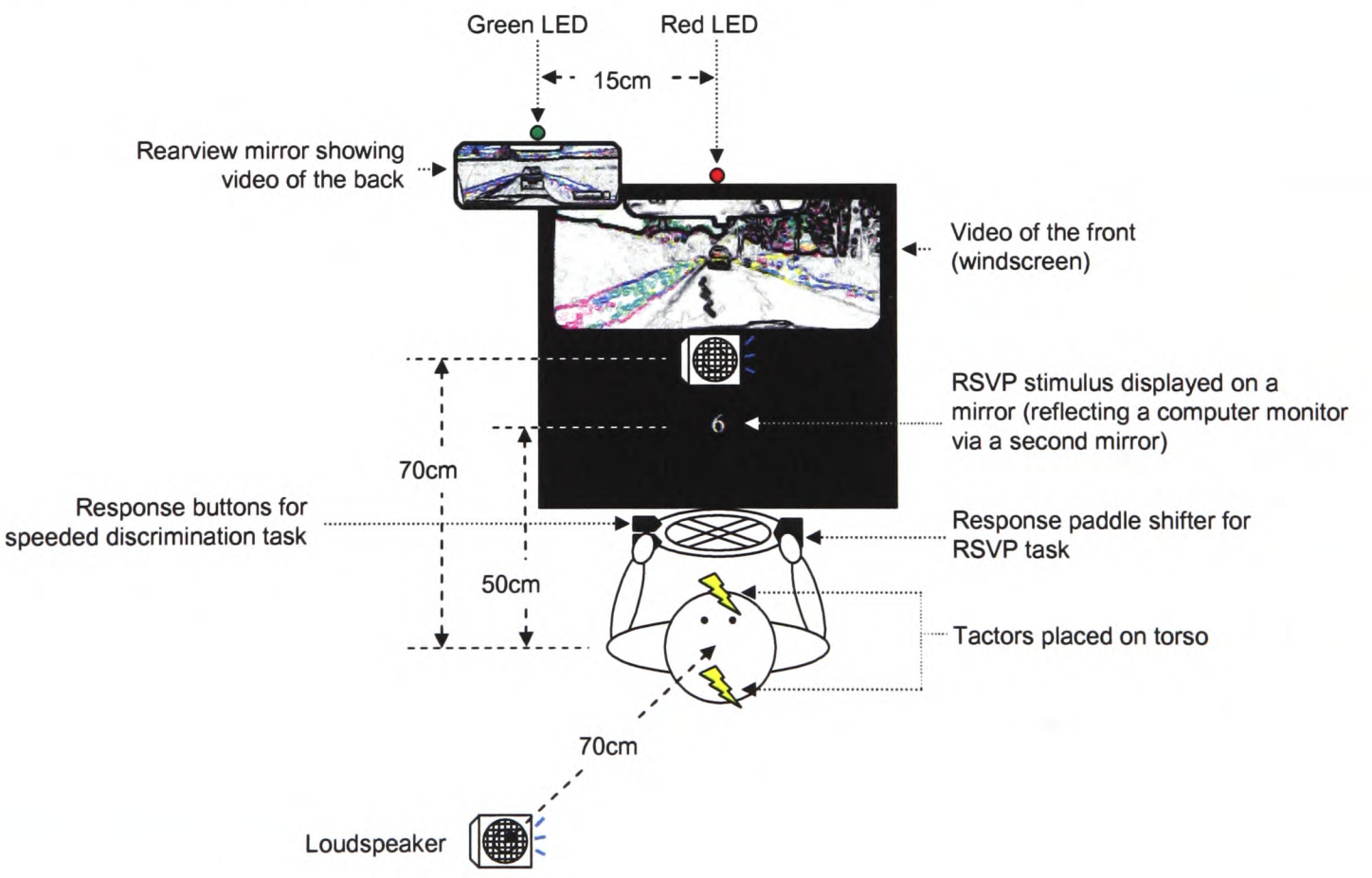


Figure 5.2 A schematic diagram of the experimental set-up used in Experiment 11.

5.1.1.2 Apparatus and materials

The experiment was conducted using the same experimental set-up as that reported in Experiments 2, 3, 7, and 8. 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 (140 cm in diameter) centred on the participants' head, one to the front and the other to their rear left-hand side, just as in Experiments 2 and 3 (see Figure 5.2 for a schematic illustration of the experimental set-up used). The vibrotactile stimuli were delivered to participants using the same tactor belt as that used previously in Experiments 7, 8, and 10. One of the tactors 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 cordless headphone (SBC-HC8355, Philips, USA) at approximately 60 dB(A) in the block of trials where the tactors were used, in order 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. 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) was used to signify target visual events at the rear. The locations of these visual stimuli were chosen artificially to provide a comparison condition for the auditory and tactile conditions.

5.1.1.3 Design

The experimental session consisted of three 6-min blocks of experimental trials, one auditory, one tactile, and the other visual, with the order of presentation counterbalanced across participants. As in the previous experiments, the 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, each 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. The temporal gap between successive target stimuli was 4800-10800 ms. The same video used in the previous experiments was presented continuously in the background, but participants were not required to give any respond to the video events (see Chapter 2.2.1.2 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.

5.1.1.4 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.

5.1.2 Results

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. An 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 the 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 consisted of target modality (auditory, tactile, or visual) and target position (front vs. back).

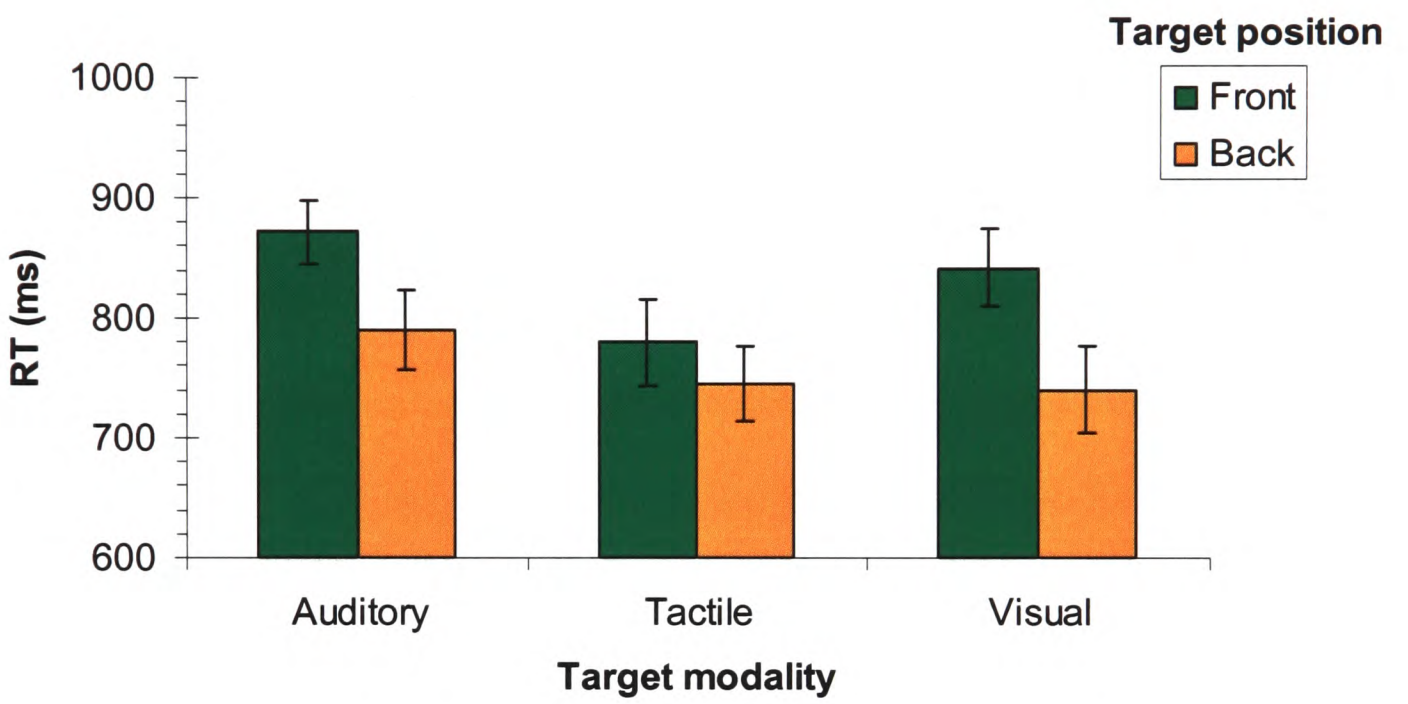


Figure 5.3 Summary graph highlighting (a) the mean RTs (in ms) and (b) the percentages of errors in the speeded target discrimination task of Experiment 11 as a function of target modality and target position. Error bars indicate the standard errors of the means.

Analysis of the RT data revealed a significant main effect of target modality, $F(2,22) = 4.6$, $MSE = 6271.6$, $p = .022$, with participants responding more rapidly to vibrotactile targets ($M = 762$ ms, $SE = 32$ ms), than to visual targets ($M = 791$ ms, $SE = 33$ ms), and with participants responding most sluggishly to auditory targets ($M = 831$ ms, $SE = 28$ ms; see Figure 5.3). Subsequent paired comparison t-tests revealed a significant difference between the auditory and tactile conditions, $t(11) = 3.1$, $p = .010$, 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, $F(1,11) = 30.3$, $MSE = 3141.8$, $p < .001$, with participants responding more rapidly to targets presented from the rear ($M = 758$ ms, $SE = 30$ ms) than from in front ($M = 831$ ms, $SE = 28$ ms). The interaction between target modality and target position was, however, not significant, $F(2,22) = 2.5$, $MSE = 2853.4$, $p = .10$.

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 ruling out a speed-accuracy trade-off account of the RT data (e.g., Müller & Findlay, 1987).

Performance in the concurrent RSVP task was also analysed 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) conducted on the mean percentage of

correct detection responses data and the mean RT data revealed no significant main effect of target modality, $F(2,22) = 2.1$, $MSE = 0.003$, $p = .15$, and $F(2,22) < 1$, *n.s.*, respectively. That is, the participants performed the RSVP task equally well in all three experimental blocks, detecting an average of 84.7% (*SE* = 2.7%) of the target digits, with a mean response latency of 596 ms (*SE* = 11 ms) and a false alarm rate of 4.5% (*SE* = 1.0%).

5.1.3 Discussion

The results of Experiment 11 demonstrate that participants can respond more rapidly to vibrotactile warning signals than to either visual or auditory warning signals.[5.1] Given the increasing visual overload reported by interface operators in many interface settings (e.g., Sorkin, 1987; Spence & Driver, 1997b), 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). In fact, some researchers have actually suggested that visual overload may arise not only from human operators having to deal with too much information, but also from a lack of knowledge or awareness regarding which of the available visual sources of information is actually most relevant at any given point in time (e.g., Perrott et al., 1996).

Participants in Experiment 11 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

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[5.1] Note that the differences between the various sensory modalities reported here were governed not only by differences in transduction latencies but also by other factors such as the distance from the source stimuli (e.g., the vibrotactile 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.

vibrotactile cues in an automobile setting may be more advantageous than the use of auditory cues not only because people can react to them more rapidly, but also because they are private to the driver, thus other car passengers should not be disturbed by their occurrence (see Triggs et al., 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 auditory noise in the driving environment to the same extent as are auditory cues (Gescheider & Niblette, 1967; although of course the ability to detect vibrotactile stimuli might be masked somewhat by vehicular vibrations; cf. Kemeny & Panerai, 2003). One reason for the slow discrimination performance reported in response to the auditory targets in Experiment 11 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 et al., 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 different sites on their abdomen, with localization accuracy being primarily determined by 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, 2005) where vibrotactile RTs would be even faster than those observed in Experiment 11, given that the waist may not be the optimal site for presenting vibrotactile stimulation (e.g., see Weinstein, 1968).

The results of Experiment 11 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 one to rule out the possibility that the overall slower responses recorded in response to the rearview mirror in Experiment 8 were due to the fact that vibrations to the back were somehow less salient (in fact, the results of Experiment 11 suggest that they may actually have been, if anything, more salient) than vibrations presented to the front. It may be worth in future studies 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 or back; cf. Kitagawa et al., 2005).

The results of Experiment 11 allow basic comparisons to be drawn between the results of the previous experiments on the auditory and tactile spatial cuing of driver attention. The results show that the efficiency with which participants can respond to dangerous road events signalled by auditory, visual, or vibrotactile warning signals depends not just on the speed with which participants can discriminate the position from which a warning signal has been presented. For instance, in contrast to the faster discrimination latencies seen for vibrotactile rather than auditory warning signals in Experiment 11, participants in the spatially-predictive auditory experiment (Experiment 3) were, on average, numerically somewhat faster (M = 1008 ms) overall than participants in the spatially-predictive vibrotactile experiment (Experiment 7; M = 1104 ms). The contrasting pattern of results reported in these two experiments would therefore appear to suggest that the cue and target modalities may interact to determine the resultant effectiveness of warning signals in real-world 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 seen visually) that also need to be taken into account (Rodway, 2005; Spence et al., 2001b) when

considering the modality in which it will be most appropriate to introduce a given warning signal.

5.2 *Perceptual vs. decisional facilitation*

The rapidly-growing body of empirical research on the nature of crossmodal links in spatial attention demonstrates that responses to target events presented in one sensory modality can be facilitated by the prior presentation of a relevant cue in another sensory modality from approximately the same spatial location (see Spence & Driver, 2004, for a recent review). Such crossmodal spatial facilitation effects have been studied in a variety of different settings, from fundamental laboratory-based research (e.g., Driver & Spence, 2004; Spence et al., 2004) to more complicated environments in applied research settings (e.g., van Erp & van Veen, 2001, 2004). However, it is unclear whether the facilitatory effects reported in many of these previous cuing studies should be attributed to response priming, attentional facilitation, or to some unknown combination of these two effects.

According to the response priming account, the facilitation of performance seen following the presentation of a warning signal cue occurs because the response appropriate to the target stimulus is primed by the cue (i.e., performance is facilitated without there necessarily being any change in the perceptual representation of the target itself). According to the attentional account, however, the presentation of the cue (or warning signal) leads to a crossmodal shift of spatial attention that facilitates the perception of targets subsequently presented near to the cue, and this attentional enhancement of target processing is what leads to improved behavioural performance. The critical research question to be addressed here then is one of understanding how

'early' in information processing the crossmodal cuing effects attributable to the presentation of a warning signal occur. From an applied perspective, the facilitation of behavioural responses to potential emergency situations is clearly beneficial no matter how that benefit is elicited (i.e., no matter whether it is elicited by response priming, attentional facilitation, or by some unknown combination of these two effects). From a theoretical point of view, however, many researchers have undertaken laboratory-based research specifically in order to try and isolate response priming (or compatibility) effects while others have focused on trying to isolate attentional facilitation effects instead (see Proctor et al., 2005; Spence & McDonald, 2004). Nevertheless, it is only by gaining a better understanding of the relative contributions of the two effects (response priming and attentional facilitation) to performance under more realistic conditions that it might, in the future, be possible to design the most effective warning signals – signals that will presumably facilitate performance at both levels.

In an attempt to eliminate the possible contribution of response priming in laboratory-based studies of crossmodal cuing, Spence and Driver (1994) proposed the use of an orthogonal cuing methodology. In a typical orthogonal cuing study, participants are instructed to respond to a dimension, or property, of the target (e.g., its colour or identity) that is orthogonal to the dimension along which cuing occurs. So, for instance, if participants are required to make red versus blue target discrimination responses for targets appearing on either the left or right, then the spatial cuing dimension (left vs. right) is orthogonal to the dimension on which responses are made (red vs. blue). The idea being that the presentation of the cue should therefore not prime a particular response, and so any residual facilitation of performance can unambiguously be attributed to attentional cuing.

The series of laboratory-based simulated driving experiments reported in Chapters 2 and 4 demonstrated that the use of various different types of spatial auditory and vibrotactile warning signals (presented from the front or rear) can facilitate performance when responding to targets presented from the front or rear. In these experiments, participants were required to brake or to accelerate in response to target visual driving events occurring in the front windscreen or the rearview mirror respectively (i.e., as required in a real driving situation). However, it is unclear whether the facilitation of responding in these previous studies reflects response priming, spatial attentional facilitation, or some unknown combination of the two effects. Experiments 12-15 were therefore designed to study whether a purely attentional component to this spatial warning signal effect could be demonstrated by requiring participants to perform an *orthogonal* discrimination task. Specifically, participants were required to make speeded discrimination responses regarding the colour of a numberplate (i.e., responses that were orthogonal to the spatial dimension of interest – the front vs. back cuing of driver attention), with the experiment otherwise being identical to the previous experiments. The results of the experiments in this chapter should therefore highlight the factors governing the facilitation reported in the earlier chapters.

It was hypothesized that if the same pattern of results could be replicated using an orthogonal discrimination task as in the previous experiments, then this would suggest that the facilitatory crossmodal cuing effects observed previously must reflect, at least in part, a spatial attentional effect. Alternatively, however, if the cues in the previous experiments simply primed the appropriate responses (i.e., braking vs. accelerating), then no such facilitation would be expected in the orthogonal experiments (given the orthogonal nature of the responses required). Experiment 12

was designed to replicate Experiment 7 where spatially-predictive vibrotactile cues (80% valid with regard to the likely location of the upcoming visual targets) were shown to facilitate subsequent responses to target visual driving events in the cued direction. Experiment 13 replicated Experiment 3, where spatial auditory car horn sounds were used as the spatially-predictive warning signals.

5.3 Experiment 12

5.3.1 Methods

5.3.1.1 Participants

Sixteen participants (mean age of 19 years, age range from 18-20 years; 3 males and 13 females) took part in Experiment 12. All of the participants reported normal tactile sensitivity and normal, or corrected-to-normal, vision. The mean driving experience of participants was 2 years (range from 6 months to 3 years). Twelve participants were right-handed and four were left-handed by self-report. The experiment lasted for approximately 60 min. All of the participants were naïve as to the purpose of the study and they all received course credit in return for their participation. The experiments were conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford.

5.3.1.2 Apparatus and materials

The experiment was conducted using the same apparatus as that reported in Experiment 7, with the sole exception that additional editing was made to the video-

recording. Specifically, additional editing was performed using Adobe® After Effects® 6.5 (Adobe Systems Incorporated, San Jose, CA) to change the colour of the numberplate from yellow (for the car in front) or white (for the car from behind; as required under British law) to either red or blue during the sudden fast approach period (duration of 1800 ms). The noncritical clips included the car in front moving away at the normal speed or the car behind retreating, with the colour of the numberplate changing to green instead. To be clear, the numberplate of one of the two cars – either the leading or following car – always changed colour whenever a vibrotactile cue was presented. The critical red and blue colour patches had the same saturation and intensity (set at 100%), with red having a hue of 0° and blue 240°. The noncritical green colour patch had a hue of 120°, with the same saturation and intensity levels as the critical colour patches. Four critical and two noncritical driving clips were created.

