

Chapter 1

Introduction

The attentional limitations associated with driving

Humans are inherently limited capacity creatures; that is, they are able to process only a small amount of the sensory information that is typically available at any given time (see Broadbent, 1958; Driver, 2001; Simons and Chabris, 1999; Spence and Driver, 1997a). Although it is unclear what the exact nature of this limited capacity is (see Posner and 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 of stimuli both in the laboratory and in a number of real-life settings (e.g., see McCarley et al., 2004; O'Regan, Rensink, and Clark, 1999; Spence and Read, 2003; Velichkovsky et al., 2002).

Over the years, attention has been defined in a number of different ways. It has, for example, been defined 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 very important element of any definition of attention, however, is its selectivity (see Driver, 2001, for a review). Among all of the various different dimensions along which the selective processing of information may take place, the spatial distribution of attention represents an area that is of great interest to many researchers, from both a theoretical and an applied standpoint (see Posner, 1978; Spence, 2001; Spence and Driver, 1994; Spence and Read, 2003).

The limited capacity of spatial attention to process sensory information in humans raises important constraints on the design and utilization of, for instance, vehicular information systems (e.g., Brown, Tickner, and Simmonds, 1969; Burke, Gilson, and Jagacinski, 1980; Chan and Chan, 2006; Mather, 2004; Spence and Driver, 1997a). The act of driving represents a highly complex skill requiring the sustained monitoring of integrated perceptual and cognitive inputs (Hills, 1980). The ability of drivers to attend selectively and their limited ability to divide their attention amongst all of the competing sensory inputs have a number of important consequences for driver performance. This, in turn, links inevitably to the topic of vehicular accidents. For instance, a driver may fail to detect the sudden braking of the vehicle in front if distracted by a passenger's conversation (or by the conversation with someone at the other end of a mobile phone; e.g., Horrey and Wickens, 2006; Spence and Read, 2003; see Chapter 2), resulting in a collision with the vehicle in front (see Sagberg, 2001; Strayer and Drews, 2004). In fact, one recent research report has shown that the presence of two or more car passengers is associated with a two-fold increase in the likelihood of a driver having an accident as compared to people who drive unaccompanied (see McEvoy, Stevenson, and Woodward, 2007b). 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, and Hayes, 2004; Wang, Knippling, and Goodman, 1996; though see also Crossen, Meijman, and Rothengatter, 2004), such as satellite navigation systems (e.g., Burnett and Joyner, 1997; Dingus, Hulse, Mollenhauer, Fleischman, McGehee, and Manakkal, 1997; Fairclough, Ashby, and Parks, 1993), mobile phones (e.g., Jamson, Westerman, Hockey, & Carstens, 2004; Patten, Kircher, Ostlund, and Nilsson, 2004; Spence and Read, 2003; Strayer, Drews, and Johnston, 2003), email (e.g., Harbluk and Lalonde, 2005; Lee, Caven, Haake, and Brown, 2001) and ever more elaborate sound systems (e.g., Jordan and Johnson, 1993). Somewhat surprisingly, this proliferation of in-vehicle interfaces has taken place in the face of extensive research highlighting the visual informational overload suffered by many drivers (e.g., Bruce, Boehm-Davis, and Mahach, 2000; Dewar, 1988; Dukic, Hanson, and Falkmer, 2006; Hills, 1980) and the widely reported claim in the literature that at least 90 per cent of the information used by drivers is visual (e.g., Booher, 1978; Bryan, 1957; Spence & Ho, forthcoming; though see also Sivak, 1996).

Given the many competing demands on a driver's limited cognitive resources, it should come as little 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 anywhere between 26 per cent (Wang et al., 1996) and 56 per cent (Treat et al., 1977) of all road traffic accidents (see also Ashley, 2001; Gibson and Crooks, 1938; Klauer, Dingus, Neale, Sudweeks, and Ramsey, 2006; McEvoy et al., 2007; Sussman, Bishop, Madnick, and Walter, 1985). 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; Noy, 1997), 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 (FTRE) collision (McGehee, Brown, Lee, and Wilson, 2002; see also Evans, 1991). The research that has been published to date suggests that driver distraction 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). Research by Strayer and Drews (2004) has also shown that mobile phone use tends to be one of the factors leading to front-to-rear-end collisions (see also Alm and Nilsson, 2001; Sagberg, 2001).

