Tactile and Multisensory Spatial Warning Signals for Drivers

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Abstract—The last few years have seen many exciting developments in the area of tactile and multisensory interface design. One of the most rapidly moving practical application areas for these findings is in the development of warning signals and information displays for drivers. For instance, tactile displays can be used to awaken sleepy drivers, to capture the attention of distracted drivers, and even to present more complex information to drivers who may be visually overloaded. This review highlights the most important potential costs and benefits associated with the use of tactile and multisensory information displays in a vehicular setting. Multisensory displays that are based on the latest cognitive neuroscience research findings can capture driver attention significantly more effectively than their unimodal (i.e., tactile) counterparts. Multisensory displays can also be used to transmit information more efficiently, as well as to reduce driver workload. Finally, we highlight the key questions currently awaiting further research, including: Are tactile warning signals really intuitive? Are there certain regions of the body (or the space surrounding the body) where tactile/multisensory warning signals are particularly effective? To what extent is the spatial coincidence and temporal synchrony of the individual sensory signals critical to determining the effectiveness of multisensory displays? And, finally, how does the issue of compliance versus reliance (or the "cry wolf" phenomenon associated with the presentation of signals that are perceived as false alarms) influence the effectiveness of tactile and/or multisensory warning signals?

Index Terms—Multisensory warning signal, tactile display, driving, spatial attention, cognitive neuroscience.

1 Introduction

For more than half a century now, researchers have been interested in the utilization of tactile (or haptic)[1] displays to assist interface operators working in visually cluttered or overloaded environments (e.g., [33] and [96]; see [27] for a recent review) and in other adverse operational conditions [15], [35], [69], [97], [101], [103]. While many studies have documented the potential benefits associated with the presentation of tactile stimuli to pilots and other interface operators (e.g., [15], [36], [47], [80], and [99]), regulatory restrictions have meant that little progress has been made in implementing such tactile displays beyond the traditional stick shaker.[2] By contrast, while research interest in the incorporation of tactile warning signals/displays in vehicles emerged more recently (e.g., [63], [77], [93], and [98]), a number of commercial vibrotactile safety systems are already available in the marketplace (albeit as optional extras), such as the lane departure warning systems available in certain models of Citroën and BMW cars (see [52] and [82]). What is more, according to the Denso Corp., one of the world's largest manufacturers of automobile parts, all new cars will be fitted with some sort of tactile stimulation device as standard by the year 2020 (C. Spence, personal communication).

Given the rapid implementation of tactile displays in vehicles over the last few years, it seems particularly timely to look at what has been learnt in terms of the optimal design of tactile and multisensory (i.e., audiotactile or visuotactile) warning signals and informational displays for drivers. We start by highlighting what we see as the costs and benefits associated with the use of tactile displays. We then go on to look at three of the specific applications for tactile displays, namely, awakening the drowsy driver, capturing the attention of the distracted driver, and finally, reducing the workload of overloaded drivers. Next, we consider the limitations associated with the use of more advanced tactile information displays in vehicles and how future warning signal design should address the perceptual/cognitive deficits faced by the growing population of aging drivers. Finally, we conclude by highlighting what we see as the most pressing questions that will need to be addressed by future research.

1. In much of the ergonomics and interface design literature, the term "haptic" is used to describe the stimulation of the participants' skin/body (e.g., [24]). However, it should be noted that in the cognitive psychology/psychophysics literature, this term has a very specific meaning, restricted to describing those tactile stimuli that impinge on the skin and which are perceived by means of a person actively palpating an object or surface, such as when actively exploring an object held in the hand. By contrast, the term "tactile" is used to describe those tactile stimuli that are delivered passively to the skin surface. Given that the majority of the tactile displays and warning signals discussed in this review involve passive tactile stimulation, we have chosen to use the term "tactile." The only tactile stimulation that would, at least to a cognitive psychologist, fall under the heading of haptic stimulation would be the active torque feedback delivered by certain steering wheel warning signals (see [77] and [93]) and the counterforce applied to the soles of a driver's feet (e.g., [48]).