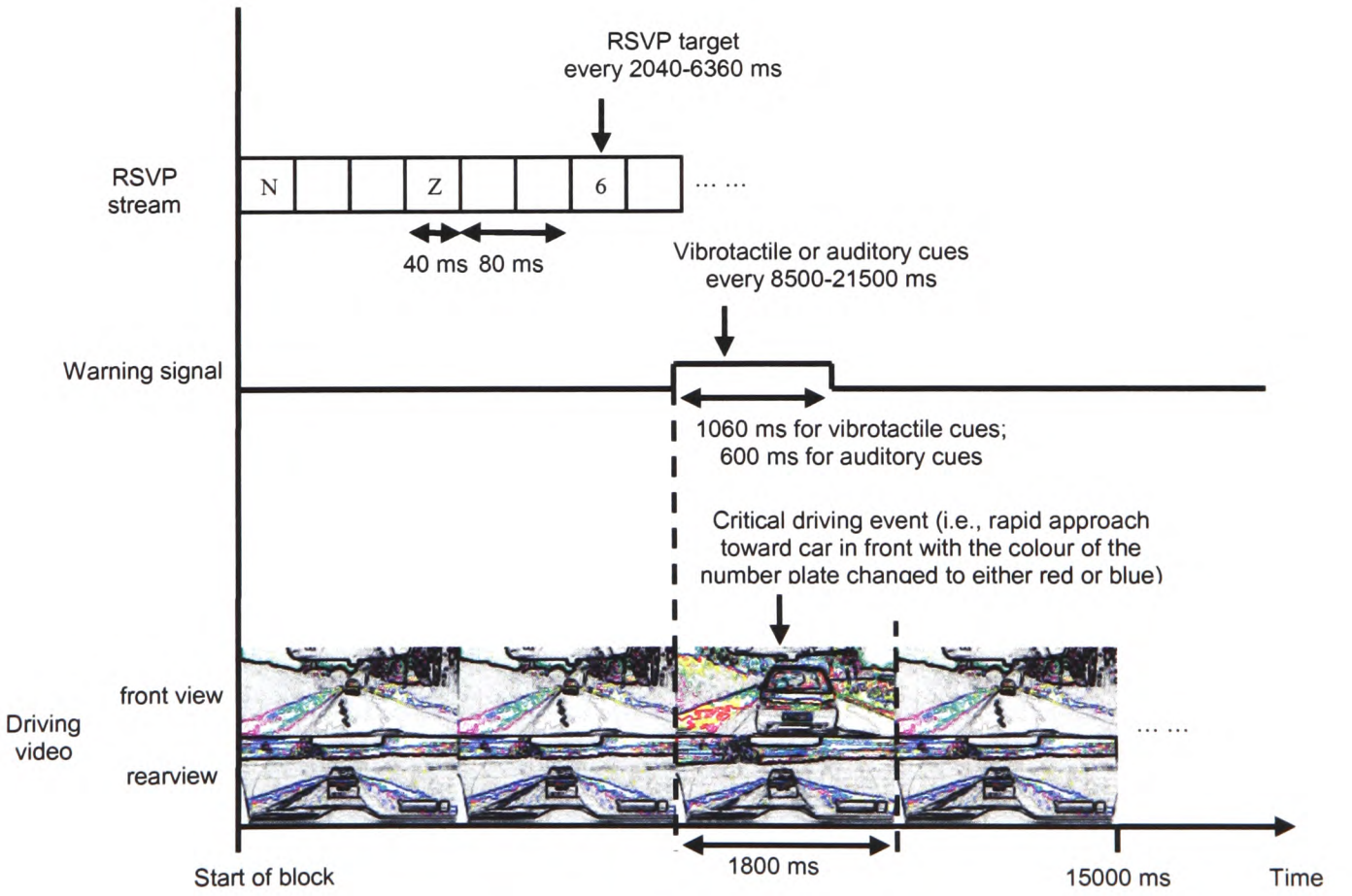


Figure 5.4 A schematic timeline showing the temporal sequence of events in Experiments 12 and 13.

5.3.1.3 Design

The experimental session consisted of eight 6 min blocks of experimental trials. The RSVP task consisted of a continuous stream of distractor letters with target digits periodically embedded within it. 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. 66 targets were presented in each block, with the temporal gap between successive target digits in the RSVP stream of 2040-6360 ms.

For the driving task, 24 randomized scenarios were presented in each experimental block. Each scenario consisted of a 15000 ms video clip and a vibrotactile cue lasting for 1060 ms (see Figure 5.4). In a given experimental block, each of the four critical driving clips was presented four times (i.e., the fast approach toward the car in front with either a red or blue target numberplate, or the fast approach of the car from behind with either a red or blue target numberplate) with a vibrotactile cue coming from the appropriate direction, and twice with a vibrotactile cue coming from the opposite direction to the visual driving event (i.e., the cues correctly predicted the direction of the targets on 80% of the trials). 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 onset of the vibrotactile cues occurred at the same point in time as in Experiment 7. Each of the four noncritical driving scenarios was presented once (i.e., the ratio of critical to noncritical trials was 83:17). The temporal gap between successive vibrotactile cues was 8500-21500 ms. In total, there were 528 RSVP targets and 192 driving trials (i.e., 160 critical and 32 noncritical trials) in a participant's experimental session.

The participants were given two practice blocks in which to familiarize themselves with the experimental set-up. In the first practice block, they only had to perform the RSVP task, which was initially presented at a slower rate that gradually increased to the experimental rate of stimulus presentation. In the second block, the participants performed both the RSVP and driving tasks as in the subsequent experimental blocks.

5.3.1.4 Procedure

The participants responded to targets in the RSVP task by pressing the right paddle shifter on the steering wheel. For the driving 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 target numberplate, and to press the lower left button (mounted 2.5 cm vertically below the upper button) in response to a blue target numberplate. The other half of the participants were instructed to use the opposite response mapping. (They were not instructed to change the pressure of the brake or accelerator pedals in response to the driving events.) For noncritical trials where the numberplate changed to green, the participants simply had to carry on without making any specific response. The red LED was illuminated for 1000 ms following an incorrect response. Participants were also instructed to keep the accelerator depressed slightly throughout the experiment in order to model realistic driving conditions.

5.3.2 Results

Trials in which participants made an incorrect response were discarded from the analysis of the RT data. On average, 3.5% of the trials were removed across

participants due to no response being made within 1800 ms of the onset of the critical visual event. False alarms, where participants incorrectly responded when the colour of the numberplate changed to green, occurred on 1.4% of catch trials. An ANOVA was performed on the RT data to assess whether the spatial direction from which the vibrotactile cues were presented had any effect on the participants' ability to respond to the critical visual driving targets presented from either the front or behind (seen via the rearview mirror). The two within-participants factors were vibrotactile cue location (front vs. back) and visual stimulus location (front vs. back).

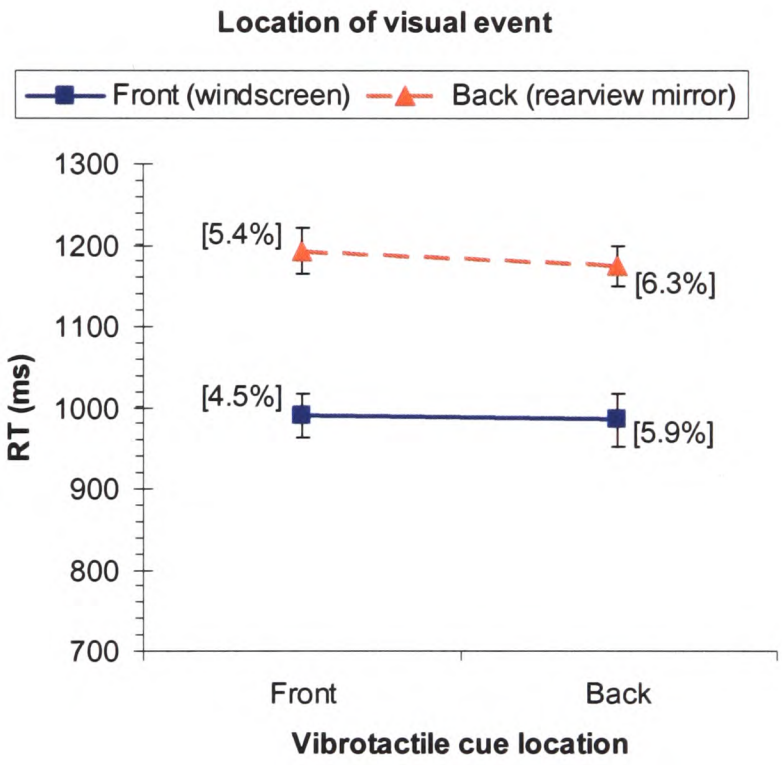


Figure 5.5 Mean RTs for the driving task in Experiment 12 as a function of the location of the spatially-predictive vibrotactile cue and the location of the critical visual event. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs.

This analysis revealed a significant main effect of visual stimulus location, $F(1,15) = 132.3$, $MSE = 4638.0$, $p < .001$, with participants responding more rapidly to critical visual events presented from the front ($M = 987$ ms) than from the rearview mirror ($M = 1183$ ms). The main effect of vibrotactile cue location was, however, not significant, $F(1,15) = 1.7$, $MSE = 1427.4$, $p = .21$, nor was the interaction between

vibrotactile cue location and visual stimulus location, $F(1,15) = 1.0$, $MSE = 817.3$, $p = .33$, suggesting that participants responded equally rapidly regardless of the spatial validity of the vibrotactile cues with respect to the location of the visual targets in the driving videos (i.e., no matter whether the cues were spatially-valid or invalid; see Figure 5.5).

A similar analysis of the error data revealed no significant main effect of vibrotactile cue location, $F(1,15) = 1.1$, $MSE = 19.4$, $p = .31$, or visual stimulus location, $F(1,15) < 1$, *n.s.*, nor any interaction between these two factors, $F(1,15) < 1$, *n.s.*

Performance in the concurrent RSVP task was analysed to ensure that participants performed the central attention-demanding visual task as instructed. Responses occurring 1500 ms or more after the presentation of a target digit were considered as invalid (i.e., false alarms). The mean percentage of correct detection responses in the RSVP task was 74.7% ($SE = 1.9\%$), with a mean RT of 577 ms ($SE =$ 9 ms) and a false alarm rate of 6.2% ($SE = 1.0\%$), which was similar to the results obtained in the previous experiments.

5.3.3 Discussion

Somewhat surprisingly, the results of Experiment 12 revealed no spatial cuing effect following the presentation of the vibrotactile cues. In fact, there was no significant difference in the latency of participants' responses as a function of whether the vibrotactile cues came from the same or opposite direction as the critical visual driving targets. The slightly faster responses following a cue from behind than from in front may reflect the possibility that vibrotactile stimuli are more salient (and/or

alerting) when presented to the back than to the front of a participant's waist (see also Experiment 11 on this point).

The null vibrotactile cuing effects reported in Experiment 12 contrast with the robust cuing effects reported in the earlier study of vibrotactile cuing of driver attention (e.g., Experiment 7 reported mean cuing effects of 66 ms and 6.8% in the RT and error data, respectively). Taken together, these two results suggest that while the presentation of a vibrotactile cue from the appropriate spatial direction on the body surface may elicit an automatic (or 'intuitive'; van Erp, 2005) response bias (cf. Prinzmetal, McCool, & Park, 2005; Spence et al., 2004), they do not necessary lead to a shift of spatial attention (that would have been expected to lead to a perceptual facilitation of colour discrimination responses).[5.2]

The results of Experiment 12 show that the presentation of a vibrotactile cue to the front or back of the participant's torso did not lead to a shift of attention in the direction cued by the vibration as indexed by a task involving the discrimination of the colour of a numberplate presented far from the participant's body. It is possible, however, that the vibrotactile cues might have resulted in the participant's attention being oriented toward the source of stimulation on the participant's torso (i.e., to peripersonal space; see Kitagawa et al., 2005; Tassinari & Campara, 1996), rather than to the extrapersonal visual space outside the car (as seen through the windscreen

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[5.2] It could be argued that spatial attention might not have influenced the detection of colour changes and the detection of angular size changes (as in the detection of a rapidly approaching car reported in Chapters 2 and 4) in the same way, thus rendering a strict comparison between the present study and the previous studies somewhat problematic. However, it should be noted that whether the spatial element is inherent in the task itself (e.g., as in the angular size change detection task) or not (e.g., as in the colour change detection task) is a constant factor within each of the experiments, and that any effects attributable to this factor should be cancelled out when the mean cuing effects within each experiment were calculated. Note that the mean cuing effects reflect the effectiveness of the spatial cues to orient the attention of the participants to the spatial location of interest. Other researchers have also reported the same pattern of attentional orienting effects across experiments no matter whether the task was to detect for a target presented alone or amongst distractors, or else to discriminate the colour of a target following the presentation of the same visual cues (e.g., see Hommel et al., 2001).

or rearview mirror). Previous research has shown that crossmodal spatial cuing effects are maximal when the cue and target are presented from the same spatial *location*, and decline as the cue-target separation is increased (Spence et al., 2004). (This contrasts with the situation for response priming, where as long as the cue primes the response, it does not really seem to matter so much what the exact spatial relationship between the cue and target is; see Procter et al., 2005, on this point). Indeed, recent neuropsychological research with patients suffering from unilateral spatial extinction has shown far more pronounced interactions between pairs of stimuli when they are both presented within the same region of space (i.e., both within peripersonal space or both within just extrapersonal space) than when they occur in different functional regions of space (i.e., one in peripersonal space and the other in extrapersonal space; e.g., Làdavas, 2002). Such results have been taken to show that the brain represents stimuli originating in these two regions of space in a somewhat distinct manner (cf. Previc, 1998, 2000).

Given that vibrotactile cues can only be presented on the body surface (i.e., in near-peripersonal space), Experiment 13 investigated whether the presentation of spatially-predictive auditory warning signals from the same functional region of space as the target visual driving events (i.e., both events presented in extrapersonal space) would facilitate performance on the numberplate colour discrimination task for targets presented from the cued location. (Note that both the rear auditory and visual stimuli originated from the rear, despite the fact that the targets were visually inspected from *in front* via the rearview mirror.)

5.4 Experiment 13

5.4.1 Methods

Ten new participants (mean age of 21 years, age range from 18-32; 6 males and 4 females) took part in Experiment 13. All of the participants reported normal hearing and normal, or corrected-to-normal, vision. The mean driving experience of participants was 4 years (range from 1-14 years). All the participants were right-handed by self-report. None of the participants had taken part in any of the earlier experiments. Six participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation.

The apparatus, materials, design, and procedure were exactly the same as those used in Experiment 12, with the sole exception that the vibrotactile cues were now replaced by auditory cues. The specification of the auditory stimuli was identical to that reported in Experiment 3. Specifically, the sound of a real car horn was used as the auditory cue. Spatially-predictive (80% valid) car horn sounds were presented from one of two loudspeaker cones placed on a virtual circle (140 cm in diameter) centred on the participants' head, one to the front and the other to their rear left-hand side.

5.4.2 Results

The results of Experiment 13 were analysed in a similar manner to those of Experiment 12. The mean false alarm rate across participants was 0.3%, and 1.3% of the trials were removed due to no response being made within 1800 ms of the onset of

the critical visual event. A two-way within-participants ANOVA was performed on the RT data with the factors of auditory cue direction (front vs. back) and visual stimulus location (front vs. back). The analysis revealed a significant main effect of auditory cue direction, $F(1,9) = 8.7$, $MSE = 1792.9$, $p = .016$, with participants responding more rapidly to critical visual events (i.e., to the colour change of the numberplate) following an auditory cue from the back ($M = 953$ ms) than from the front ($M = 992$ ms).

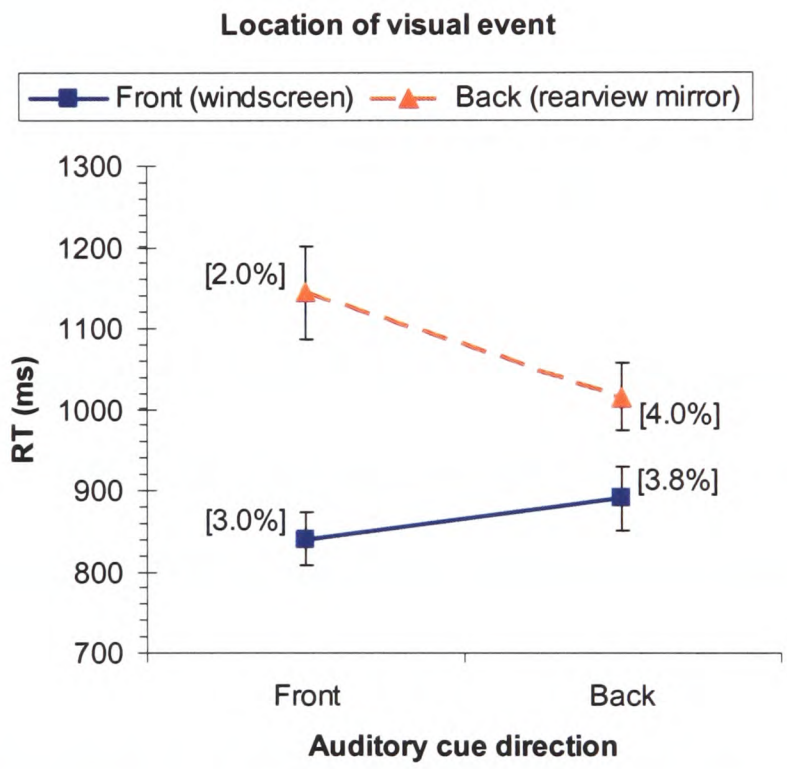


Figure 5.6 Interaction between the direction of the spatially-predictive auditory cue and the location of the critical visual event in the driving task in Experiment 13. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs.

The main effect of visual stimulus location was also significant, $F(1,9) = 34.8$, $MSE = 13225.4$, $p < .001$, with participants responding more rapidly to critical visual events presented from the front ($M = 865$ ms) than from the rear ($M = 1080$ ms), as in Experiment 12. However, in contrast to Experiment 12, the interaction between these factors was also significant, $F(1, 9) = 25.7$, $MSE = 3104.8$, $p < .001$. Participants responded more rapidly when the auditory cue and visual target stimulus were

presented from the same direction (i.e., on validly cued trials; M = 928 ms) than when the auditory cue was presented from the opposite direction to the visual stimulus (i.e., on invalidly cued trials; M = 1017 ms). Subsequent paired comparison t-tests revealed that these spatial cuing effects were significant both for targets presented through the front windscreen (mean cuing effect of 50 ms), $t(9) = -3.3$, $p = .010$, and for those presented in the rearview mirror (M = 129 ms), $t(9) = 4.7$, $p = .001$ (see Figure 5.6).

A similar analysis of the error data again revealed no significant main effect of auditory cue direction, $F(1,9) = 1.7$, $MSE = 11.8$, $p = .22$, or of visual stimulus location, $F(1,9) < 1$, *n.s.*, nor any interaction between these two factors, $F(1,9) < 1$, *n.s.* Analysis of the IE data also revealed a significant interaction between auditory cue direction and visual stimulus location, $F(1,9) = 25.9$, $MSE = 2653.5$, $p < .001$, with significant spatial cuing effects being reported for targets presented both from the front, $t(9) = -4.4$, $p = .002$, and from the rear, $t(9) = 3.4$, $p = .007$. Thus, a speed-accuracy trade-off account of the cuing effects reported in the data could be ruled out (see Duncan, 1980).

The mean percentage of correct detection responses in the concurrent RSVP task was 71.9% (SE = 4.1%), with a mean RT of 585 ms (SE = 13 ms) and a false alarm rate of 7.6% (SE = 2.5%). These results were very similar to those reported in Experiment 12.

5.4.3 Discussion

Participants in Experiment 13 responded significantly more rapidly to target visual driving events (the sudden change in the colour of a car's numberplate) occurring in the same direction as the auditory warning signal than when they were presented from opposite directions. These results replicate the crossmodal spatial

facilitation effects observed in the previous auditory cuing study when participants had either to brake or to accelerate in response to their sudden approach toward the car in front or the rapid approach of the car behind (Experiments 1-5). These results also allow one to rule out response priming as the sole explanation of the crossmodal effects in the auditory cuing experiments reported previously. Taken together, these findings support the idea that informative auditory warning signals can effectively orient a driver's spatial attention to a particular region of space (in this case, to front or rear extrapersonal space), leading to a facilitation of responses to visual events occurring subsequently in that direction (e.g., Spence et al., 2004).