The potential benefits associated with improving the situation awareness of drivers to road dangers such as impending collisions are huge. To put this into some kind of 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 per cent (Suetomi and Kido, 1997; see also 'The mobile phone report', 2002). Given that a number of different forward collision warning systems now exist, it has become increasingly important to determine the optimal means of assisting

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 in an attempt to get them to adjust their speed voluntarily instead (Hunter, Bundy, and Daniel, 1976; Janssen and Nilsson, 1993).

In fact, the technology now exists to enable ‘intelligent’ cars to detect dangerous road situations on the road ahead (e.g., such as adaptive radar cruise control systems and computerized safety systems that enable cars to communicate with each other prior to potential collisions), which in theory means that the cars of the future could potentially soon take control away from the driver and become autonomous (Knight, 2006). However, at present, car manufacturers and governmental organizations appear to prefer that the control of the car remains in the hands of the drivers (though see Smith, 2008). The primary reason for this is related to the legal implications and issues arising should an accident occur during automatic cruising, such as those relating to liability for the accident (see Hutton and Smith, 2005; Knight, 2006). Therefore, investigations into the design of optimal warning signals that can alert drivers to potential dangers are essential given the increasing availability of advanced driver assistance systems (see Yomiuri Shimbun, 2008).

A great deal of empirical effort has gone into studying how best to alert and warn inattentive drivers of impending road dangers. For example, a number of researchers have suggested that non-visual (e.g., auditory and/or tactile) warning signals could be used in interface design (e.g., Deatherage, 1972; Hirst and Graham, 1997; Horowitz and Dingus, 1992; Lee et al., 2004; Sorkin, 1987; Stokes, Wickens, and Kite, 1990; see Table 1.1).

Multisensory integration

It is our belief that one increasingly important way in which to design effective in-car interfaces is by understanding the limitations of the human brain’s information processing system (see Spence and Ho, forthcoming). This area of research is known as ‘neuroergonomics’ (e.g., see Fafrowicz and Marek, 2007; Sarter & Sarter, 2003). Traditional theories of human information processing have typically considered individual sensory modalities, such as audition, vision and touch, as being independent. In particular, the most influential multiple resource theory (MRT) on human workload and performance originally proposed by Christopher Wickens in 1980 (see e.g., Wickens, 1980, 1984, 1992, 2002) more than a quarter of a century ago specifically postulated the existence of independent pools of attentional resources for the processing of visual and auditory information (Hancock, Oron-Gilad, and Szalma, 2007; see Figure 1.1). According to the multiple resources account, when people are engaged in concurrent tasks that consume their visual and auditory resources simultaneously, such as talking on the mobile phone while driving, there should be no dual-task cost due to the putative independence of the attentional resources concerned. That is, according to Wickens’ theory, the conversation is processed

Table 1.1 Advantages of non-visual (auditory and/or tactile) warning signals for interface design

Purported advantages of non-visual over visual warning signals	Study
Responses to auditory and tactile signals typically more rapid than to visual signals.	Jordan (1972); Nelson, McCandlish, and Douglas (1990); Todd (1912)
Non-visual warning signals should not overload the driver's 'visual' system (cf. Sivak, 1996).	McKeown and Isherwood (2007); though see Spence and Driver (1997b); Spence and Read (2003)
Inherently more alerting.	Campbell et al. (1996); Gilmer (1961); Posner, Nissen, and Klein (1976)
Non-visual warnings do not depend for their effectiveness on the current direction of a driver's gaze. They are perceptible 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 a second.	Bristow, Haynes, Sylvester, Frith, and Rees (2005); Hirst and Graham (1997); Stanton and Edworthy (1999)
Non-visual warning signals tend to be judged as less annoying than many other kinds of warning signal.	Lee et al. (2004); McGehee and Raby (2003)

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.