5.5 *Differential effects of auditory and vibrotactile cuing*

The facilitatory effects of crossmodal spatial attentional cuing were observed following the presentation of spatially-predictive auditory warning signals (Experiment 13), but not following the presentation of spatially-predictive vibrotactile warning signals (Experiment 12). These findings contrast with the significant crossmodal spatial facilitation effects evidenced following the presentation of both spatially-predictive auditory and vibrotactile warning signals in the previous experiments (see Figure 5.7). There are at least two possible explanations for the differential effects of auditory and vibrotactile cuing on performance in the experiments reported here. First, it may be that audition and touch affect visual spatial attention in somewhat different ways. For although it has been argued previously that spatial attention may function in the same manner across the various sensory modalities (see Spence & Driver, 2004), the translation (or switching of attention) from touch to vision has been shown to be less efficient (i.e., more time-consuming)

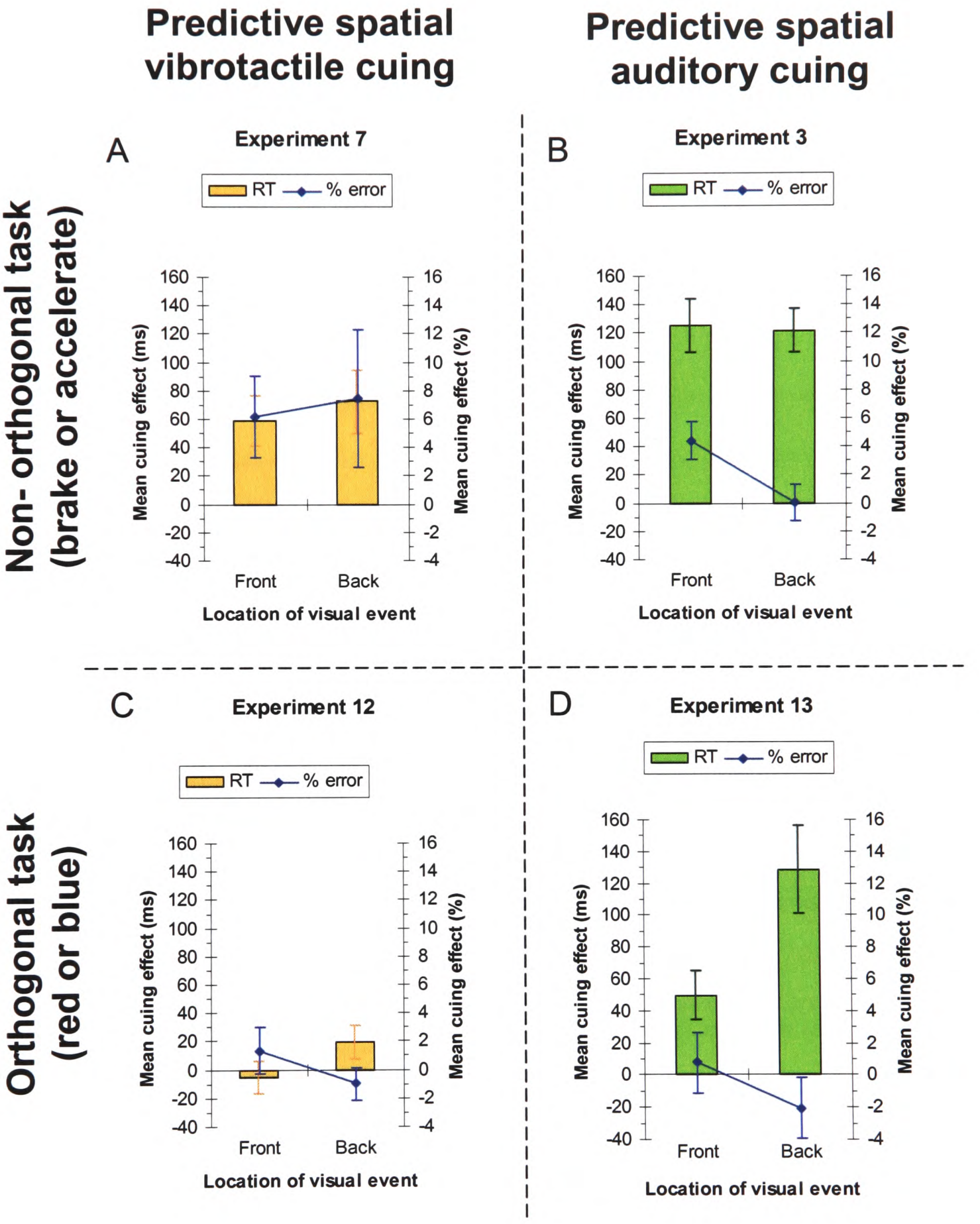


Figure 5.7 Summary of the mean cuing effects following vibrotactile (Experiment 12) and auditory (Experiment 13) cuing (A & B, respectively), spatially-predictive vibrotactile cuing in Experiment 7 (C), and spatially-predictive auditory cuing in Experiment 3 (D). Error bars indicate the standard errors of the means.

than from audition to vision (see Spence et al., 2001b). The change in the colour of the numberplate (which was superimposed on a rapidly approaching, i.e., looming, car) in the orthogonal discrimination experiments reported in this chapter may have been more attention-capturing (cf. Franconeri, Simons, & Junge, 2004; Turatto & Galfano, 2001) than the rapid approach toward the car in front or the rapid approach of the car from behind in the previous experiments. Consequently, the change of the colour of the numberplate may have more automatically (and/or rapidly) captured the participants' attention in Experiments 12 and 13. Given that tactile information is transduced at the receptor surface (i.e., skin) more slowly than auditory stimuli at the basilar membrane of the ear (see Spence & Squire, 2003; Zampini, Brown, Shore, Maravita, Roder, & Spence, 2005), it might be suggested that participants in Experiment 12 may not have had sufficient time to localize the vibrations and to shift their spatial attention to the visual driving task from the RSVP task prior to their (Experiment 13), but not following the presentation of spatially-predictive vibrotactile warning signals (Experiment 12). These findings contrast with the significant crossmodal spatial facilitation effects evidenced following the presentation of both spatially-predictive auditory and vibrotactile warning signals in the previous experiments (see Figure 5.7). There are at least two possible explanations for the differential effects of auditory and vibrotactile cuing on performance in the experiments reported here. First, it may be that audition and touch affect visual spatial attention in somewhat different ways. For although it has been argued previously that spatial attention may function in the same manner across the various sensory modalities (see Spence & Driver, 2004), the translation (or switching of attention) from touch to vision has been shown to be less efficient (i.e., more time-consuming) than from audition to vision (see Spence et al., 2001b). The change in the colour of

the numberplate (which was superimposed on a rapidly approaching, i.e., looming, car) in the orthogonal discrimination experiments reported in this chapter may have been more attention-capturing (cf. Franconeri, Simons, & Junge, 2004; Turatto & Galfano, 2001) than the rapid approach toward the car in front or the rapid approach of the car from behind in the previous experiments. Consequently, the change of the colour of the numberplate may have more automatically (and/or rapidly) captured the participants' attention in Experiments 12 and 13. Given that tactile information is transduced at the receptor surface (i.e., skin) more slowly than auditory stimuli at the basilar membrane of the ear (see Spence & Squire, 2003; Zampini, Brown, Shore, Maravita, Roder, & Spence, 2005), it might be suggested that participants in Experiment 12 may not have had sufficient time to localize the vibrations and to shift their spatial attention to the visual driving task from the RSVP task prior to their attention being captured automatically by the onset of the visual target (i.e., by the colour change of the numberplate itself).

However, the results of Experiment 11, where the relative speed with which people could discriminate the direction (front or back) from which warning signals were presented in the different sensory modalities was investigated, reveals this explanation to be incorrect. In that experiment, it was found that participants could discriminate the direction of vibrotactile warning signals significantly more rapidly than the direction of auditory warning signals, presumably because of the difficulty people have in localizing auditory stimuli within confined spaces (e.g., Catchpole et al., 2004; Moore & King, 1999).

Alternatively, however, it could also be argued that the colour discrimination task itself may simply have been less sensitive to the distribution of spatial attention than the looming (i.e., braking/accelerating) task used in the previous experiments,

with the latter task in some sense involving the integration of spatial information over time (cf. Spence et al., 2004). There are two reasons why such an account can be ruled out: First, several researchers have previously shown reliable spatial attentional orienting effects using colour discrimination tasks (e.g., see Hommel et al., 2001). Second, the reliable spatial cuing effects observed with auditory cuing in Experiment 13 argue against the colour discrimination task simply being insensitive to the distribution of spatial attention. Hence, it is very unlikely that the use of the colour discrimination task represents a major factor contributing to the null vibrotactile cuing effect observed in Experiment 12.

Researchers have suggested that the use of vibrotactile cues may provide an 'intuitive' means of presenting directional information in interface displays, such as in situation-awareness and navigation systems for pilots and drivers (e.g., Rupert, 2000a; van Erp, 2005; van Erp & van Veen, 2004). For instance, van Erp and van Veen showed that drivers could respond more rapidly following navigational messages presented in a bimodal (tactile and visual) display than when the messages were presented unimodally (i.e., via touch or vision only). Participants also reported significantly lower subjective mental workload ratings with the touch only display, as compared to when using the visual only or bimodal displays.

Van Erp (2005) recently reported that people seem to have no trouble in localizing vibrotactile stimuli presented to their torsos, and can indicate the associated direction in the external environment accurately (albeit with a consistent mislocalization bias toward the navel or spine). However, the results of Experiment 12 suggest that vibrotactile cues are in some sense limited. Indeed, when assessing the effectiveness of vibrotactile cues in conveying information, it may be useful to break the role of such vibrotactile stimuli into distinct categories, namely, their ability to

direct spatial attention to the location of the critical target event, their ability to prime the response appropriate to that target event, and finally their ability to act as a means of information transfer to an interface operator.

The most likely explanation for the difference in the effectiveness of auditory and vibrotactile cuing in Experiments 12 and 13 comes from recent evidence suggesting that the brain represents stimuli occurring in peripersonal space somewhat differently from those occurring in extrapersonal space (e.g., Previc, 1998, 2000; Rizzolatti, Fadiga, Fogassi, & Gallese, 1997; Spence & Driver, 2004). It may be that the remapping of a front or back directional cue on the torso (i.e., in peripersonal space) to a target visual event taking place in a location farther away in extrapersonal space is less efficient than when the cue and target both occur within the same functional region of space (i.e., both within peripersonal space or both within extrapersonal space). In this regard, it would be interesting in future research to examine how people subjectively represent extrapersonal and peripersonal space in driving situations (e.g., does the peripersonal vs. extrapersonal distinction equate to events happening within the car vs. outside the car, respectively, cf. Kitagawa & Spence, 2005). Understanding the representation of near-peripersonal space may therefore assist us in interpreting the present findings (see Kitagawa et al., 2005; Làdavas & Farnè, 2004).[5.3]

[5.3] It would also be interesting to examine what role, if any, the fact that a driver is moving rapidly in a predictable direction have on the shape and border of peripersonal versus extrapersonal space (cf. Gibson & Crooks, 1938).

5.6 Experiment 14

If, as recent cognitive neuroscience data suggests, the brain really does handle peripersonal and extrapersonal space in qualitatively different ways (Làdavas, 2002; Previc, 1998; Spence & Driver, 2004; Weiss et al., 2000), then it might be predicted that the crossmodal spatial facilitation effects observed in Experiment 13 would be eliminated if the spatial auditory cues were actually presented from sources that were much closer to the participants' body (just as was the case for the vibrotactile cues used in Experiment 12). If, however, crossmodal spatial facilitation effects were still to be present in this situation, then it would suggest that for the differential effects of auditory and vibrotactile cues on visual spatial attention in the driving situation, there must be another cause. Experiment 14 was therefore designed to investigate whether the presentation of the same spatial auditory cues used in Experiment 13 from locations closer to the participants' body would eliminate the crossmodal spatial facilitation effects observed previously.

5.6.1 Methods

Ten participants (mean age of 20 years, age range from 18-22; 3 males and 7 females) took part in Experiment 14. All reported normal hearing and normal, or corrected-to-normal, vision. Their average driving experience was 1.7 years (range from 1 month to 5 years). Nine participants were right-handed and one was left-handed by self-report. None of the participants had taken part in any of the preceding experiments reported in this thesis. Seven participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation.

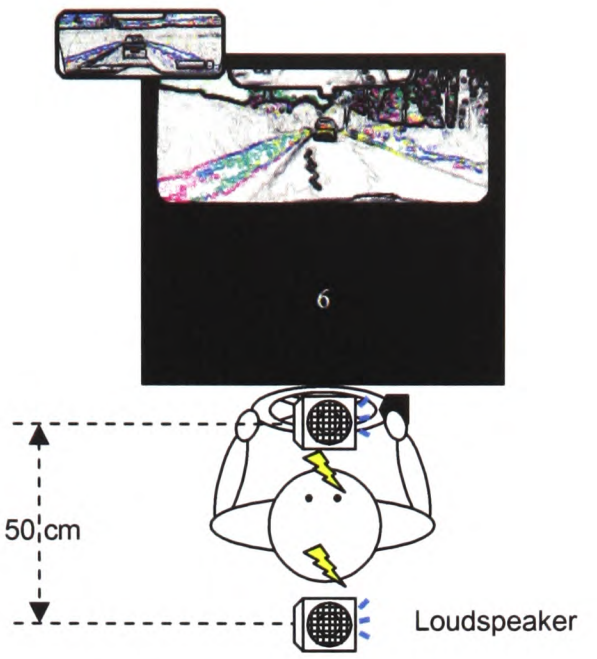


Figure 5.8 A schematic diagram of the experimental set-up used in Experiments 14 and 15.

The apparatus, materials, design, and procedure of the experiment were exactly the same as in Experiment 13, with the exception that the location from which the auditory cues were presented were now much closer to the participants' body. Specifically, the two loudspeakers were placed on a virtual circle (50 cm in diameter) centred on the participants' head, one to the front and the other to the back of their head (see Figure 5.8). The loudspeakers were placed 130 cm above the floor such that the participants could see the visual stimuli directly below the front loudspeaker.

5.6.2 Results

The results of Experiment 14 were analysed in a similar manner to those of Experiment 13. The mean false alarm rate across participants was 2.3%, and 0.9% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual event. A two-way within-participants ANOVA was performed on the RT data with the factors of auditory cue direction and visual stimulus location. This analysis revealed a significant main effect of visual stimulus location, $F(1,9) = 57.0$, $MSE = 5120.3$, $p < .001$, with participants responding more rapidly to critical

visual events presented from the front (M = 856 ms) than to those presented from the rear (M = 1027 ms), as in Experiment 13 (see Figure 5.9). However, in contrast to the results of Experiment 13, the main effect of auditory cue direction was not significant, nor was the interaction between auditory cue direction and visual stimulus location, both $F(1,9) < 1$, *n.s.*, suggesting that the spatial validity of the auditory cues with respect to the location of the visual targets did not facilitate participants' responses.

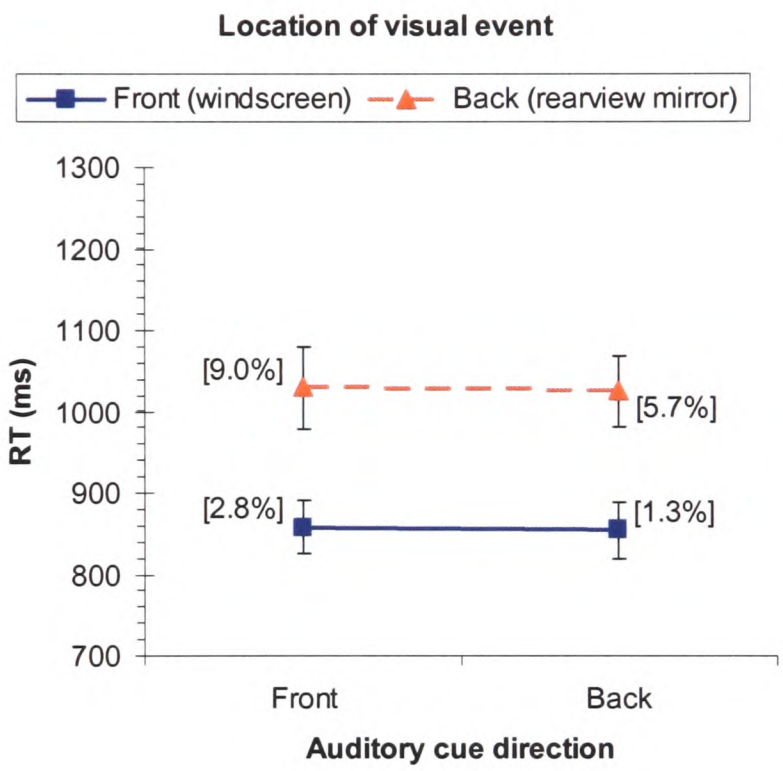


Figure 5.9 Mean RTs for the driving task in Experiment 14 as a function of the direction of the spatially-predictive auditory cue presented close to head and the location of the critical visual event. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs.

A similar analysis of the error data revealed a significant main effect of visual stimulus location, $F(1,9) = 16.0$, $MSE = 17.9$, $p = .003$, with participants making more errors in response to visual target events presented from the rear (M = 7.4%) than in response to those presented from the front (M = 2.0%). The main effect of auditory cue direction was, however, not significant, $F(1,9) = 4.3$, $MSE = 13.8$, $p = .07$, nor was the interaction between these two factors, $F(1,9) < 1$, *n.s.*

The mean percentage of correct detection responses in the concurrent RSVP task was 75.1% (*SE* = 3.3%), with a mean RT of 588 ms (*SE* = 17 ms) and a false alarm rate of 5.9% (*SE* = 1.8%). These results were very similar to those reported previously.

5.6.3 Discussion

Consistent with the hypothesis derived from recent cognitive neuroscience research suggesting that the brain represents the various functional regions of space surrounding the body differently, no spatial cuing effect of the presentation of spatial auditory cues could be obtained when the loudspeakers presenting the auditory cues were moved from the extrapersonal space far away from the body (coinciding with the location of the monitor in which the visual stimuli were seen) to locations closer to the participant's own body (in peripersonal space, as in the case of the vibrotactile stimuli, even though the sources of the auditory cues were not touching the participant's body per se). Taken together, these findings suggest that the perceptual/attentional enhancement of a target representation may require the presentation of a cue from the same functional region of space as the target, regardless of the sensory modalities in which the cue and target are presented.

One potential confound, however, with the set-up used in Experiment 14 was that the placement of the two auditory sources was susceptible to potential front-back confusions (Geissler, 1915; Stevens & Newman, 1936), thus limiting the spatial property of the auditory cues (meaning that the condition would resemble more of a nonspatially-predictive auditory cuing case, as in Experiment 2. Note though that a significant spatial cuing effect was found in Experiment 2 with the presentation of 50% valid auditory car horn sounds from loudspeakers located far away from the

participants' body). In order to address this issue, a replication of Experiment 14 was conducted with the use of white noise bursts instead of auditory car horn sounds. Previous studies suggest that participants find it easier to localize white noise bursts than pure tones presented from proximal sources (Deatherage, 1972; Spence & Driver, 1994; Stevens & Newman, 1936).

5.7 Experiment 15

Experiment 15 was therefore designed to replicate Experiment 14 to investigate whether the null spatial cuing effect with the use of auditory cues presented from close to the body was an artefact of the difficulty with which participants might have in localizing the spatial auditory car horn sounds. If the same pattern of results as in Experiment 14 could be obtained, then the evidence will provide further support for the hypothesis that there exist different functional region of space around the body that the brain handled in a qualitatively different manner.

5.7.1 Methods

Ten participants (mean age of 21 years; age range from 18-28; 3 males and 7 females) participated in Experiment 15. Their average driving experience was 3.2 years (range from 1 month to 10 years). Nine of the participants were right-handed and one was left-handed by self-report. None of them have participated in any of the previous experiments reported in this thesis. Five of the participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation.

The apparatus, materials, design, and procedure were exactly the same as those used in Experiment 14, with the sole exception that instead of the sound of a

real car horn, white noise bursts consisting of consecutive bursts for 50 ms on and 50 ms off for a total duration of 600 ms (44100 Hz; 66 dB(A)) were used as the auditory stimuli. Spatially-predictive (80% valid) white noise bursts were presented from one of two loudspeaker cones placed on a virtual circle (50 cm in diameter) centred on the participants' head (see Figure 5.8).

5.7.2 Results

The results of Experiment 15 were analysed in a similar manner to those of Experiment 14. The mean false alarm rate across participants was 1.8%, and 0.6% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual event. A two-way ANOVA was performed on the RT data with the within-participants factors of auditory cue direction and visual stimulus location. The analysis revealed a significant main effect of visual stimulus location, $F(1,9) = 109.2$, $MSE = 1883.8$, $p < .001$, as in Experiment 14, but no significant main effect of auditory cue direction, $F(1,9) < 1$, *n.s.*, nor any two-way interaction, $F(1,9) = 1.0$, $MSE = 8401.7$, $p = .33$ (see Figure 5.10).

A similar analysis of the error data again revealed no significant main effect of auditory cue direction, $F(1,9) < 1$, *n.s.*, or visual stimulus location, $F(1,9) < 1$, *n.s.*, nor any interaction between these two factors, $F(1,9) = 2.0$, $MSE = 12.0$, $p = .19$.

The mean percentage of correct detection responses in the RSVP task was 81.3% ($SE = 2.0\%$), with a mean RT of 563 ms ($SE = 10$ ms) and a false alarm rate of 5.9% ($SE = 1.2\%$), similar to those reported in the earlier experiments.

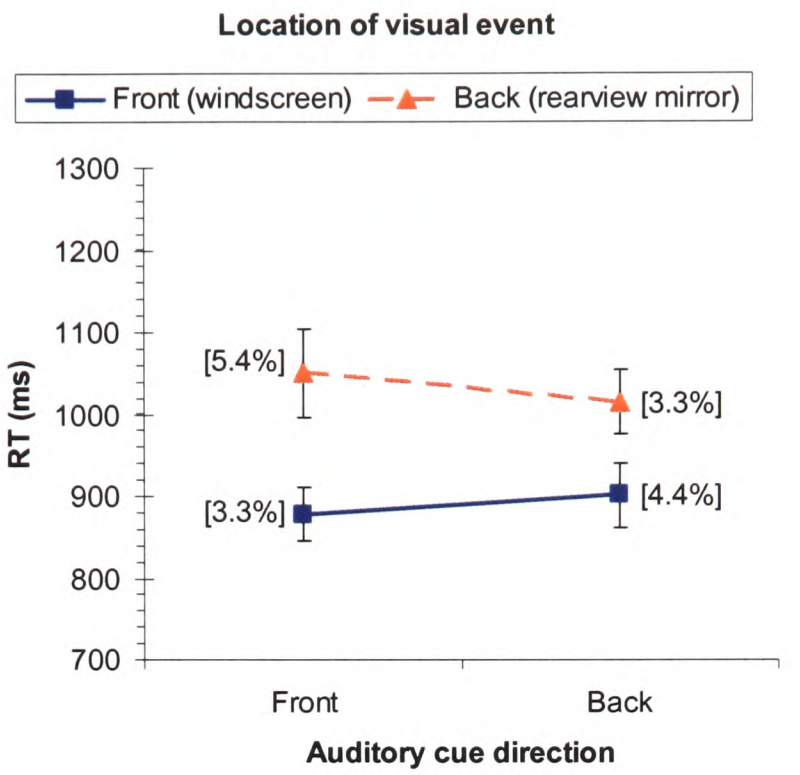


Figure 5.10 Mean RTs for the driving task in Experiment 15 as a function of the direction of the spatially-predictive auditory white noise bursts presented close to head and the location of the critical visual event. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs.

5.7.3 Discussion

The results of Experiment 15 failed to show any significant spatial cuing effect for auditory white noise bursts presented from sources close to the head of the participants, once again provides evidence in support of the functional region of space hypothesis. Between-experiments analyses were conducted to compare the spatial cuing effects found in the three orthogonal auditory cuing experiments. A between-experiments analysis of the mean cuing effect in the RT data obtained in Experiments 13-15 revealed a significant difference, $F(2,27) = 5.1$, $MSE = 4003.6$, $p = .013$ (see Figure 5.11). Post-hoc comparison (LSD) showed a significant difference between spatially-predictive auditory car horn sounds presented far from head and that presented close to head, $p = .004$, and between spatially-predictive auditory car horn

sounds presented far from head and spatially-predictive auditory white noise bursts presented close to head, $p = .044$, but not between the two spatially-predictive auditory cues both presented close to head, $p = .32$. The analysis of the mean cuing effect in the error data failed to show any statistically significant across the three experiments, $F(2,27) < 1$, *n.s.*

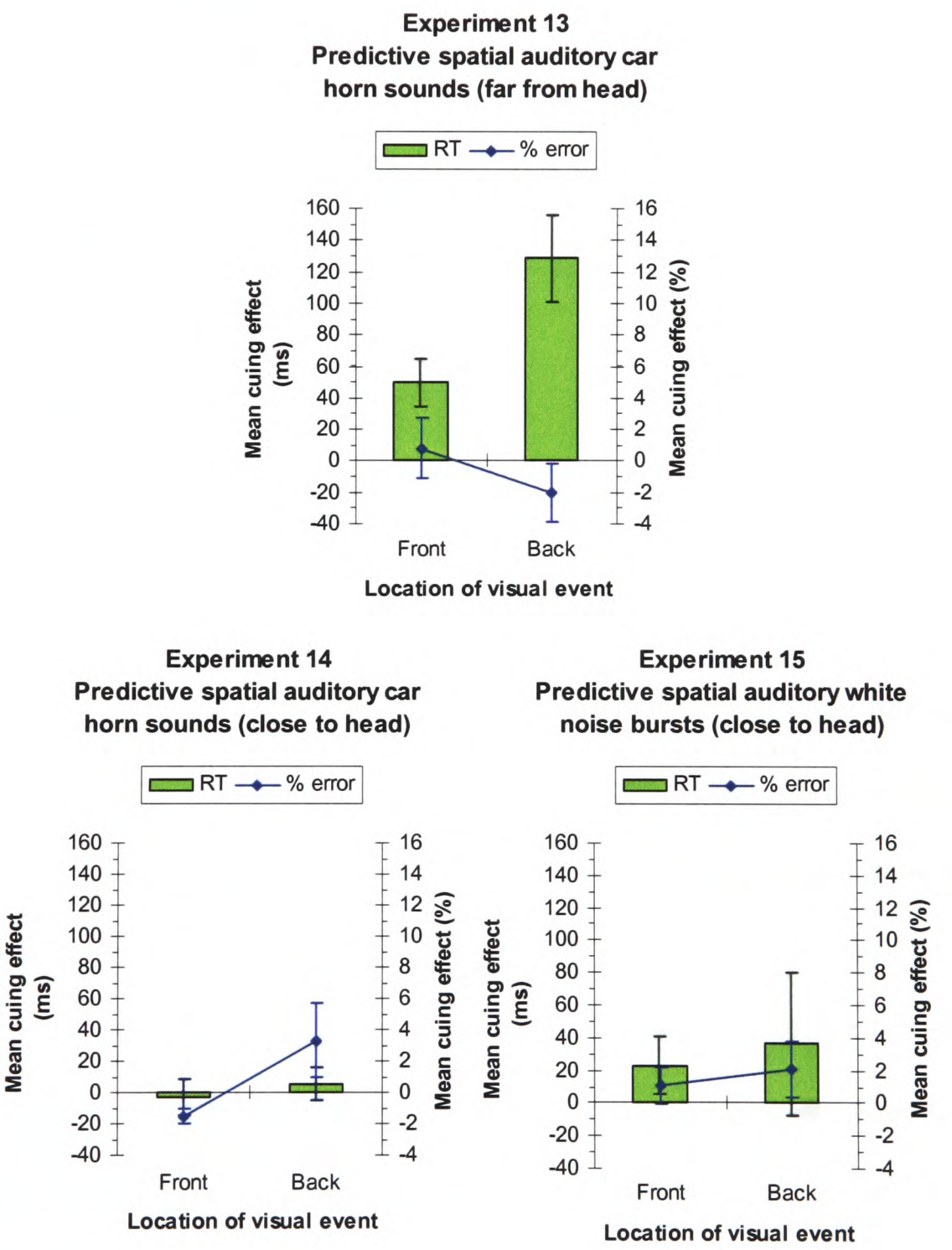


Figure 5.11 Summary of the mean cuing effects following spatially-predictive auditory car horn sounds presented far from head (Experiment 13), spatially-predictive auditory car horn sounds presented close to head (Experiment 14), and spatially-predictive auditory white noise bursts presented close to head (Experiment 15). Error bars indicate the standard errors of the means.

Overall, the results of Experiments 12-15 together suggest that in order for a spatial multisensory warning signal to effectively enhance a person's perceptual representation of the cued spatial location, the cue has to be presented from the same functional region of space as the target event. Otherwise, a spatial cue may only inform the potential target direction and prime the appropriate response, rather than leading to any attentional shift to the cued direction. Both vibrotactile and auditory cues presented on/close to the torso in the personal/peripersonal space were not effective in enhancing the spatial representation of a visual target event presented from the extrapersonal space away from the torso, even though these cues were effective in priming the appropriate behavioural responses in the applied level (see Chapters 2 and 4).

5.8 Experiment 16

Researchers working on the topic of multisensory integration have postulated a superadditive effect of multisensory neurons in their responding to multisensory stimuli over the linear sum of the effects of exposure to the two sensory stimuli independently, at least under a certain subset of conditions (see e.g., Calvert et al., 2004; Stein & Meredith, 1993; Stein, Stanford, Wallace, Vaughan, & Jiang, 2004). Related findings from applied research (e.g., Selcon et al., 1995; van Erp & van Veen, 2004) also suggest that the redundant use of multisensory signals that provide congruent information can produce a bigger facilitation effect than when unimodal signals are presented in isolation. For instance, taking the example of turning the steering wheel, several researchers have already demonstrated that the presentation of tactile cues via the steering wheel can facilitate a driver's turning of the wheel in a

particular direction (e.g., Proctor et al., 2005; cf. Schumann & Naab, 1992; Wang, Proctor, & Pick, 2003). According to the multisensory approach, tactile cues might be made to be even more effective if they were to be combined with congruent visual cues on the steering wheel itself. The use of such congruent multisensory cues is believed to be far more effective than one might expect given the effectiveness of each kind of unimodal cue when presented in isolation (van Erp & van Veen, 2004): This is because multisensory integration can give rise to synergistic, or superadditive, outcomes (i.e., to outcomes that are larger than the simple linear sum of the component parts; e.g., Calvert et al., 2004; Stein & Meredith, 1993; though see also Holmes & Spence, 2005; Spence & Driver, 1999; Stein et al., 2004).

Experiment 16 was thus designed to assess the effectiveness of the presentation of multisensory warning signals. Given that facilitatory effects were found when auditory or vibrotactile warning signals were presented alone, it was hypothesized that an enhanced facilitation effect would be observed. As discussed earlier in this chapter, vibrotactile cues originating from the torso of participants/drivers could intuitively alert them to the spatial direction of a potential collision while auditory cues originating from the same location as the critical visual target events could lead to attentional facilitation or perceptual enhancement for stimuli occurring at that spatial location. As a result, the maximal facilitation effect was expected if multisensory integration functions in an additive manner. On the other hand, it could be argued that two stimuli originating from different spatial locations (though always providing congruent information about the potential direction of the visual target event) might interfere with each other in that spatial attention is divided between the two when they were simultaneously presented. If this were true, a small facilitatory effect (or even an inhibitory effect) might be observed.

5.8.1 Methods

Twelve participants (mean age of 20 years, age range from 18-24; 6 males and 6 females) took part in Experiment 16. Their average driving experience was 2 years (range 5 months to 6 years). Eleven participants were right-handed and one was left-handed by self-report. None of the participants had taken part in any of the preceding experiments. Nine participants received course credit, the rest received a £5 UK sterling gift voucher in return for their participation.

The apparatus, materials, design, and procedure were exactly the same as those used in Experiments 3 and 7. In particular, the auditory stimuli consisted of the sound of a real car horn (8000 Hz; 66 dB(A)), presented through one of two loudspeaker cones placed on a virtual circle (140 cm in diameter) centred on the participants' head, one to the front and the other to their rear left-hand side (as in Experiments 2 and 3). The vibrotactile stimuli were delivered to participants using the same tactor belt as that used previously in Experiments 7 and 8, with one tactor positioned in the middle of the participant's stomach while the other in the middle of their back. The multisensory cues consisted of an auditory cue and a vibrotactile cue lasting for 600 ms, both presented from the same spatial direction throughout the experiment (such that they always provided congruent information with regard to the potential direction from which the visual target event was likely to occur). The multisensory cues were spatially-predictive, that is, they were 80% valid with respect to the visual target direction.

5.8.2 Results

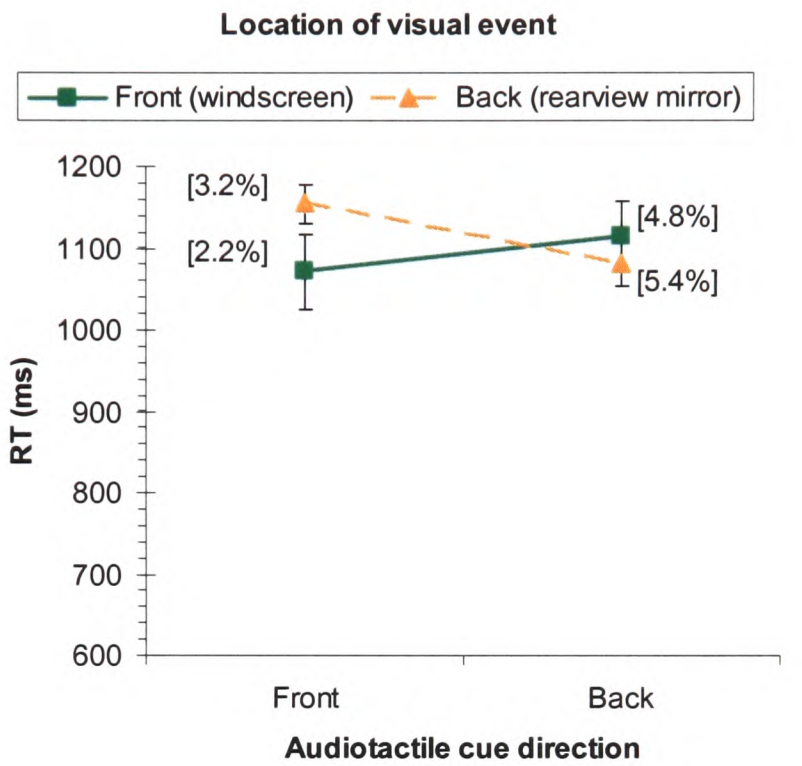


Figure 5.12 Interaction between the direction of the spatially-predictive multisensory cue and the location of the critical visual event in the driving task in Experiment 16. Percentages of errors are indicated by numerical values in parentheses. Error bars indicate the standard errors of the RTs.

The results of Experiment 16 were analysed in a similar manner to those of Experiments 3 and 7. The mean false alarm rate across participants was 12.2%, and 2.4% of the trials were removed due to no response being made within 1800 ms of the onset of the critical visual event. A two-way ANOVA was performed on the RT data with the within-participants factors of multisensory cue direction (front vs. back) and visual stimulus location (front vs. back). The analysis revealed no significant main effect of multisensory cue direction, $F(1,11) = 1.4$, $MSE = 2098.1$, $p = .26$, or visual stimulus location, $F(1,11) < 1$, *n.s.* The two-way interaction between multisensory cue direction and visual stimulus location was, however, highly significant, $F(1,11) = 26.9$, $MSE = 1517.3$, $p < .001$. Subsequent paired-comparison *t*-tests revealed a significant

spatial cuing effect for visual target events presented from the back, $t(11) = 8.1$, $p < .001$, but failed to reach significance for those presented from the front, $t(11) = -1.9$, $p = .09$ (see Figure 5.12).

A similar analysis of the error data revealed no significant main effect of multisensory cue direction, $F(1,11) = 2.2$, $MSE = 31.6$, $p = .17$, or visual stimulus location, $F(1,11) < 1$, *n.s.*, nor any two-way interaction, $F(1,11) < 1$, *n.s.*

The mean percentage of correct detection responses in the RSVP task was 68.3% ($SE = 2.8\%$), with a mean RT of 577 ms ($SE = 12$ ms) and a false alarm rate of 5.6% ($SE = 0.8\%$), similar to those reported in earlier experiments.

5.8.3 Discussion

Consistent with the results of Experiments 3 and 7, significant spatial cuing effects were reported in Experiment 16 with participants responding more rapidly to visual target events presented from the valid than the invalid direction as the multisensory cue. A between-experiments analysis was performed in order to assess the effects of the use of spatial multisensory cues over unimodal spatial auditory or unimodal vibrotactile cues. A three-way mixed ANOVA was performed on the IE data with the between-participants factor of cue type (auditory in Experiment 3, vibrotactile in Experiment 7, or multisensory in Experiment 16), and the within-participants factors of cue direction (front vs. back) and visual stimulus location (front vs. back). This analysis revealed a significant main effect of cue type, $F(2, 37) = 3.3$, $MSE = 275060.8$, $p = .049$, with the fastest overall performance being reported when the cues were auditory (Experiment 3; overall IE score of 1052 ms) than when they were multisensory (Experiment 16; $M = 1152$ ms) or vibrotactile (Experiment 7; $M = 1304$ ms). Post-hoc multiple comparison with Bonferroni adjustment showed a

significant difference between auditory and vibrotactile cuing, $p = .049$, but not between multisensory and auditory cuing, $p = 1.0$, or between multisensory and vibrotactile cuing, $p = .41$.

Thus, the between-experiments analysis failed to show any statistically significant advantage of multisensory cuing over unimodal (auditory or tactile) cuing. These results suggest that the use of multisensory warning signals is no better than the best of the individual unimodal warning signals. However, the results here also failed to reveal any performance decrement with the use of multisensory cues, thus suggesting that the use of redundant cues may not harm performance after all. Although the multisensory cues were always presented at the same time, the disparity in spatial locations could have mitigated the combined effectiveness of the use of multisensory cuing (cf. Colonius & Diederich, 2004). Note also the between-participants experimental design. Therefore, in future studies it would be nice to replicate these findings using a within-participants design.

One current topic of interest in the area of multisensory warning signal design is the relative effectiveness of unimodal versus bimodal and/or multimodal signals. To date, published studies have demonstrated mixed findings with regard to the superiority of multisensory over single channel (or unimodal) information presentation (e.g., Selcon et al., 1995; Spence & Driver, 1999; see also Campbell et al., 1996). One important distinction to be made here is between multisensory signals that convey the same information (i.e., that are, in some sense, redundant) versus those giving information about different, perhaps interdependent, aspects of the same event (cf. Fidell, 1982). With regard to the former situation, a number of studies have demonstrated benefits of redundant sources of information presentation. For instance, Selcon et al. (1995) compared the speed with which participants could detect and

respond to the presentation of a number of different combinations of visual and/or auditory spatial and/or verbal missile approach warning signals. They observed significantly faster response latencies when two to four sources simultaneously gave the same piece of information than when only a single type of cuing was used. Hence, the multisensory warning signals used in Selcon et al.'s study would appear to have resulted in an additive effect on human performance. It should be noted, however, that it is unclear whether the cues facilitated performance simply by priming the correct response and/or whether they also led to a genuine attentional facilitation effect (cf. Miller, 1982; Spence & Driver, 1999).

On the other hand, Spence and Driver (1999) reported bimodal audiovisual warning signals to be no more effective than unimodal auditory signals in capturing a participant's spatial attention in a laboratory-based cuing study where response priming explanations of their results were ruled out (by cuing the participant's attention in a dimension – left vs. right – that was orthogonal to the response dimension along which participants were required to respond – up vs. down –; see Spence & Driver, 1997a). It is perhaps worth noting one limitation with the majority of previous studies of crossmodal attentional capture, namely that they have typically assessed the ability of a spatial cue (presented either unimodally or bimodally) to capture attention under conditions where the participants only task involves responding as rapidly and accurately to the frequently-presented target stimuli (i.e., under single task conditions; see Spence et al., 2004, for a review). This situation is in many ways quite different to the typical situation in which multisensory warning signals would need to be maximally effective, that is, when an interface operator is engaged in another highly attention-demanding task and where the warning signal needs to be sufficiently salient, and attention-capturing, to break through. However, in

this regard, recent research by van der Lubbe and Postma (2005) has shown that unimodal auditory and visual cues can break through and capture a person's attention even under conditions where they are trying to maintain the focus of their spatial attention elsewhere. It will therefore be particularly interesting in future studies to investigate further whether multisensory warning signals are any more effective in 'breaking through' and capturing interface operators' attention than unimodal warning signals when the interface operators are involved in another highly attention-demanding task, similar to the case illustrated in Experiment 16.