The evidence that has emerged from both behavioural and neuroimaging studies over the last decade or so has, however, argued against this traditional view (see Navon, 1984). Instead, the recently developing multisensory approach to human information processing has put forward the view that people typically integrate the multiple streams of sensory information coming from each of their senses (e.g., vision, audition, touch, olfaction and taste) in order to generate coherent multisensory perceptual representations of the external world (e.g., see the chapters in Calvert, Spence, and Stein, 2004; Spence and Driver, 2004). In fact, the multisensory integration of inputs from different sensory modalities appears to be the norm, not the exception. What is more, the research published to date has shown that multisensory integration takes place automatically under the majority of experimental conditions (see Navarra, Alsius, Soto-Faraco, and Spence, forthcoming, for a review). 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 the modality-specific level and/or at the crossmodal level that is shared between different sensory modalities (as well as at the perceptual; see Lavie, 2005, and also at the response selection stages; see Levy, Pashler, and Boer, 2006; Pashler, 1991; Schumacher et al., 2001).

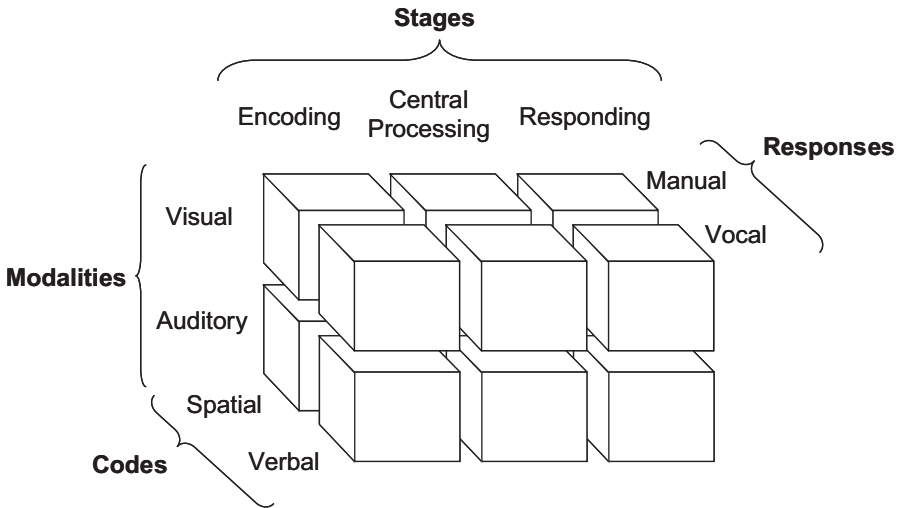


Figure 1.1 Schematic diagram of the Multiple Resource Theory of human workload and performance proposed by Wickens (e.g., 1980, 2002)

The extensive body of evidence that has emerged from recent laboratory-based research has provided support for the existence of robust crossmodal links in spatial attention between different sensory modalities (see Spence and Driver, 2004; Spence and Gallace, 2007). In particular, the available research now suggests that the efficiency of human multisensory information processing can be enhanced if the relevant information provided to the different senses is presented from approximately the same spatial location (see Driver and Spence, 2004) at approximately the same time (Spence and Squire, 2003). The research has also shown that it is normally harder to selectively attend to one sensory signal if a concurrent (but irrelevant) signal coming from another sensory modality is presented from approximately the same location (see Spence and Driver, 1997b; Spence, Ranson, and Driver, 2000b). This also implies that it may be harder to ignore a sensory signal in one sensory modality if it is presented at (or near) the current focus of a person's spatial attention in another sensory modality (see Spence et al., 2000b).

Crossmodal links in spatial attention have now been observed between all possible combinations of auditory, visual and tactile stimuli (Spence and Driver, 1997a, 2004). These links in spatial attention have been shown to influence both exogenous and endogenous attentional orienting (Klein, 2004; Klein and Shore, 2000; Posner, 1980; see Driver and Spence, 2004; Spence, McDonald, and Driver, 2004, for reviews). Exogenous orienting refers to the stimulus-driven (or bottom-up) shifting of a person's attention whereby the reflexive orienting of attention occurs as a result of external stimulation. By contrast, endogenous orienting refers to the voluntary shifting of a person's attention that is driven internally by top-down control. A variety of laboratory-based research has suggested that independent mechanisms may control these two kinds of attentional orienting (e.g., Berger, Henik, and Rafal, 2005; Hopfinger and West, 2006; Klein and Shore, 2000; Santangelo and Spence, forthcoming; Spence and Driver, 2004).