There is now a growing body of empirical research comparing the effectiveness of unimodal feedback signals to multisensory feedback signals in a variety of different interface settings (e.g., Akamatsu, MacKenzie, & Hasbroucq, 1995; Cockburn & Brewster, 2005; Vitense et al., 2003). For example, Akamatsu et al. have shown that the use of combined tactile, auditory, and visual feedback signals in a mouse-pointing task was no more effective than the unimodal tactile signal by itself. Their results presumably reflect the fact that an operator may select the most appropriate sensory channel for feedback depending on the task at hand (see also Burke et al., 1980; Cockburn & Brewster, 2005).

Taken together, it seems that the potential benefit or costs/interference attributable to the introduction of multisensory warning signals depends to a large extent on the nature of the task being performed. For instance, in a study by Hirst and Graham (1997) on braking responses following the presentation of collision avoidance warnings, a lower incidence of collisions and increased time-to-collision braking scores (calculated by dividing inter-vehicle distance by relative speed, i.e., a higher score indicates better performance) were reported for the combined use of an abstract head-up visual display with either an auditory tone of 500 Hz or a speech

warning ('danger ahead'), instead of the combined use of a pictorial visual cue with either the tone or speech cue, but no difference in overall effectiveness was reported as a function of whether the visual cue was combined with a non-speech or speech cue.

A possible alternative account of the mixed multisensory facilitation effects reported in previous studies is in terms of the time-window-of-integration model put forward by Colonius and Diederich (2004; see also Miller, 1982; Mordkoff & Egeth, 1993), given that the occurrence of multisensory integration is dependent on both the temporal and spatial configuration of the stimuli presented (see also Stein & Meredith, 1993). Colonius and Diederich's two-stage model predicts that for multisensory signals to be maximally effective, they should be presented close together in time in order for multisensory integration to occur, and that the spatial proximity of the signals will determine the magnitude and sign of this integration effect (e.g., one signal may inhibit the other if the multisensory signals are presented from distinct spatial locations; see also Holmes & Spence, 2005; Stein & Meredith, 1993). This could possibly account for the lack of multisensory facilitation effect over-and-above unimodal spatial cuing reported here. Note also that for multisensory warning signals to be effective, designers should avoid presenting incongruent information even via different sensory channels (e.g., Selcon, Taylor, & Shadrake, 1991).

From an applied perspective, the results reported in this thesis when taken together suggest that the use of vibrotactile and auditory warning signals in automobile interface design to inform drivers of the occurrence of time-critical events outside the car is both effective and practical means of reducing visual workload while at the same time effectively capturing a driver's attention (and/or priming the appropriate response). The findings also imply that response compatibility is an

important factor in multisensory interface design, and may facilitate performance whenever the warning signal and the relevant target event are presented from approximately the same direction. However, the additional benefits attributable to attentional facilitation may only occur when the warning signal and target event locations match much more closely (i.e., when they are both presented within the same functional region of space).

CHAPTER 6

OLFACTORY CUING

The preceding chapters have examined the relative effectiveness of various different auditory and tactile warning signals. In this final experimental chapter, another class of warning signal that may also be used in driving, namely, olfactory signals, is considered (e.g., see Deatherage, 1972; Grayhem, Esgro, Sears, & Raudenbush, 2005; RAC Foundation, 2005). To date, there has been controversy concerning the specific effects of olfactory stimulation on task performance, with a number of studies showing null effects while others have shown significant effects. In this chapter, the results of two experiments that investigated the differential effects of olfactory stimulation on dual-task performance under conditions of varying task difficulty are presented.

6.1 Previous studies of olfactory cuing

Several researchers have reported that the presentation of certain odours (such as lavender, lemon, muguet, and peppermint) can modulate human performance (e.g., Millot, Brand, & Morand, 2002; Raudenbush, Corley, & Eppich, 2001), cognition (e.g., Baron & Thomley, 1994; Moss, Cook, Wesnes, & Duckett, 2003), and emotion (e.g., Ludvigson & Rottman, 1989; Michael, Jacquot, Millot, & Brand, 2003). For

instance, Millot et al. reported that the presentation of an ambient odour, no matter whether it was the pleasant odour of lavender or the unpleasant odour pyridine (which smells like rotten fish), resulted in a 10% decrease in response latencies to simple auditory and visual stimuli relative to a no-odour baseline condition. In another influential early study, Warm, Dember, and Parasuraman (1991) reported a marked improvement in cognitive performance in a sustained visual attention task. In their between-participants design, Warm et al. reported an overall performance advantage of about 20% in the number of visual targets (a total of 40 targets over a time course of 40 min with stimuli presented at a rate of 24 events/min) detected by different groups of participants periodically exposed to either peppermint or muguet (lily of the valley) odour (30 s bursts every 5 min), as compared to a no-odour (i.e., air) control group of participants.

Several other researchers have, however, failed to obtain any significant effect of odour on human performance. For instance, Gilbert, Knasko, and Sabini (1997) reported no significant effect of the presence of either pleasant or unpleasant odours, when compared to a no-odour baseline, on participant's performance on either a clerical coding task or on a task requiring them to cross-out target digits from a page of random numbers. Meanwhile, Ilmberger, Heuberger, Mahrhofer, Dessovic, Kowarik, and Buchbauer (2001) reported no effect of the presentation of ylang-ylang, 1.8-cineole, menthol, peppermint, or jasmine on speeded visual target detection performance. The lack of any significant effect of the presence of odour on task performance in these latter studies may partly be due to the insensitivity of the specific tasks used to the alerting manipulations (cf. Frick, 1995), or to a specific failure of olfactory alerting when using these particular odorants. Note that not only is there a question about whether natural essential oils are better than synthetic odorants,

but also whether one variety of odorants, such as peppermint, is more effective than any of the other varieties. In addition, the performance differences obtained in all of the above studies may well be caused by the discrepancy between the different groups of participants tested, given the use of between-participants designs and the large individual differences typically found in terms of olfactory perception (e.g., Dalton, Doolittle, & Breslin, 2002; O'Connell, Stevens, & Zogby, 1994; cf. Keren, 1993).

Another potentially important factor in this area of research may be the fact that performance can be affected either positively or negatively depending on the a participant's initial level of arousal or stress (e.g., Degel & Koster, 1999; cf. Yerkes & Dodson, 1908), with alerting and sedative odours acting in an opposing manner to either increase or reduce stress levels. To date, however, no one has examined the differential effects of odours on tasks of varying difficulty. Note also the potentially important distinction here between the use of continuously presented ambient odours (e.g., Michael et al., 2003; Millot et al, 2002) versus periodically presented bursts of odours (e.g., Warm et al., 1991), as people's sensitivity to odorants typically decreases with prolonged or repeated exposure to the same olfactory stimulus (i.e., due to, for example, adaptation effects; e.g., see Dalton, 2000).

6.2 Experiment 17

Experiment 17 was designed to investigate the effect of the presentation of a synthetic peppermint odour on dual-task performance, given the mixed results reported in previous studies. Peppermint was chosen because many other researchers have argued for its alerting properties (e.g., Schuler & Raudenbush, 2005; Warm et al., 1991). It was hypothesized that the odour of peppermint should improve participants'

concentration (and/or alertness), and hence possibly lead to better performance in both monotonous simple detection and discrimination tasks. The two tasks used in Experiment 17 consisted of a RSVP task in which participants had to detect target digits embedded amongst a stream of distractor letters, and a vibrotactile front/back discrimination task that required either a compatible or incompatible response (see Fitts & Seeger, 1953) to vibrotactile stimuli presented to the participants' torso. By manipulating response compatibility in this manner, the difficulty of the task could be varied while keeping the stimuli and task constant (see Proctor et al., 2005, for a recent review of the literature on response compatibility effects in an applied context). A within-participants design was chosen, with all of the participants being tested in both the peppermint odour and neutral air conditions, in order to minimize any possibility that individual differences in olfactory perception would affect performance (e.g., Dalton et al., 2002; O'Connell et al., 1994).

6.2.1 Methods

Sixteen participants (mean age of 25 years, age range from 18-35 years; 8 males and 8 females) participated in Experiment 17. All of the participants had normal, or corrected-to-normal, vision, normal tactile sensitivity, and normal olfaction by self-report. The experiment lasted for approximately 45 min. The experiment was conducted in accordance with the guidelines laid down by the Department of Experimental Psychology, University of Oxford. Ten of the participants received a £5 UK sterling gift voucher in return for their participation, the rest received course credit.

The participants rested their chin on a chinrest mounted on the edge of a desk. Synthetic peppermint odour (408571, diluted at a concentration of 10% in diethyl

phthalate, 526305, Quest International, Ashford, England) was used as the olfactory stimulus. A custom-built computer-controlled olfactometer was used to deliver the odorants. The flow of medical air through the olfactometer was controlled by a flow regulator (CONCOA 03-054, Utrecht, The Netherlands) connected to a gas cylinder at a rate of 7.5 L/min. The tubes delivering the olfactory stimuli were attached to the chinrest, with the tubes directed toward the participants' nose from below (at a distance of about 4 cm). A LCD monitor (screen refresh rate of 60 Hz) positioned 70 cm directly in front of the chinrest was used to display the visual stimuli for the RSVP task. The RSVP stimuli consisted of 17 distractor letters and six target digits (cf. Soto-Faraco & Spence, 2002). The RSVP characters were 8 mm x 8mm in size. The participants responded to targets in the RSVP stream via a response box held in their left hand. The two tactors (2.54 cm x 1.85 cm x 1.07 cm, VBW32, Audiological Engineering Corp., Somerville, MA) used to present the vibrotactile signals were attached to a Velcro belt fastened around the participant's waist. One of the tactors was placed in the middle of the participant's stomach, the other in the middle of their back. The belt and the tactors were fastened directly over the top of any clothing that the participant happened to be wearing. The tactors were driven by a 200 Hz signal at an intensity sufficient to deliver clearly perceptible vibrotactile stimuli through clothing. Two footpedals were placed on the floor at a comfortable distance from the participants, one below the toes and the other below the heel of their right foot. White noise was delivered through cordless headphones (SBC-HC075, Philips, USA) at approximately 60 dB(A) in order to mask any background noise.

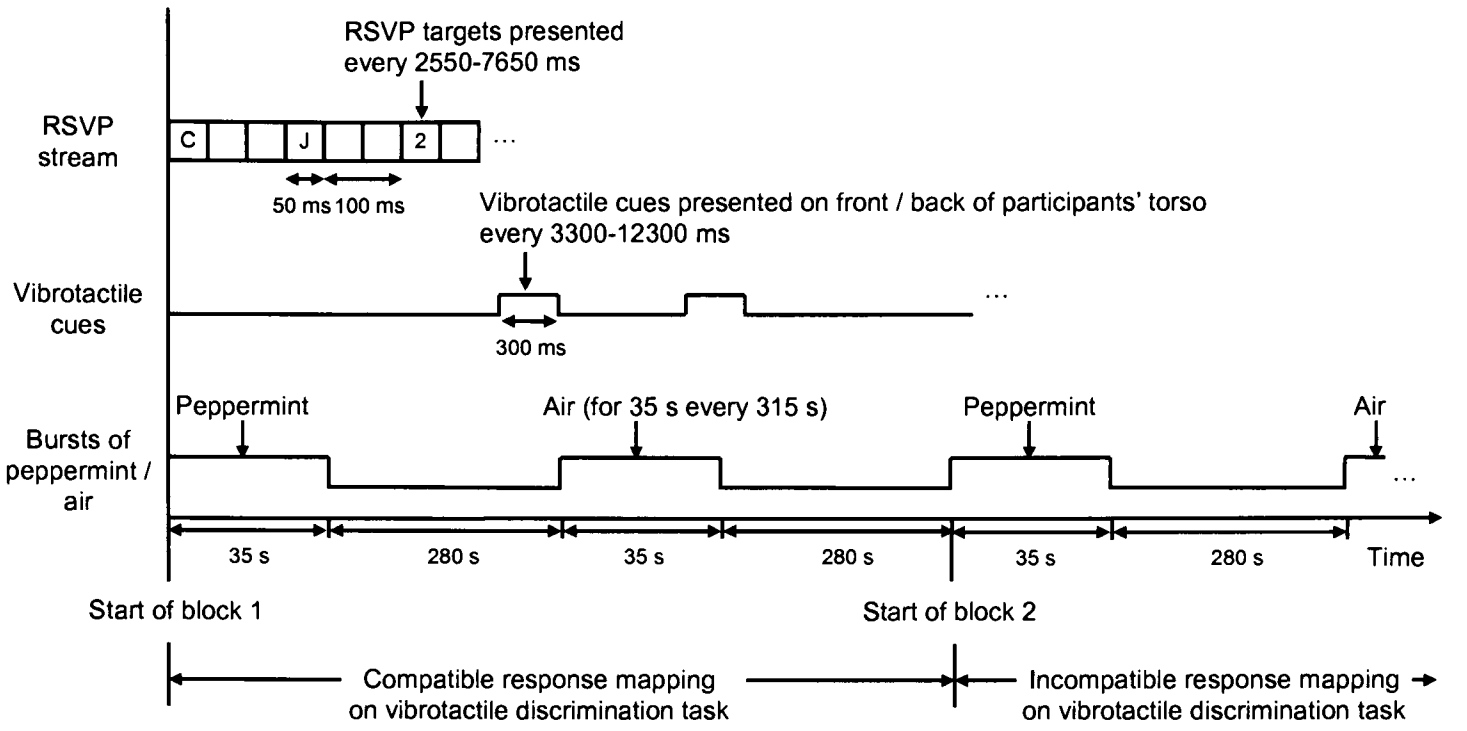


Figure 6.1 A schematic timeline showing the temporal sequence of events in Experiment 17.

The experimental session consisted of four 10½-min blocks of experimental trials. The RSVP task consisted of a continuous stream of distractor letters with target digits embedded periodically within it. Each item in the RSVP stream was presented for 50 ms, with a blank gap of 100 ms before the onset of the next stimulus (see Figure 6.1). Ninety-six targets were presented in each block of trials, with a temporal gap of 2550-7650 ms between successive target digits in the RSVP stream. For the vibrotactile discrimination task, 32 randomized vibrotactile stimuli were presented for 300 ms in each block (half to the participants' front, half to their back), with a gap of 3300-12300 ms between successive vibrotactile stimuli. The timing of targets in the two tasks was independent.

The peppermint odour or clean air was presented for 35 s at the start of each experimental block, after which no olfactory stimulus was presented for the next 4 min and 40 s. The air or peppermint odour, whichever had not been presented at the start of the experimental session, was then presented for 35 s, with no olfactory stimulus being presented for the remainder of the block. An intermittent presentation

procedure was used for the olfactory stimuli to allow time for recovery from any olfactory adaptation (see Dalton, 2000). Note that participants might have perceived the presentation of the peppermint odour to be shorter or longer than the 35 s duration of actual stimulus delivery. The order of presentation of the peppermint odour and air conditions was counterbalanced across participants.

The participants were given two 2-min practice blocks in which to familiarize themselves with the tasks. In the first block, the participants only performed the RSVP task, which was initially presented at a slower rate that gradually increased to the experimental rate of stimulus presentation. In the second block, the participants performed both the RSVP and vibrotactile discrimination tasks as in the subsequent experimental blocks. Air was delivered through the olfactometer throughout the second practice block.

The participants responded to targets in the RSVP task by pressing a response button with their left thumb. The participants were instructed to keep both footpedals depressed throughout the experimental session, and to lift their toes in response to vibrotactile targets presented on their stomach (i.e., front) and their heel in response to vibrations presented on their back in the compatible response mapping condition, or to lift their heel for vibrations on their stomach and their toes for vibrations on their back in the incompatible response mapping condition, in alternate blocks of experimental trials. The decision to use a left hand response for the RSVP task and a right foot response for the vibrotactile discrimination task was chosen in order to minimize any possible confusion on the part of participants as to whether they should try to respond to both tasks simultaneously. The order of presentation of the compatible and incompatible response mapping sessions was counterbalanced across participants. The participants were instructed to breathe naturally through their nose

during the experiment. They were also instructed to give speeded responses to both tasks, without prioritizing either task.

6.2.2 Results

Performance in the vibrotactile discrimination task and in the RSVP task during the period when olfactory stimulation (i.e., peppermint or air) was presented was analysed separately. Trials on which participants responded incorrectly were discarded from the analysis of the mean RT data. Responses occurring 1800 ms or more after the onset of a vibrotactile stimulus, or 1500 ms or more after the presentation of a target RSVP digit were considered invalid (i.e., they were treated as false alarms; < 3% of trials overall). A three-way ANOVA was performed on the error data from the vibrotactile discrimination task with the two within-participants factors of odour condition (peppermint vs. air) and response mapping (compatible vs. incompatible), and the between-participants factor of order of presentation (peppermint vs. air first).

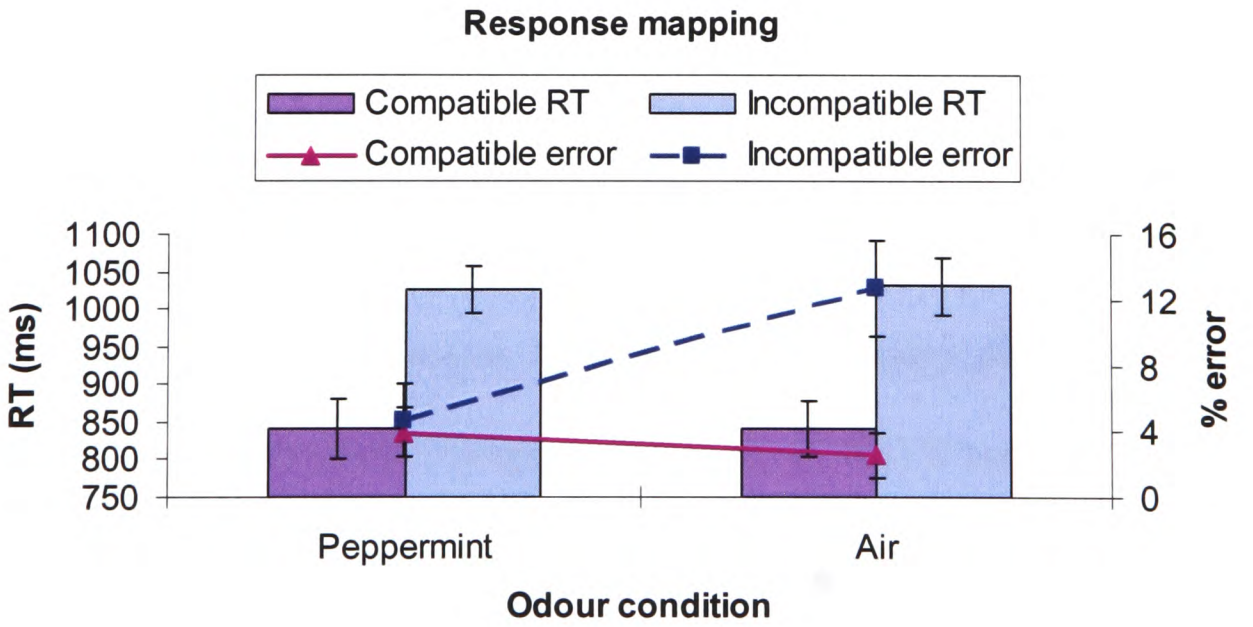


Figure 6.2 Interaction between the odour and response mapping in the RT and error data from the vibrotactile discrimination task used in Experiment 17. Error bars indicate the standard errors of the means.

Analysis of the error data revealed a significant main effect of odour condition, $F(1,14) = 4.6$, $MSE = 38.4$, $p = .049$, with participants making fewer errors when the peppermint odour was presented ($M = 4.3\%$) than when air was presented ($M = 7.6\%$). There was also a significant main effect of response mapping, $F(1,14) = 4.9$, $MSE = 96.2$, $p = .043$, with participants making fewer errors in the compatible condition ($M = 3.2\%$) than in the incompatible condition ($M = 8.7\%$) overall. There was no significant main effect of order of presentation, $F(1,14) < 1$, *n.s.*, nor was there any significant interaction between the three factors, $F(1,14) = 1.1$, $MSE = 31.1$, $p = .32$. The interaction between odour condition and response mapping was, however, significant, $F(1,14) = 11.2$, $MSE = 31.1$, $p = .005$. Participants made more errors when the peppermint odour (mean error rate = 3.9%) instead of air was presented ($M = 2.6\%$) in the compatible response mapping condition, but fewer errors when the peppermint odour ($M = 4.7\%$) rather than air ($M = 12.7\%$) was presented in the incompatible condition, as expected (see Figure 6.2). A similar analysis of the RT data revealed a significant main effect of response mapping, $F(1,14) = 24.6$, $MSE = 22752.6$, $p < .001$, with participants responding significantly more rapidly in the compatible condition ($M = 841$ ms) than in the incompatible condition ($M = 1028$ ms). None of the other main effects or interactions were significant, all Fs < 1, *n.s.*

Three-way ANOVAs were performed on the error and RT data from the RSVP task in order to assess the effects of olfactory stimulation and response mapping in the vibrotactile discrimination task on RSVP task performance. The two within-participants factors were odour condition and response mapping, and the between-participants factor was order of presentation. Analysis of the error data revealed no significant main effects or interactions, all Fs < 1, *n.s.* (except $F(1,14) = 3.0$, $MSE = 29.0$, $p = .10$, for the main effect of response mapping). A similar analysis

of the RT data revealed a significant main effect of response mapping, $F(1,14) = 6.2$, $MSE = 4809.0$, $p = .026$, with participants responding more rapidly in the RSVP task when a compatible response mapping was used to respond to the vibrotactile targets ($M = 605$ ms) than when an incompatible mapping was used ($M = 648$ ms). None of the other main effects or interactions were significant, all Fs < 1, *n.s.* These analyses reveal that while participants responded more slowly in the RSVP task when the vibrotactile discrimination task was presumably more demanding (i.e., when the stimulus-response mapping was incompatible), participants' performance on the RSVP task was not differentially affected by the presentation of the peppermint odour versus air (mean error rates and RTs were 10.2% and 627 ms for the peppermint odour, and 9.9% and 625 ms for air, respectively). The possibility of gender differences was also tested as an additional factor in the data analysis (cf. Brand & Millot, 2001; Dalton et al., 2002), but the analyses revealed no significant main effect of gender, nor any interactions involving this factor in either task.

6.2.3 Discussion

The results of Experiment 17 show that dual-task performance can be facilitated by the presentation of an olfactory stimulus, in line with the findings of Warm et al.'s (1991) previous study. However, in contrast to their interpretation of peppermint as an alerting odour, the results of Experiment 17 cannot so easily be explained in terms of a conventional alerting effect (i.e., faster but less accurate performance in the presence of odour than in its absence; e.g., Posner, 1978; Spence & Driver, 1997a). Instead, these results indicate that while the presentation of the peppermint odour led to a lower percentage of errors in the incompatible response-

mapping version of the vibrotactile discrimination task than when air was presented, response latencies were not significantly affected by the presence versus absence of the odour. In addition, the presentation of the peppermint odour did not influence performance on the RSVP task, nor did it influence performance when the response mapping of the vibrotactile discrimination task was compatible. The peppermint odour may have facilitated performance specifically in the incompatible response mapping condition by improving participants' concentration, thus leading to fewer errors (over the air control condition). This account is based on the assumption that participants had to disrupt the natural response association by using some sort of cognitive control mechanism in the incompatible response mapping condition (cf. Austen, Soto-Faraco, Enns, & Kingstone, 2004; Rogers & Monsell, 1995).

On average, participants made significantly more mistakes (M = 8.7%) and responded more slowly (M = 1028 ms) in the incompatible response mapping condition than in the compatible condition (M = 3.2% and 841 ms), thus supporting the view that participants found the incompatible condition far more difficult than the compatible condition. In fact, the manipulation of response compatibility in Experiment 17 allowed for the distinction of the three putative components of the attentional network highlighted by Posner and colleagues, namely alerting, orienting, and control processes (see Posner & Petersen, 1990), to be made. It seems probable that the incompatible response mapping condition specifically targeted the involvement of central control processes. Indeed, in future research, it will be interesting to examine further the specific effects of various odours on each of these

three putative attentional systems.[6.1]

Importantly, the results of Experiment 17 may also provide a potential explanation for the mixed results obtained in previous studies that have attempted to assess the influence of olfactory stimuli on human performance. For while certain studies have demonstrated a significant facilitatory effect of the presentation of olfactory stimuli on human performance (e.g., Millot et al., 2002; Warm et al., 1991), others have failed to demonstrate any such effect (e.g., Gilbert et al., 1997; Ilmberger et al., 2001). The results of Experiment 17 suggest that while peppermint odour and other potentially 'alerting' odours may facilitate performance under more demanding experimental conditions, they may not affect performance when the tasks are relatively easy (such as in the incompatible vs. compatible condition in Experiment 17, respectively; cf. Spence et al., 2000c, for evidence that crossmodal effects may be more pronounced under more demanding task conditions). Note also that the olfactory modulation of performance reported in Experiment 17 was demonstrated using a within-participants design, and with the same experimental materials and design for all participants, thus ruling out individual differences in odour perception as a possible explanation of the modulatory effect (see e.g., Dalton et al., 2002; O'Connell et al., 1994; cf. Keren, 1993).

[6.1] One possible explanation for the lack of any differential effect of the presence versus absence of the olfactory stimulus in the RSVP task may be that the peppermint odour does not significantly influence performance in tasks requiring the maintenance of a sustained state of awareness, as in the case of the RSVP task used here. Alternatively, however, it is also important to consider the logical possibility that the presentation of the odour may simply have preferentially facilitated tasks involving the left hemisphere (cf. Royet & Plailly, 2004). In other words, perhaps the peppermint odour only affected the vibrotactile discrimination task as it required a right foot (i.e., left hemisphere) response in Experiment 17, whereas responses to the RSVP task were given by the left hand (i.e., right hemisphere). However, this seems to be an unlikely explanation for the present results given that the lateralization of olfactory processing is typically only seen for specific processes, such as the left brain specialization for the emotional processing involved in pleasantness judgments, and the right brain specialization for memory processes such as olfactory familiarity judgments (see Royet & Plailly, 2004).

The results of Experiment 17 provide the first empirical demonstration that olfactory stimulation can facilitate *tactile* performance in a dual-task setting (cf. Spence, Kettenmann, Kobal, & McGlone, 2000a; Spence, Kettenmann, Kobal, & McGlone, 2001a), and so extends previous research demonstrating the effect of odours on visual task performance (e.g., Baron & Kalsher, 1998; Warm et al., 1991; see also Gottfried & Dolan, 2003) to a vibrotactile spatial discrimination task for the first time. Future experiments should investigate the effect of the presentation of peppermint in other complex tasks in order to further support the robustness of the facilitatory effects reported here.

6.3 Experiment 18

Experiment 18 was conducted in order to investigate further whether the effect of the presentation of peppermint odour on task performance reported in Experiment 17 was specific to the odour of peppermint, or if olfactory stimulation by any odour would result in a similar performance enhancement. The same experimental design as in Experiment 17 was used, with the sole exception that cinnamon and lavender odours were presented instead of the peppermint odour. Cinnamon odour was chosen for its potential 'alerting' effect (e.g., Zoladz & Raudenbush, 2005), which was comparable to the 'alerting' odour of peppermint (e.g., Warm et al., 1991) used in Experiment 17. Thus, results from Experiment 18 could be used to validate the effect of a class of odorants commonly-labelled as 'alerting' odours. Lavender odour, contrary to its commonly-known 'relaxing' property, has also been shown by some researchers to improve concentration, enhance mathematical abilities, and speed up

responses to simple auditory and visual target stimuli (Degel & Koster, 1999; Diego et al., 1998; Millot et al., 2002; though see Ludvigson & Rottman, 1989).

6.3.1 Methods

Sixteen new participants (mean age of 24 years, age range from 18-33 years; 7 males and 9 females) took part in Experiment 18. All of the participants had normal, or corrected-to-normal, vision, normal tactile sensitivity, and normal olfaction by self-report. The experiment lasted for approximately an hour. Twelve of the participants received a £5 UK sterling gift voucher in return for their participation, the rest received course credit.

The apparatus, material, design, and procedure of the experiment were exactly the same as in Experiment 17, with the exception that synthetic cinnamon leaf (414973) and synthetic lavender odours (441142, both diluted at a concentration of 10% in diethyl phthalate, 526305, Quest International, Ashford, England) were now presented instead of the peppermint odour. The experimental session consisted of four 12-min blocks of experimental trials. Each experimental block started with the presentation of one of the three odour conditions (cinnamon, lavender, or clean air) for 35 s, after which no olfactory stimulus was presented for the next 3 min and 25 s. After that, one of the two odours that had not been presented at the start of the block was presented for 35 s, again followed by a no olfactory stimulation period of 3 min and 25 s, before the remaining odour condition was presented for 35 s, with no olfactory stimulus being presented for the remainder of the block. The order of presentation of the sub-block conditions was approximately counterbalanced across participants.

6.3.2 Results

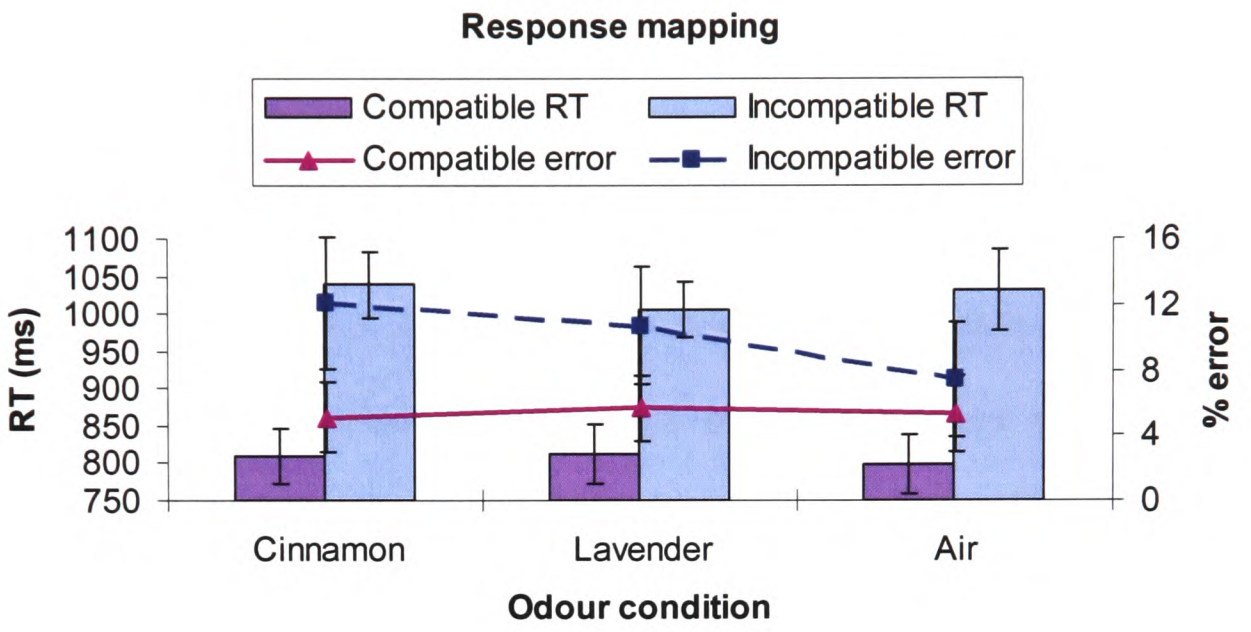


Figure 6.3 RT and error data from the vibrotactile discrimination task in Experiment 18 as a function of odour and response mapping. Error bars indicate the standard errors of the means.

Performance in the vibrotactile discrimination task and in the RSVP task during the period in which olfactory stimulation (i.e., cinnamon, lavender, or air) was presented was analysed separately in a similar manner to Experiment 17. Trials on which participants responded incorrectly were discarded from the RT analysis. Responses occurring 1800 ms or more after the onset of a vibrotactile stimulus, or 1500 ms or more after the presentation of a target RSVP digit were considered invalid. A two-way ANOVA was performed on the error data from the vibrotactile discrimination task with the within-participants factors of odour condition (cinnamon, lavender, or air) and response mapping (compatible vs. incompatible). Analysis of the error data revealed no significant main effect of odour condition, $F(2,30) < 1$, *n.s.*, or response mapping, $F(1,15) = 2.9$, $MSE = 178.3$, $p = .11$, nor any interaction between these two factors, $F(2,30) < 1$, *n.s.* The mean error rates for the cinnamon, lavender, and air conditions when a compatible response mapping was used were 5.1%, 5.7%,

and 5.3%, respectively, while those in the incompatible condition were 12.1%, 10.7%, and 7.4%, respectively (see Figure 6.3). A similar analysis of the RT data revealed a significant main effect of response mapping, $F(1,15) = 98.3$, $MSE = 11724.6$, $p < .001$, with participants responding significantly more rapidly in the compatible condition ($M = 806$ ms) than in the incompatible condition ($M = 1026$ ms). However, the main effect of odour condition was not significant, nor was the interaction between these two factors, both $F(2,30) < 1$, *n.s.* These analyses revealed that while participants responded more slowly when the task was presumably more demanding in the incompatible than in the compatible conditions, just as that reported in Experiment 17, performance on the vibrotactile discrimination task was not differentially affected by the presentation of the cinnamon or lavender odours as compared to the air control condition.

Two-way ANOVAs were performed on the error and RT data from the RSVP task with the within-participants factors of odour condition and response mapping. Analysis of the error data again revealed no significant main effects or interactions, all Fs < 1, *n.s.* A similar analysis of the RT data also revealed no significant main effect of odour condition, $F(2,30) = 2.4$, $MSE = 1540.3$, $p = .11$, or response mapping, $F(1,15) < 1$, *n.s.*, nor any interaction between them, $F(2,30) < 1$, *n.s.*

6.3.3 Discussion

The results of Experiment 18 therefore failed to reveal any significant effect of either the cinnamon or lavender odorants on the performance of either task. It is impossible to say on the basis of the results of Experiment 18 what the major factors accounting for the insignificant results may have been. It is possible that the intensity of the odorants used in the present study may simply have been too low. It would

therefore be interesting in future studies to investigate whether the classification of a particular odour as pleasant/relaxing versus unpleasant/arousing relates to its intensity (cf. Distel & Hudson, 2001). Taken together, it seems reasonable to question the effectiveness of cinnamon as an alerting odour in driving settings (cf. RAC Foundation, 2005; Zoladz & Raudenbush, 2005), as an improvement in concentration was evidenced from the presentation of the peppermint odour reported in Experiment 17, while no such effect was found with the presentation of cinnamon under similar testing condition (cf. Frick, 1995).

6.4 General discussion of olfactory cuing

All in all, even though researchers are still uncertain with regard to the specific effects of certain odorants on human information processing, the potential use of odours in multisensory interface design is growing (e.g., Bodnar, Corbett, & Nekrasovski, 2004; Bounds, 1996; Deatherage, 1972; Kaye, 2004). For instance, some researchers in the car industry have already started to investigate the possibility of stimulating this relatively underutilized sense to generate a more pleasurable driving experience (see Spence, 2002, for a review), to calm aggressive drivers with pleasant odours (Rinspeed, 2005; Ury, Perkins, & Goldsmith, 1972), or even to prevent drowsy drivers from falling asleep at the wheel (e.g., Baron & Kalsher, 1998; cf. Otmani, Pebayle, Roge, & Muzet, 2005; though see Badia, Wesensten, Lammers, Culpepper, & Harsh, 1990; Carskadon & Herz, 2004). It will be interesting to study the time-locked effects of odour presentation, which may be useful for the design of future warning systems, such as the use of olfactory cues in cars to keep drowsy drivers awake while avoiding the aversive elements present in many other alerting

signals (e.g., Bounds, 1996; cf. Parasuraman et al., 1997). The use of a simulated driving task, such as that reported in the preceding chapters, might provide a particularly appropriate means to address this question.

In fact, it is possible that 'unpleasant' odours, such as smell of the perspiration given off by an anxious person, might prove to be even more effective than pleasant odours in alerting a person (see Miltner, Matjak, Braun, Diekmann, & Brody, 1994; Prehn, Ohrt, Sojka, Ferstl, & Pause, 2006). For instance, Prehen and colleagues recently studied the effects of the presentation of chemosensory anxiety signal on the startle reflex. An increased startle reflex amplitude (as measured by electromyography (EMG) of participant's eye-blink activities) was recorded when participants were presented with anxious human sweat samples collected from donors before an oral academic examination, as compared to conditions either when the participants smelled chemosensory stimuli collected while the donors were exercising or when the participants smelled unused cotton pads (control). The findings from Prehen et al.'s study therefore suggest that chemosensory anxiety signals may act to pre-attentively prepare behavioural responses in humans.

On a practical level, however, it does not seem particularly useful for interface designers to present unpleasant odours, especially given the importance of olfactory cues to consumer choice (Ellison & White, 2000). It is important to note, however, that odours have been shown to be minimally effective once people are asleep (e.g., Badia et al., 1990; Carskadon & Herz, 2004), and so further research on the differential effects of various olfactory stimuli on human performance at the border between wakefulness and sleep will be needed before their widespread use in cars could be recommended.

CHAPTER 7

CONCLUSIONS

7.1 Key findings

The research outlined in this thesis has attempted to demonstrate the feasibility and effectiveness of applying theoretical insights from the robust evidence of the existence of crossmodal links in spatial attention between various different sensory modalities to the design of multisensory warning signals in driving. In particular, the spatial properties inherent in auditory cues (either because the cues were presented spatially, or because of the informational content of the verbal cues) were shown to improve the efficacy of a driver's responses to target visual driving events presented subsequently in the cued direction. In addition, facilitatory spatial cuing effects were extended from the use of auditory cues to the sense of touch. The presentation of vibrotactile spatial cues around the waist of a driver was shown again to be an effective means to orient driver attention. On the basis of the robust evidence of potential beneficial effects of spatial cuing in driving, a driving simulator study was conducted that further demonstrated the significant improvement in drivers' reaction to front-to-rear-end collisions with the aid of vibrotactile cues that indicated the likely direction of the potential dangerous driving events.

Taking the research one step further, the series of orthogonal cuing experiments (Chapter 5) suggested that intervention can be introduced both at the perceptual and decisional stages in human information processing to improve the mental processing time of drivers during a potential collision event, and consequently facilitate their behavioural responses (i.e., collision avoidance). To this end, the present research demonstrates that attentional facilitation (or perceptual enhancement) will only occur if the warning signal and target event are both located within the same functional region of space, while decisional facilitation (or response priming) can occur if the cue and target are directionally congruent (even if the two stimuli occur in different functional regions of space). The findings imply that response compatibility may be an effective tool in multisensory interface design, with additional benefits attributable to attentional facilitation evidenced only if interface designers consider rigorously the spatial distribution of the relevant events (i.e., of the spatial relationship between the critical driving events and the cues used to warn the driver about these events).