Current approaches to the design of auditory warning signals

Over the years, a number of different approaches to the design of effective auditory warning signals have been proposed. These include the use of spatially-localized auditory warning signals (e.g., Begault, 1993, 1994; Bliss and Acton, 2003; Bronkhorst, Veltman, and van Breda, 1996; Campbell et al., 1996; Humphrey, 1952; Lee, Gore, and Campbell, 1999), the use of multisensory warning signals (e.g., Hirst and Graham, 1997; Kenny, Anthony, Charissis, Darawish, and Keir, 2004; Mariani, 2001; Mowbray and Gebhard, 1961; Selcon, Taylor, and McKenna, 1995; Spence and Driver, 1999; see also Haas, 1995; Spence and Ho, forthcoming) and the use of synthetic warning signals (such as auditory earcons; e.g., Lucas, 1995; McKeown and Isherwood, 2007) that have been artificially engineered to deliver a certain degree of perceived urgency.

To date, these various different 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 and Acton, 2003; Fitch, Kiefer, Hankey, and Kleiner, 2007). Meanwhile, other researchers have reported favourably on the potential use of directional sounds in confined spaces (e.g., Cabrera, Ferguson, and Laing, 2005; Catchpole, McKeown, and 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, and Dennis, 1991; Graham, 1999; Haas and Casali, 1995; Haas and Edworthy, 1996). It would appear, therefore, that unless auditory earcons can somehow be associated with intuitive responses on the part of the driver (Graham, 1999; Lucas, 1995), they should not be used in dangerous situations to which an interface operator (and, in particular, the driver of a road vehicle) may only rarely be exposed, since they may fail to produce the appropriate actions immediately (see also Guillaume, Pellieux, Chastres, and Drake, 2003).

Given these limitations in 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 idea being that they should inherently convey the meaning of the events that they are meant to signify (e.g., Blattner, Sumikawa, and Greenberg, 1989; Gaver, 1989; Gaver, Smith, and O'Shea, 1991; Lazarus and Höge, 1986; McKeown, 2005). Over the years, the effectiveness of a variety of different 'urgent' auditory icons has been evaluated in terms of their ability to capture a person's attention, and perhaps more importantly, to elicit the appropriate behavioural responses from them (e.g., see Deatherage, 1972; Oyer and 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 need less time in order to learn the appropriate behavioural responses to such signals (e.g., Begault, 1994; Lucas, 1995). However, while the research that has been

published to date has shown that people do indeed tend to respond more rapidly to auditory warning signals as the perceived urgency increases (e.g., Burt, Bartolome, Burdette, and Comstock, 1995; Haas and Casali, 1995), the use of urgent auditory icons is not without its own 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 therefore appear that highly urgent signals may sometimes elicit such rapid responses that interface operators can end up responding to the warning signal before they have had sufficient time in which to evaluate the situation properly in order to know what the most appropriate response would have been (see Bliss and Acton, 2003; Graham, 1999). Furthermore, the empirical research that has been conducted to date does not provide unequivocal support for the claim that auditory icons necessarily make for 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 and Isherwood, 2007; see also Oyer and Hardick, 1963). For example, in one recent study, McKeown and Isherwood assessed the perceived unpleasantness of twenty different environmental sounds. They found a strong correlation between the perceived urgency of the sounds and how unpleasant people rated those sounds as being (see Figure 1.2). Therefore, while the approach of trying to develop auditory warning signals that elicit an intuitive response from drivers would, at first glance, seem like a good one, the fundamental problem appears to be that any sound that is perceived by a person as being urgent will most likely also be

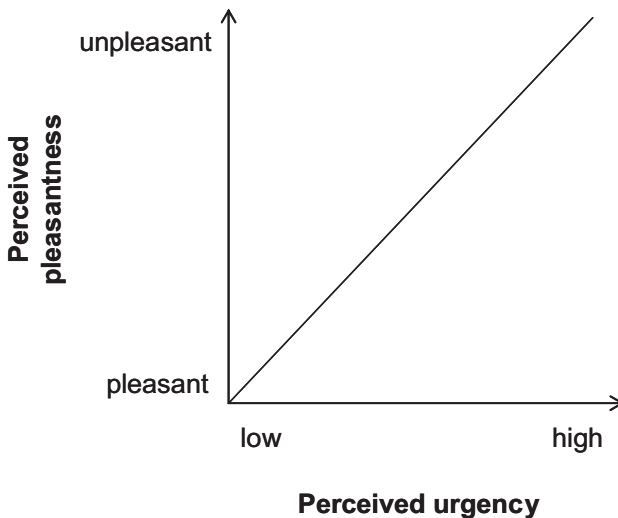


Figure 1.2 Graph showing the linear relationship between the perceived degree of urgency of an auditory icon and its perceived degree of pleasantness

judged as unpleasant, and thus will be unlikely to be accepted by the end user of an interface (see McKeown and Isherwood, 2007; cf. Lazarus and Höge, 1986).