Indeed, recent cognitive neuroscience research has shown that stimuli occurring in peripersonal space are treated differently by the brain than stimuli presented in extrapersonal space (see Graziano, Gross, Taylor, & Moore, 2004; Graziano, Reiss, & Gross, 1999; Previc, 1998, 2000; Rizzolatti et al., 1997; Weiss et al., 2000). For instance, stimuli in near-peripersonal space may be considered to be more behaviourally relevant, thus demanding immediate attention. The results of the speeded target discrimination experiment (Experiment 11) reported in Chapter 5 showed that people can make front versus back discrimination responses to vibrotactile stimuli presented on their torso significantly more rapidly than auditory stimuli originating from locations farther away, perhaps demonstrating an 'alerting'

effect (cf. Kitagawa et al., 2005; Spence & Squire, 2003). Nevertheless, the benefits of such a speeding-up of responses can be overridden by the attentional facilitation (and/or multisensory integration) effects that may be maximal only when the cue and target events are actually located in the same functional region of space (see Chapter 5). This notion of cue-target co-location is consistent with the optimal multisensory integration account that predicts maximal effectiveness of integration for stimuli originating from the same spatial location (cf. Colonius & Diederich, 2004; Stein & Meredith, 1993; though see Murray et al., 2005).

Spence and Driver (1999) also argued that the multisensory warning signals that have been used to date may not have been optimized for the human perceptual system in terms of the relative time of onset of the various sensory components of the warning signal. In particular, research suggests that humans may be optimized to respond to multisensory (i.e., audiovisual) events occurring at a distance of approximately 10 m (e.g., Spence & Squire, 2003). At this distance, the delays in the transmission of auditory signals (i.e., sound waves) through the air cancel out the visual delays associated with the chemical transduction of light at the retina, and so both signals are thought to 'arrive' centrally in the brain at the same time (e.g., Pöppel, 1988). As such, there are reasons to believe that humans may respond more efficiently to audiovisual warning signals presented from close to the interface operator if they are presented asynchronously such that the auditory signal is delayed somewhat with respect to the visual signal (i.e., to simulate the optimal arrival time of an event actually presented at a distance of 10 m; cf. Chan & Chan, 2006). A similar argument can also be made with respect to the presentation of bimodal visuotactile warnings, given that variable delays in the arrival time of vibrotactile stimuli (when compared to visual stimuli) are associated with their transmission through the human body (see

Harrar & Harris, 2005; Spence et al., 2001c), depending upon the distance of the stimulation site from the person's brain (von Békésy, 1963). This outstanding question regarding temporal variations of multisensory signals is clearly an important subject of future research.

Taken together, therefore, the results of these previous studies suggest that while warning signals presented close to a driver's head or body may be more effective in alerting or generating a near-automatic response from the driver, these warning signals do not necessarily lead to any attentional facilitation of the processing of events occurring in the spatial direction indicated by the signals. Given these results, the combined use of signals presented close to the head and/or body of a driver in order to alert or arouse them, together with signals presented spatially (either virtually or actually) to enhance subsequent processing of any events occurring in that region of space (cf. Lee et al., 1999; Menning, Ackermann, Hertrich, & Mathiak, 2005; Previc, 2000) may prove to represent a particularly effective form of multidimensional (or multisensory) warning signalling. Experiment 16 provided just a preliminary demonstration of the future potential for such design. Further investigation specifying the corresponding parameters across different sensory modalities is required.

A relevant concern regards the automaticity of responses and reliance on technology. The generation of near-automatic responses from a driver may be desirable under conditions where the warning signals are highly reliable and that the driver is under high workload, thus having limited spare resources to analyse the situation prior to producing a speeded response. However, this is not necessarily beneficial and may have adverse effects particularly if risk perception is undermined. This links to the question of whether drivers really drive more safely with the

provision of safety warnings: In an analysis of driver behaviours after the mandatory implementation of safety features like seat-belt and air bags in cars, researchers have found that drivers of cars equipped with safety features appear to behave more aggressively, pushing their cars closer to the limit. As a result, it would appear that drivers offset the original positive intention of safety innovation by actually imposing additional danger or risk to road safety (see Evans & Graham, 1991; Peltzman, 1975; Peterson, Hoffer, & Millner, 1995; see also Adams, 1995), with the advantageous effect of safety features becomes evident only several years after their mandatory introduction.

7.2 Peripersonal mirror space

The design of the driving experiments reported in this thesis was based on the well-learnt association between the rear space behind a driver and its representation in the rearview mirror positioned in front of a driver. The process of learning the 'affordance' of mirrors has been argued to play an important role in shaping the perception of mirror space (see Loveland, 1986). Interestingly, Binkofski et al. (2003) found that individuals with mirror apraxia (i.e., lesions of the posterior parietal cortex that caused deficits in reaching for objects visible only via a mirror) have a dissociation between their body schema and the peripersonal space, with mirror apraxia affecting the processing of stimuli presented in the peripersonal space inspected via a mirror yet keeping the processing of stimuli presented on their body surface viewed via a mirror intact. Binkofski et al. claimed that their findings supported the idea of a unique body schema representation that exists in the mirror space (independent of its representation in the actual world under direct viewing).

Whether this is an innate representation or shaped by the fact that the mirrored space of the outer world is normally for external manipulation while the mirrored image of one's own body is for bodily reference is unknown. Nevertheless, these findings do suggest a special processing mechanism for the representation of mirrored stimuli (see also von Fieandt, 1966).

There is no clearly defined borderline as to the boundary of peripersonal and extrapersonal space (see Previc, 2000). Given studies showing that this boundary will somehow extend or contract as a person uses a tool, it is of particular interest to investigate how and why tool-use modifies body schema and spatial representations (see Farnè & Làdavas, 2000; Holmes & Spence, 2004). It remains an outstanding question for future research as to whether a driver internalizes in some sense the car to become part of his/her body image (see Paillard, 1993, p. 40; Riddoch, 1941, p. 221). This is particularly interesting given that a driver's perception of the various regions of space around his/her body will determine his/her perception of the 'field of safe travel' (see Gibson & Crooks, 1938), which ultimately relates to the issue of traffic accidents. Note that the region of protective space surrounding the body has been argued to extend furthest in the direction of sight (e.g., Dosey & Meisels, 1969; Hall, 1966; Horowitz, Duff, & Stratton, 1964; Sommer, 1959), and that it becomes somewhat expanded under conditions where an individual feels threatened (e.g., Dosey & Meisels, 1969; Felipe & Sommer, 1966). Once again, these are clearly very interesting directions for future research.

7.3 Ecological validity

One of the major debates in driving research in recent years relates to the ecological validity of laboratory-based studies and, in particular, their generalizability to situations of real-world driving. It would certainly be very useful therefore in future research to investigate the extent to which the findings from the laboratory-based experiments reported here scale-up to modulate driving performance under more ecologically-valid conditions. In this regard, the successful replication of the laboratory-based vibrotactile cuing research findings with the use of a high-fidelity driving simulator (Experiment 10) demonstrates the feasibility of implementing vibrotactile warning signals in real-world applications. What is even more promising is the fact that the facilitation of driving performance attributable to the presence of the vibrotactile cues is much larger than might have been expected on the basis of the laboratory-based driving studies. The facilitatory effect in braking RTs of a magnitude of over 1/3 s found in Experiment 10 is clearly important for collision avoidance considering the overall RT of 0.7 s and 1.5 s respectively for expected and unexpected emergency braking (Green, 2000).

Given the simple stimulation used in the present research, it is important to examine whether the present findings uphold in conditions with more complicated patterns of vibrations and with vibrations signalling not just collision events (front/back) but extending to signalling, for example, lane changing and/or navigational messages. It is therefore important to assess the quantity and quality of information that can be transmitted by the sense of touch. Future studies should also examine auditory spatial cuing in a driving simulator under more realistic conditions,

such as in the presence of background noise (e.g., radio) and with a reduced frequency of occurrence to better approximate the expected rare occurrence of collision events in actual driving situations.

One may, of course, question even the ecological validity of findings from studies conducted in a driving simulator, which, to some extent, once again represents a controlled experimental environment with different demands (e.g., regarding the perception of risk and safety) than those found in real-world driving. Critics of simulator studies are typically concerned that such differences in demand characteristics may result in different behaviours on the part of drivers (e.g., Alm & Nilsson, 1995). However, it should be noted that several studies have argued that driving simulator studies are both more ethical and more cost effective than on-road testing (see Haigney & Westerman, 2001), and at the same time provide good validity for measures of performance such as speed control (see Reed & Green, 1999). Although the applicability of driving simulator studies to real-world driving should never be asserted unquestioningly, simulated driving nevertheless offers an acceptable test environment for the better understanding of driver behaviour (cf. Kemeny & Panerai, 2003; McLane & Wierwille, 1975).

7.4 Future directions for multisensory interface design research

It is only by understanding the underlying nature of multisensory information processing and the brain's representation of crossmodal space (as increasingly being revealed by cognitive neuroscience research; see Spence & Driver, 2004) that one will be able to start designing multisensory warning signals that are genuinely optimized

for the vagaries and information processing limitations of the human operator. Relevant to human limitations is the issue of aging drivers. Older drivers are likely to suffer even more from sensory overload than younger drivers (see Dukic et al., 2006; Ponds, Brouwer, & van Wolffelaar, 1988; Verwey, 2000), yet they constitute an ever growing segment of the population. It is thus interesting to investigate the possibility of supporting their sensory perception by the presentation of redundant warning signals to two or more sensory modalities, or by the presentation of amplified warning signals to a given sensory modality. One goal for my future research is to examine the possibility of sensory substitution in driving. It is particularly interesting to study the viability of substituting visual information wholly (or partially) by tactile information in driving as this will have important implications not only for driving under poor conditions such as in low visibility, but will also impact on driver rehabilitation, in particular, for those individuals with impaired cognitive and/or sensory abilities.

In conclusion, designers need to create the most ecological warning signals that can elicit an intuitive response from drivers to the appropriate spatial location where a critical emergency event may occur. The investigation into crossmodal interactions in spatial attention is suggestive of the generic spatial property in the human information processing system. Given that humans have only limited cognitive resources (e.g., 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 may have important implications for multisensory interface design, particularly for situations of high informational load (cf. Bliss & Dunn, 2000), 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, for example, 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 warning devices that can facilitate the appropriate deployment of a driver's attention. The development and implementation of multisensory in-car interfaces that are designed around the mechanisms of a driver's brain offer a promising future.

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APPENDIX

ISOTROPY AND VISUAL MODULATION OF HAPTIC FORCE DIRECTION DISCRIMINATION ON THE HUMAN FINGER

Experiments 19 and 20 were conducted to investigate haptic force direction discrimination thresholds in adult humans. Haptic force vectors originating from one of five different force directions were presented to the index finger of participants. Discrimination thresholds were measured using a three-interval one-up three-down adaptive procedure (Levitt, 1971). In contrast to the literature on the anisotropy of haptic perception, the results of Experiments 19 and 20 suggest that the acuity of the haptic perception of force direction is not directionally dependent. The discussion focuses on the relative contributions of haptic and visual information to the generation of coherent multisensory percepts.

A.1 Introduction

Force information is an important attribute of haptic perception. For instance, as a person uses his/her fingers to explore a surface during active haptic exploration,

the constant update of force feedback cues inform the person about his/her experience, such as whether he/she is moving along a smooth and sloping surface. A number of researchers have noted that the experience of force cues dominates haptic sensation in the sense that when conflicting geometrical and force information are presented, participants will typically perceive the shape of an object in a manner that is consistent with the information provided by the force cues rather than with that provided by the geometric cues (Robles-De-La-Torre & Hayward, 2001). A recent study on the perception of curvature (Drewing & Ernst, 2006) has demonstrated that participants give a higher weight to force cues than position cues when the arches of a virtual object are shallow, and a higher weight to position cues than force cues when the arches are convex. Such results thereby generalized the force-dominance view of Robles-De-La-Torre and Hayward (2001) to a model of weighted force and position cues in haptic curvature judgments.

Although much is known about the perception of force magnitude (Jones, 1989; Pang, Tan, & Durlach, 1991), few studies have investigated the perception of force direction (though see Klein, 1977) presumably due to the lack of experimental apparatus capable of delivering 3-dimensional force vectors in a controlled manner. The advent of force-feedback haptic devices now makes it possible to measure, for example, people's sensitivity to changes in force direction. This is an important metric for designers of haptic virtual environments since the perception of virtual objects by humans depends on both the magnitude and the direction of reactive forces. Two experiments were designed to assess the ability of human participants to perceive force direction. Specifically, Experiment 19 investigated whether force direction discrimination thresholds are isotropic and Experiment 20 examined whether the

visual representation of vector directions has any influence on the haptic discrimination of force directions.

A.2 Experiment 19

A.2.1 Methods

A.2.1.1 Participants

Twenty-five participants (mean age of 28 years, age range from 21 to 39 years; 15 males and 10 females) participated in Experiment 19. All of the participants had a normal sense of touch. Twenty-four of the participants were right-handed and one was ambidextrous by self-report. The participants were recruited by word of mouth and received US$5-10 for their participation. The experiment was conducted in accordance with the Institutional Review Board ethical guidelines at both Stanford University and Purdue University.

A.2.1.2 Apparatus and materials

The participants were seated in front of a 48.3 cm (19 inch) computer monitor in a quiet experimental room. They were instructed to insert their right index finger into the thimble of a PHANToM force-feedback device (SensAble Technologies, Inc., Woburn, MA), placed 30 cm away from the monitor in the direction of the participant's right hand, occluded from the direct view of the participants by a box cover (see Figure A.1). A computer keyboard was placed at a comfortable distance

(a)



(b)

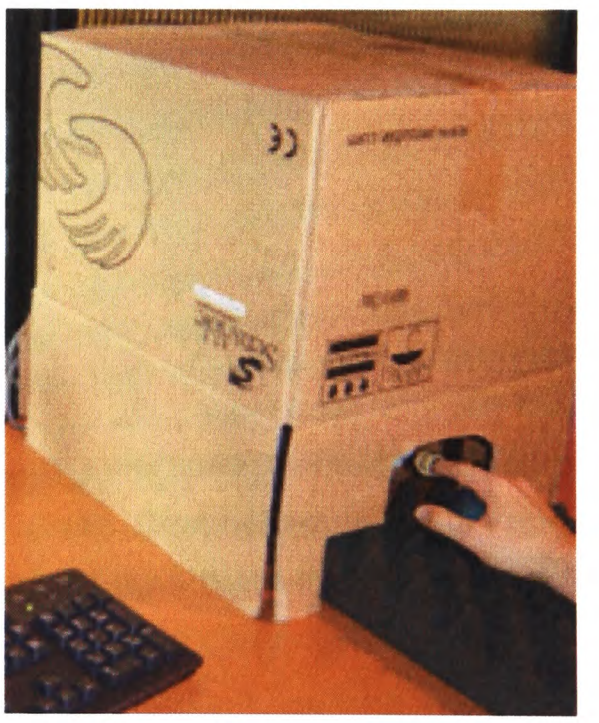


Figure A.1 The experiment setup in Experiment 19. (a) Participant rested the palm of their right hand on a gel ball and inserted their right index finger into the thimble of the PHANToM device. (b) During the experiment itself, the PHANToM device and the participant's right index finger were hidden from direct view.

such that the participants could give their responses with their left hand. The participants were instructed to rest their right arm on the table, and to hold a deformable gel ball gently in their right hand with their index finger pointing away

from their body. The gel ball was used to prevent participants from making excessive hand or arm movements that might have given them any additional kinaesthetic cues. The experiment involved a force being applied to the participant's finger inserted in the thimble, subtly moving the finger in the direction of the applied force until the participant provided an opposing force to maintain the finger in a stable position.

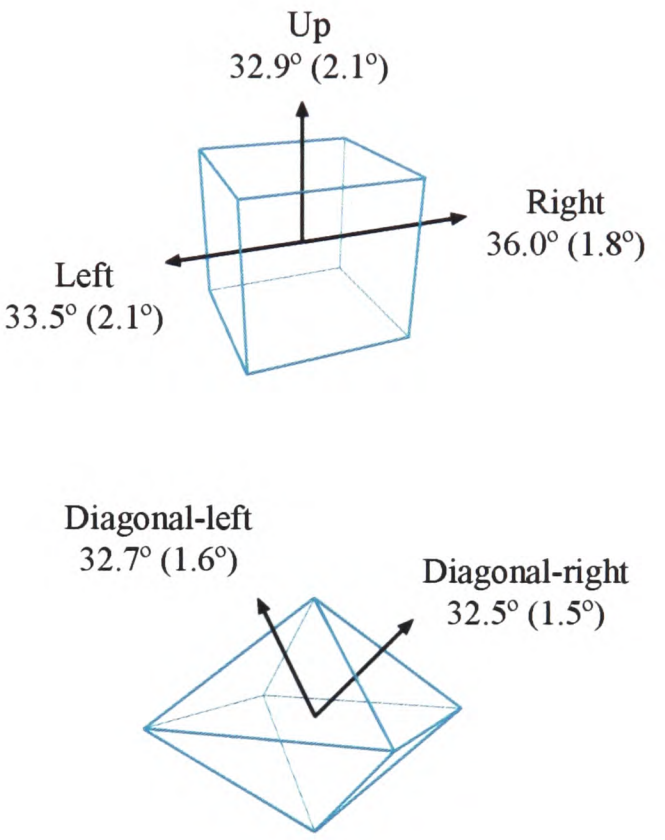


Figure A.2 The five force vectors used as the reference force directions in Experiment 19, together with the estimated mean thresholds of haptic force direction discrimination reported in Experiment 19 (and their standard errors in parentheses).

A.2.1.3 Stimuli

The haptic stimuli were generated by the PHANToM force-feedback device. Five reference force vectors were used. They included the normal vectors corresponding to the top (up), left, and right sides of a cube centred at the workspace of the device, and the normal vectors corresponding to the upper-front two faces of an octahedron (i.e., diagonal-left and diagonal-right; see Figure A.2). The magnitude of

the force vectors were always presented in the same way throughout Experiment 19. The force magnitude was ramped up linearly from 0 to 2 N over 500 ms, and then ramped down linearly to 0 N over the next 200 ms. The maximum magnitude of 2 N was chosen so that the forces were clearly perceptible to all participants. The gradual increase in force gave the participants time to apply opposing forces in order to maintain the position of their finger inside the thimble. It also kept the haptic device stable and quiet throughout the experiment. No visual information was given concerning the nature of the stimuli.

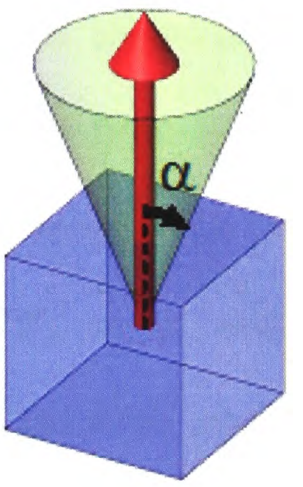


Figure A.3 An illustration of the relationship between the reference and target force directions (i.e., α).

A.2.1.4 Procedure

A three-interval one-up three-down adaptive procedure was used (Levitt, 1971). Five separate threads of the adaptive procedure were interleaved for the five reference force direction conditions. On each trial, one reference force direction was randomly chosen from the five references with equal *a priori* probabilities. The participant was presented with three stimulus intervals: two corresponding to the randomly chosen reference force direction (reference stimulus), and the other corresponding to a force direction that deviated from the reference by a certain amount (target stimulus). The interval during which the target stimulus was presented was randomly selected from

three intervals with equal *a priori* probabilities. The independent variable was the angle between the reference and target stimuli, denoted by α (see Figure A.3). Given a value of α, the target stimulus could lie anywhere on the cone with the reference force vector as the axis and with an angle of α. In other words, the orientation of the plane formed by the reference and target force vectors was randomly selected with the constraint that the angle formed by the two vectors was exactly α.

Each trial began with the force-feedback device gently pulling the participant's right index finger to an initial starting position. The beginning and the end of the pulling were indicated by single and double audio beeps, respectively, presented at a clearly superthreshold level from two computer loudspeakers, one placed on either side of the monitor. The three stimulus intervals followed immediately. The numbers '1', '2', or '3' were displayed in large font on the computer screen to mark each of the three intervals. The participants' task was to indicate the odd (i.e., target stimulus) interval by pressing '1', '2', or '3' on the keyboard (corresponding to interval one, two, or three, respectively). No feedback on performance was provided.