One potentially 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 and Hellier, 2006; cf. Bruce, et al., 2000; Simpson, McCauley, Roland, Ruth, and Williges, 1987). As suggested by Edworthy and Hellier in their comprehensive 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 Dibben and Williamson, 2007; Ho, Reed, and Spence, 2007b; Ramsey and 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 and 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) have assessed the effectiveness of presenting auditory signals at different times to warn distracted drivers of an impending collision with a stationary vehicle on the road ahead. 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 in their driving simulator study. This facilitation of performance included shorter accelerator release times as well as 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 the presentation of an early warning signal allows a driver more time in which 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, and Olofinboba, 1997; Shinar, 1978). What is more, as soon as the false alarm rate for a warning signal becomes too high, interface operators may well begin to perceive it as being a nuisance and therefore start to ignore it. Thus, the danger is that interface operators may become desensitized to future warning signals (see Bliss and 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 and Corso, 1993). It is therefore crucial that the collision warning signal is presented at the appropriate moment in time.

Collision avoidance

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’ (including perceptual processing) and ‘braking distance’ (i.e., the time required to program and execute a motor response). A review by Hills (1980) suggested that the ‘thinking distance’ required to brake while driving a car corresponds to a reaction time 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 in explaining the performance of the majority of drivers. Researchers have argued 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 per cent 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 and Dingus, 1992).

In addition, in a meta-analysis of braking reaction time studies, Green (2000) reported that drivers had an average reaction time of 700 ms for a fully-expected event as compared to a reaction time of 1500 ms for an unexpected event. In his analysis, Green broke the total perception-brake reaction time into three major components, specifically, mental processing time (a combination of sensation, perception, and response selection and programming), movement time and device reaction time. While the reaction time of the device clearly constitutes a technical problem, some researchers have suggested that movement time (i.e., lifting the foot off the accelerator pedal in order to depress the brake pedal) can be improved on by training (see Levy et al., 2006). In any case, one key question in warning signal design is concerned with speeding up the mental processing of drivers (i.e., at the perceptual and decisional stages of human information processing).

Recent developments in tactile warning signal design

In addition to the traditional design of visual and auditory interfaces, 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., Fitch et al., 2007; Gallace, Tan, and Spence, 2007; Gilliland and Schlegel, 1994; Jones, Gray, Spence, and Tan, 2008; Jones and Sarter, forthcoming; Rupert, 2000b; Sklar and Sarter, 1999; Spence & Ho, submitted; van Erp and van Veen, 2004, 2006; Wood, 1998; Zlotnik, 1988). The communication of information by touch has been successfully demonstrated in a number of different application areas, such as in the aerospace domain to assist the spatial orientation of pilots and astronauts (e.g., Rochlis and Newman, 2000; Rupert, Guedry, and Reschke, 1994). For instance, somatosensory cues have been shown to help improve the situation awareness of astronauts, who otherwise rely mainly on visual cues, in confusing situations in altered sensory environments, such as under conditions of weightlessness (Rochlis and Newman, 2000).

Van Erp, Jansen, Dobbins, and van Veen (2004) reported two case studies demonstrating that directional and distance information can be communicated by using 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, however, be noted that despite these applied research efforts, no such systems are currently in place in aeroplanes. Instead, 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' the design process.

The rapid growth of interest in tactile interface design is supported by the older body of applied research on tactile sensation and perception dating back to the early work of Fenton in the 1960's. For example, 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 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 to suggest a reduced subjective workload on the part of drivers when using tactile instead of visual navigation displays. Van Erp and van Veen studied the effectiveness of left/right vibrotactile cues presented to a driver's thigh via factors embedded in the seat in terms of their ability to provide navigational messages to drivers under conditions of normal and high workload. 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 and van Veen, 2001), it should be noted that the comparison of their data in the bimodal and unimodal conditions unfortunately failed to reach statistical significance. Similarly, in another study of car drivers, Fitch et al. (2007) also failed to demonstrate that their participants found it any easier to respond to the location (from eight possible locations) that had been cued when audiotactile cues were compared to unimodal auditory (or tactile) cues. Overall, the findings of these two studies therefore fail to provide any strong support for the claim that redundant information presented simultaneously to different senses may prove useful in the design of multimodal, or multisensory, systems (see also Jackson and Selcon, 1997; Oviatt, 1999; Spence and Driver, 1999). Recent research by Santangelo and his colleagues (Santangelo and Spence, 2007; Santangelo, Ho, and Spence, 2008) has, on the other hand, shown that bimodal cues are significantly better than unimodal cues, at least when they are presented from the same spatial location (see Chapter 7).