The initial value of α was set at 40° for all five conditions. The value of α was increased after each incorrect response, and decreased after three consecutive correct responses. Initially, the magnitude of α changed by increments of 8°, and then by 2° after the first three reversals. A reversal occurred when α changed from increasing to decreasing, or vice versa. The value of α was calculated independently for each thread of the five adaptive procedures based on the participant's response history under that condition. Each thread of the adaptive procedure would terminate after twelve reversals at the 2° step size. Each condition typically contained about 60-90 trials. The experiment terminated after all five threads were completed.

Each participant was tested with all five reference force directions. The experimental session consisted of one practice block and one experimental block of trials. The practice block consisted of ten trials. The experimental block consisted of trials from the five interleaved threads of adaptive procedure corresponding to the five reference force directions. A complete run lasted for approximately 60-75 min for each participant.

A.2.2 Results

The mean thresholds of each participant was estimated by first calculating six averages from the peaks and valleys corresponding to the values (i.e., the displacement angle between the reference and target forces) of the last twelve reversal amplitudes. The mean and standard error were then derived from these six averages (cf. Brisben, Hsiao, & Johnson, 1999).

An ANOVA of the mean thresholds with the factor of reference force direction (up, left, right, diagonal-left, or diagonal-right) revealed no significant main effect, $F(4,96) = 1.2$, $MSE = 44.2$, $p = .32$ (see Figure A.2). A comparison between the diagonal-left/diagonal-right group versus the up/left/right group was also performed to examine whether the two groups differed on the hypothesis that the latter group corresponded to cardinal directions. The results showed no significant difference between the two groups, $t(24) = -1.5$, $p = .14$.

A.2.3 Discussion

In contrast to the extensive literature on the anisotropy of haptic perception (e.g., Essock, Krebs, & Prather, 1997; Gibson & Craig, 2005), the results of Experiment 19 suggested that the perception of force direction was not directionally

dependent (cf. Essock et al., 1997). This means that the acuity of haptic force direction perception is more-or-less the same regardless of the direction from which the force is applied. While it may have been the case that the isotropy of haptic force direction discrimination thresholds resulted from a failure to properly align the relative positions of the PHANToM device (hence its cardinal directions) to the human torso, it should be noted that achieving such alignment would represent a challenging task. Nevertheless, the haptic force direction thresholds (see Figure A.2) should prove particularly useful for the design of haptic devices and for fine-tuned rendering algorithms. For example, the relatively large discrimination thresholds (>30°) provide an upper bound for the amount of distortion that can be introduced by force-smoothing algorithms in order to achieve better stability and smoother object surfaces without introducing any discernable artefacts. Note though that the generalization of these findings may be limited to force direction perception on the fingertip and/or the specific force magnitude profile tested. Note also that it is debatable whether the spatial reference frame for haptic perception is necessarily centred on certain body parts (such as the head or hand, i.e., involving an egocentric frame of reference) or rather instead on an allocentric frame of reference (i.e., defined by environmental cues, cf. Luyat, Gentaz, Corte, & Guerraz, 2001). It would therefore be interesting in future research to examine the discrimination thresholds for forces applied to other body parts, such as, for example, the palm, wrist, forearm, etc. (see Toffin, McIntyre, Droulez, Kemeny, & Berthoz, 2003; cf. Gibson & Craig, 2005).

Toffin et al. (2003) examined the capacity of adult human participants to reproduce forces applied to their hand by instructing the participants to either passively perceive a reference force on a joystick and adjust a subsequently-presented force to the same direction as the reference force, or to actively remember the

reference force and reproduce a force that was sufficient to resist the reference force. Toffin et al. examined 24 reference force directions in the horizontal plane and found no anisotropy in the perception of force direction, just as in Experiment 19. Toffin et al. concluded that humans encode the effort required to reproduce a perceived force rather than encoding the perceived force vector information. Toffin et al.'s findings hint at the rather poor sensitivity of haptic force discrimination, again consistent with an overall mean threshold of 33.5° reported in Experiment 19. It should, however, also be noted that the ability to reproduce a force direction or movement may be distorted at the stage of motor response, and that this should be distinguished from the ability to perceive a given force direction.

A.3 Experiment 20

The multisensory integration approach to human information processing (e.g., see the chapters in Calvert, Spence, & Stein, 2004) suggests that people integrate the sensory information available to their various different sensory modalities (e.g., vision, audition, touch, olfaction, and taste) in order to generate a coherent multisensory perceptual experience of the external world. Given the poor haptic resolution of force direction, and given that the maximum-likelihood estimation (MLE) theory suggests that the most accurate modality normally dominates over the other sensory inputs (Ernst & Banks, 2002; Ernst & Bulthoff, 2004), one might predict a larger influence of vision over haptics in force direction discrimination when some form of conflict is introduced (cf. Holmes & Spence, 2005). However, it is important to note that the MLE model is typically only applicable for small conflicts (i.e., of up to approximately 11% difference between the constituent signals). Beyond this point,

people may start to treat the sensory stimuli as representing separate and independent perceptual events (cf. Rock & Harris, 1967). The investigation of the integration of visual-haptic information is important both for real-world interactions and for interactions taking place in virtual environments. Previous studies have examined the various parameters for such visual-haptic integration. Back in the 1960s, Rock and colleagues (Rock & Harris, 1967; Rock & Victor, 1964) investigated the extent to which vision dominates the sense of touch and biases the haptic perception of size and shape (see also Gibson, 1933). Since then, many other researchers have also examined situations of multisensory conflict (e.g., see Diewert & Stelmach, 1977; Kinney & Luria, 1970; Klatzky, Lederman, & Reed, 1987; Klein, 1977; Lederman, Thorne, & Jones, 1986; Pick, Warren, & Hay, 1969; Seizova-Cajic, 1998; Snijders, Holmes, & Spence, in press; van Beers, Wolpert, & Haggard, 2002; Wall & Harwin, 2000; Welch & Warren, 1980).

Experiment 20 was thus designed to examine the influence of visual information on the perception of haptic force direction, with the visual information being either congruent or incongruent with the haptic forces that were presented. In Experiment 20, participants made force direction discrimination responses similar to those described above in Experiment 19, with the sole exception that in one condition, congruent visual information that indicated the valid direction of the haptic force was presented, while in another condition, incongruent visual information was presented, or else no visual information was presented (the haptic only condition).

A.3.1 Methods

Twenty participants (mean age of 26 years, age range from 21-39 years; 15 males and 5 males) participated in this experiment. All of the participants had normal,

or corrected-to-normal, vision, and a normal sense of touch. Seventeen of the participants were right-handed, one was left-handed, and two were ambidextrous by self-report. The participants were recruited by word of mouth and did not receive any compensation for their participation. The experiment was conducted in accordance with the Stanford University Institutional Review Board ethical guidelines, and lasted for approximately 45 min.

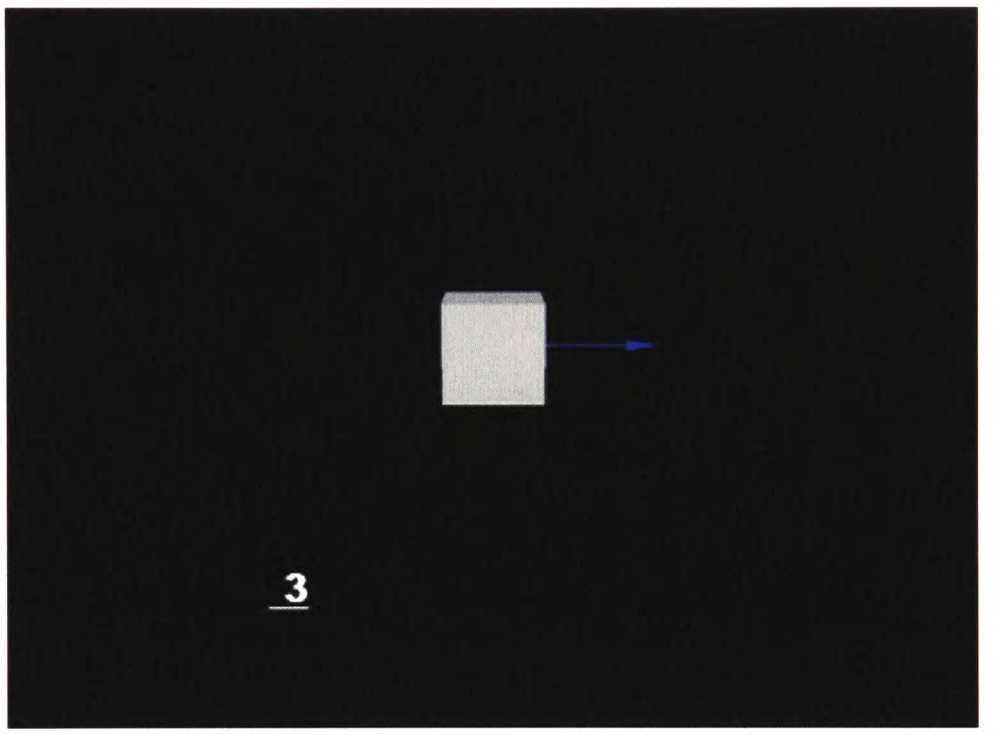


Figure A.4 A screenshot of the visual information that participants in Experiment 20 saw on the computer monitor. Note that the length of the arrow changed in synchrony with the haptic force magnitude.

The apparatus, material, design, and procedure of the experiment were the same as those used in Experiment 19, with the following exceptions: In addition to the haptic stimuli (as described above in Experiment 19), a visual stimulus, consisting of a white cube (size 3.5 x 3.5 x 1.0 cm) positioned at the centre of the computer monitor, was also presented (see Figure A.4). An arrow was displayed to indicate the direction of the force vector. The length of the arrow changed in synchrony with the force magnitude. That is, it appeared to shoot out from the centre of the cube until it

reached its maximum length of 3.5 cm, and then shrank back to the centre of the cube. The cube was opaque and only the portion of the arrow outside the cube was visible.

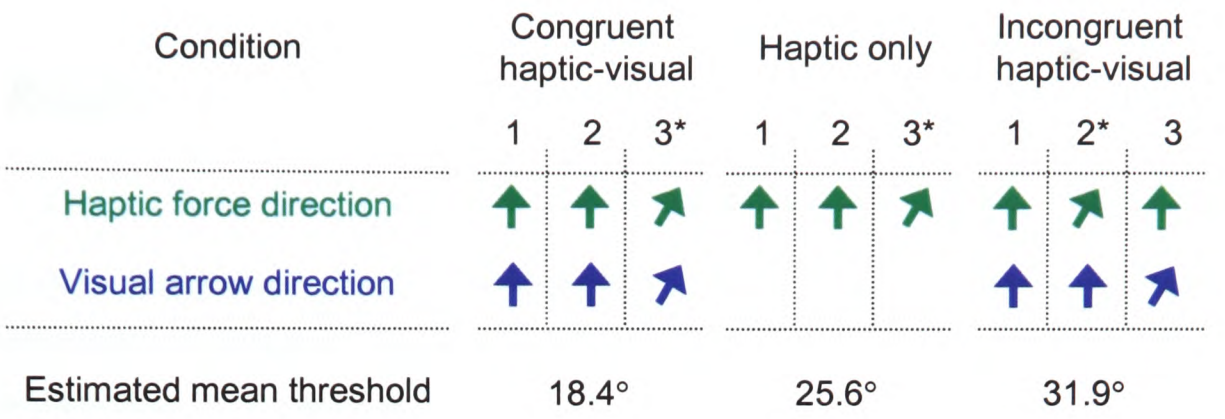


Figure A.5 An illustration of a sample trial in each of the three conditions in Experiment 20. In this example, the target force direction occurred in the interval indicated by *. The estimated mean thresholds for each condition reported in Experiment 20 are also shown.

Each participant was tested with one of the five reference force directions, which were counterbalanced across participants (i.e., four participants for each reference force direction). Instead of the five separate threads of adaptive procedure used in Experiment 19, each participant was presented with trials from each of three conditions: haptic cues only (H), haptic cues with congruent visual information (HVcong), and haptic cues with incongruent visual cues (HVincong). The three conditions differed only in the way in which the visual information was presented. During the H condition, the visual display consisted of the cube but no arrows. During the HVcong condition, the visual display included an arrow whose direction (and magnitude) always agreed with the applied forces. During the HVincong condition, the direction of the visual arrow was no longer consistent with the direction of the haptic force vector at all times. Figure A.5 shows a sample trial in each of the three conditions. Three separate threads of adaptive staircases were run for each of the three conditions, with trials from the three conditions presented randomly intermixed in the same experimental block of trials. The participants were told prior to the start of the

experiment that the visual information might sometimes be misleading, and that they should therefore respond according to the *haptic* sensation felt.

A.3.2 Results

Table A.1 Estimated mean thresholds and their standard errors (in parentheses), in degrees, as a function of experimental condition and reference force direction for Experiment 20.

	Force Direction					
Condition	Up	Right	Left	Diagonal-right	Diagonal-left	Mean
Haptic with congruent visual (HVcong)	12.7	11.9	19.5	21.9	26.0	18.4
	(0.8)	(3.1)	(9.2)	(5.2)	(3.3)	(2.4)
Haptic only (H)	28.4	23.4	20.0	21.0	35.5	25.6
	(1.2)	(2.1)	(1.2)	(3.1)	(4.8)	(1.7)
Haptic with incongruent visual (HVincong)	26.8	26.0	27.2	35.3	44.3	31.9
	(1.8)	(1.2)	(3.8)	(7.3)	(8.0)	(2.6)

The mean threshold of each participant was calculated in a similar manner to those of Experiment 19. Table A.1 shows the estimated mean thresholds for α as a function of the three conditions. A two-way ANOVA was performed on the estimated mean threshold data to assess what effect, if any, the presence of congruent versus incongruent visual cues had on participants' haptic discrimination thresholds for different force directions. The within-participants factor was condition (H, HVcong, or HVincong) and the between-participants factor was reference force direction (up, left, right, diagonal-left, or diagonal-right).

The analysis revealed a significant main effect of condition, $F(2,30) = 20.1$, $MSE = 45.5$, $p < .001$. The participants could, on average, discriminate between target and reference forces at α of 25.6° (SE = 1.7°) when no visual information was presented (condition H). Subsequent paired comparison t-tests between condition H and conditions HVcong and HVincong showed that the presence of congruent visual information resulted in a significant improvement in the discrimination threshold to 18.4° (SE = 2.4°), $t(19) = 3.2$, $p = .005$, while the presence of incongruent visual information led to a significant impairment in discrimination performance to 31.9° (SE = 2.6°), $t(19) = -3.3$, $p = .004$. A paired comparison t-test between conditions HVcong and HVincong also revealed a significant difference between the two conditions, $t(19) = -5.5$, $p < .001$. The main effect of reference force direction was, however, not significant, $F(4,15) = 2.7$, $MSE = 157.5$, $p = .07$, nor was the interaction between condition and reference force direction, $F(8,30) = 1.5$, $MSE = 45.5$, $p = .20$, suggesting that the direction in which the forces were presented to the participants' finger did not affect their discrimination performance per se.

A.3.3 Discussion

Consistent with the notion that haptic perception is influenced by visual information (cf. Klein, 1977), a significant effect of congruency was found with congruent visual information lowering the haptic force direction discrimination threshold to 18.4° from a threshold of 25.6° seen in the haptic only condition, while the incongruent visual information led to an increase in the threshold to 31.9°. Consistent with the findings reported in Experiment 19, the results of Experiment 20 also failed to reveal any statistically significant difference across the five force directions tested.

Presumably the haptic force discrimination thresholds obtained in Experiment 20 in the presence of congruent visual information may be closer to those of a visual only condition (an overall mean of 3.3°) reported in a follow-up experiment.[A.1] However, given that the visual information was valid (i.e., reliable and useful for the haptic task) on only 2/3 of the trials where visual cues were present, and that the haptic only condition was interleaved in the experimental run, the participants might have concentrated on the haptic task (as, in fact, they were instructed to do) while weighing the visual information as relatively less important (or at least attempting to ignore it).

Battaglia, Jacobs, and Aslin (2003) suggested that endogenous attention may have a residual effect on the optimal integration of multisensory information. In particular, Battaglia and colleagues pointed out that the MLE model may fail to account for any residual perceptual biases that observers might have. They found that the MLE model consistently underestimated the extent to which participants in an audiovisual spatial localization experiment biased their responses to vision. This means that the role of visual capture in general may not have been accounted for satisfactorily by the MLE model.

It seems intuitive that haptic information would provide the most accurate sensory cues with regard to the discrimination of force direction. As a result, haptic cues should dominate when they are in conflict with vision. However, the results of

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[A.1] A follow-up experiment was conducted in which four participants (mean age of 28 years, age range from 24-32 years; 3 males and 1 female; all with normal or corrected-to-normal vision) were tested in a vision only vector direction discrimination experiment. The experiment was conducted in a manner similar to that reported in Experiment 19, with the exception that the participants' task was to discriminate the force vector displayed on the computer monitor (the same visual information presented in Experiment 20), in the absence of any haptic information. The same three-interval one-up three-down adaptive procedure was used with five separate threads of adaptive procedure for the five reference direction conditions for each participant. The same data analysis method used in Experiment 19 was applied to the visual only data. The mean discrimination threshold found in the visual only experiment was 3.3°, which was considerably smaller than the HVcong threshold of 18.4° reported in Experiment 20.

Experiment 20 suggest that vision can modulate haptic perception, thus hinting at the need for some reconsideration of how to determine what constitutes the 'most accurate' modality in any given context.

One may argue that the visual estimates available to the participants were artificially assigned by the experimenter (i.e., the participants did not see the force being applied to their finger per se, but rather a visual representation of the force direction, and the participants had prior knowledge that the visual cue might not correspond to the haptic force direction felt). Thus, it could be argued that the visual cues were more salient than those normally available when making force direction judgments in a real-world situation. It is also possible that these findings reflect sensory interference, or some kind of Garner interference effect (i.e., crossmodal interference taking place at a more decisional, rather than perceptual, level of information processing; see Garner, 1970; Spence & Walton, 2005).

In Experiment 20, the haptic and visual information were presented from two distinct spatial locations (an experimental set-up which is common to the majority of visual-haptic studies). The setting resembled that of the familiar manipulation of a computer mouse placed on the side of a person and used to control the mouse pointer displayed on a computer monitor (placed directly in front of a person; see Holmes & Spence, 2006). Given recent evidence that spatial proximity can influence the integration of visual and haptic cues (see Gepshtein, Burge, Ernst, & Banks, 2005; Soto-Faraco, Lyons, Gazzaniga, Spence, & Kingstone, 2002), the effects of visual cues on haptic force perception might be expected to be more pronounced when the visual cues are presented from the same spatial location as the haptic stimuli, as opposed to from different positions, such as in Experiment 20.

A.4 Conclusions

In conclusion, the findings from Experiments 19 and 20 suggest that (1) haptic force direction discrimination is not directionally dependent (i.e., it appears to be isotropic); and that (2) the recommended force direction discrimination threshold for use in the design of haptic devices is on the order of 25-33°. Note that these thresholds are, if anything, likely to be elevated under conditions where people have to attend to other locations (or to divide their attention between different sensory modalities), as compared to the best-case scenario tested in the two experiments outlined above, where the participants were explicitly instructed to direct their full attention to the discrimination of force directions applied to their index finger (cf. Spence, Nicholls, & Driver, 2001). Accordingly, system designers may be able to take advantage of an even larger tolerance than the threshold values suggested here, given that attention will not necessarily be concentrated on the manipulation of the haptic tool alone. With respect to the integration of visual-haptic information, designers of haptic virtual environments nevertheless need to pay close attention to the parameters of signal reliability (Ernst & Banks, 2002), attentional bias (Battaglia et al., 2003; Spence et al., 2001b), and spatial proximity (Gepshtein et al., 2005) of the visual and haptic information sources.

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