It is worth noting that in-car interfaces with vibrating functions have already been implemented in several recently-released models of car (e.g., BMW 5 Series's vibrating steering wheel and Citroën C6's vibrating seat). 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 for stimuli presented to the torso (e.g., Ho and Spence, 2007; Jones et al., 2008; Linderman, Yanagida, Sibert, and Lavine, 2003), head (e.g., Gilliland and Schlegel, 1994), hands (e.g., Burke et al., 1980; Jagacinski, Miller, and Gilson, 1979; Vitense, Jacko, and Emery, 2003), wrists (e.g., Sklar and Sarter, 1999), buttocks (e.g., Lee et al., 2004; McGehee and Raby, 2003) and feet (e.g., Godthelp and Schumann, 1993; Janssen and Nilsson, 1993; Janssen and Thomas, 1997), no one has yet attempted to systematically examine the relationship between the

body site stimulated and the nature of the driving task being (or to be) performed. Thus, it remains uncertain whether tactile stimulation, regardless of the body part being stimulated, will necessarily result in the same degree of improvement on a particular task. The alternative here is that optimal human performance in a particular task may be related to tactile stimulation on a specific body-site. So, for example, it might be the case that vibrating a driver's wrists represents the optimal means of getting them to perform an action with their hands. Note that research on stimulus-response compatibility effects suggests that there may indeed be important synergies between the stimulation of particular body parts and specific task requirements (e.g., see Fitts and Seeger, 1953; Kantowitz, Triggs, and Barnes, 1990; Proctor, Tan, Vu, Gray, and Spence, 2005). It is also worth mentioning at this point that it remains an open question as to whether tactile icons ('tactons'; for example, vibrations of various rhythm and/or roughness that can be reliably discriminated by people) exist (see Brewster and Brown, 2004; Brown, Brewster, and Purchase, 2005; see also Enriquez, MacLean, and Chita, 2006), as they might potentially provide a whole new range of possibilities for interface designers in terms of the artificial engineering of complex messages to convey information to users via the sense of touch (see Gallace et al., 2007, for a recent review).

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., involving combined proprioceptive and tactile cuing) on the accelerator pedal had beneficial effects in a collision avoidance system (see also Janssen and Nilsson, 1993; Tijerina, Johnston, Parmer, Pham, Winterbottom, and Barickman, 2000). On the other hand, Schumann, Godthelp, Farber, and Wontorra (1993) contrasted various different kinds of tactile feedback with auditory warnings as a means of signalling to drivers whether to remain in lane when engaged in passing manoeuvres. They reported that drivers were more responsive to tactile or proprioceptive cues, such as the vibration of the steering wheel or force feedback cues resisting the driver's control input to change lanes, as compared to auditory warnings. Lee et al. (2004) have also compared the effectiveness of auditory and haptic collision warnings presented in either 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.

Critical factors for effective collision warning signal design

It is important to note that it will not be sufficient for future in-car warning signals simply to be optimized for their ability to capture a driver's spatial attention (Spence, 2001). Instead, they must also be optimized for (i.e., be 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 both unisensory and multisensory warning signals (which will be delineated in the chapters that follow)

should therefore be optimized to elicit the most effective response by combining an understanding of the different brain pathways involved in information processing and the particular combinations of multisensory signals that are the 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 recent evidence that has emerged from both behavioural and neuroscience studies suggests that we may now be in a position where our understanding of the multisensory nature of human information processing is such that we can start to apply the insights gained from recent studies of crossmodal links in spatial attention to the design of applied multisensory interfaces (e.g., Spence and Driver, 1997a, 1999; Spence and Ho, 2008, forthcoming). In particular, one of the central aims of this book is to investigate the role of spatial attention in the domain of developing more ergonomic unisensory and multisensory warning signals for car drivers (i.e., to try and develop signals that elicit more efficient and effective responses from car drivers). Given that it has been argued that driving is predominantly a visual task (cf. Sivak, 1996), it is important to examine whether the use of non-visual warning signals can be used to effectively orient a driver's visual attention to the appropriate location. The neuroscience approach to multisensory attentional capture by warning signals has been made possible by the resolution in the experimental psychology literature that there exist robust crossmodal links in spatial attention between audition, vision and touch (see Spence and Driver, 2004; Spence and Gallace, 2007). However, it is also important to acknowledge the potential performance trade-off that may be associated with the utilization of additional sensory modalities of information to car drivers. In particular, laboratory-based research has shown that there is a cost associated with having to divide one's attention between multiple different sensory modalities at the same time (Spence and Driver, 1997; Spence, Nicholls, and Driver, 2001).

The chapters that follow in this book investigate the stage(s) in information processing at which the facilitatory effects elicited by such spatial multisensory warning signals occur (see Figure 1.3). For instance, 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 found.

The subsequent chapters are structured as follows: Chapters 2 and 3 provide reviews of the literature regarding the potential limitations in human information processing that constrain the performance of drivers who are distracted by trying to perform a secondary task. In particular, we focus on the consequences of talking on a mobile phone while driving (Chapter 2) and on listening to the radio (Chapter 3). On the basis of this review of the literature on distracted (and/or drowsy) drivers, we are able to highlight some of the key features that any attention-capturing warning signal needs to achieve if it is to effectively capture a driver's attention. In Chapter 4, we review the existing literature on auditory warning signals and report on the potential facilitation in responsiveness to collision situations with the presentation of spatial and/or meaningful auditory cues. Chapter 5 reviews the recent development

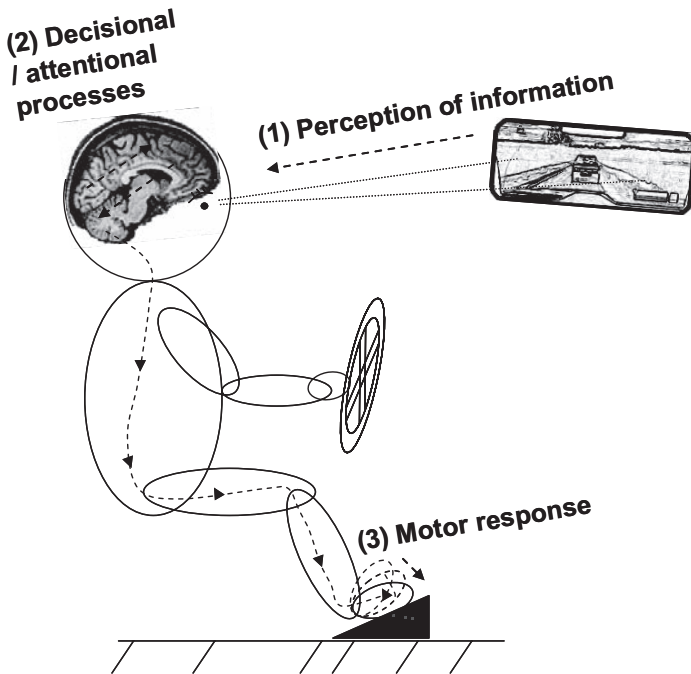


Figure 1.3 Schematic diagram showing the basic stages in information processing at which facilitatory effects on performance elicited by the presentation of spatial multisensory warning signals may occur

of vibrotactile in-car interfaces and discusses their purported ‘intuitive’ property. In Chapter 6, we provide an in-depth investigation into the relative contributions of perceptual enhancement and decisional facilitation to the effects discussed in the preceding experimental chapters. Chapter 7 further examines the spatial relationship between combined audiotactile (multisensory) cues and highlights the important role that multisensory integration can play in facilitating the disengagement of a person’s spatial attention from a concurrent highly perceptually-demanding task. Finally, in Chapter 8, we highlight the most important findings to have emerged from the warning signal experiments that are described in this book. We then go on to discuss some of the possible directions for multisensory interface research in the coming years, including evaluating the potential for olfactory cues in modulating the behaviour and/or mental state of drivers.