2. This device was specifically designed to capture a pilot's attention under certain "flight-critical" conditions, such as when a plane is close to stalling (see [30]).

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2 Assessing the Costs and Benefits of Tactile Displays

It has long been acknowledged that drivers (and other interface operators) often suffer from visual overload (see [87], for a recent review, though see also [79]). As such, researchers have, for many years, contemplated the potential use of a variety of nonvisual displays. While the majority of this research has focused on the development of effective in-vehicle auditory signals and displays (see [19], [41], and [64]), some researchers have also considered the possibilities associated with the use of tactile displays and warning signals (e.g., [44]). Indeed, it is interesting to note that the skin represents the largest of our senses (accounting for approximately 18 percent of our body mass; see [65]) but, at present, is little used while driving (see [87]). When considering the implementation of nonvisual information displays in vehicles, it soon becomes apparent that tactile warning signals have a number of potential advantages relative to their more widely studied auditory counterparts.

It is our belief that the stimulation of the skin offers great potential in terms of capitalizing on a currently underutilized sensory channel of communication to deliver warning signals and other kinds of information without necessarily overloading the driver's limited attentional resources (see [63], [76], and [105], though see also [83]). Indeed, many researchers have claimed that tactile stimuli may be automatically attention capturing [75] and, hence, that a person does not need to "look out" for tactile warning signals in order for them to automatically capture a driver's or other interface operator's attention [63] (see [74] for evidence that tactile stimuli do not always capture people's attention automatically, at least not when their concentration is engaged elsewhere).

Tactile displays have the advantage that tactile perception is relatively unaffected by the level of background auditory noise (see [3] and [9], though see also [32]). This contrasts with the case of auditory warning signals and displays, where trying to ensure the audibility of the warning signal over any background road noise [81] and/or the sound of the car stereo [42] represents a very real problem. On the other hand, one might, of course, also worry that certain tactile cues (such as those delivered to the driver's seat) would be rendered ineffective should a driver happen to be wearing thick clothing (see [55]). However, a number of studies have now shown that tactile warning signals can operate through a variety of everyday clothing [38], [39], [63] and even through the soles of a driver's shoes [48]. On the other hand, it should also be noted that whole-body vibration (which can be considered as a form of tactile noise) is likely to have a more detrimental effect on the processing of tactile warning signals than on the processing of auditory signals.

Tactile displays have the advantage that they allow for the delivery of information targeted specifically at the driver. That is, in contrast to the more commonly used auditory warning signals, passengers need not be made aware of (or distracted by) any tactile warning signals that happen to be delivered to the driver's body. Furthermore, within the confined space of the car interior, tactile warning signals are much easier to localize than auditory warning signals (e.g., see [24] and [94], though see also [45]). Thus, tactile cues seem to offer a particularly effective means of presenting directional signals to drivers. This relates to the claim that tactile cues are "intuitive" (see [38] and [40]), although it should be noted that a precise definition for this term is currently still lacking. Nevertheless, the notion that such infrequent warning signals need to have an easily recognizable meaning or directly capture a driver's attention (see [88]) is now widely accepted [93]. To give but one example here of the potential benefit of tactile over other kinds of warning signals, Janssen and Nilsson [48] reported that presenting a counterforce (consisting of an increase of 25 N) on the gas pedal whenever drivers were too close to the vehicle that was ahead of them resulted in safer driving behavior in their simulator study than when the same warning information was presented by a visual or auditory warning signal instead.

While the aforementioned discussion should have made clear the many potential benefits associated with the use of tactile over other kinds of warning signals, especially in the context of the car (or other vehicle) interior, it is important to note that there are also some important constraints limiting the successful incorporation of tactile displays into commercial vehicles. First and in contrast to many other domains, such as for astronauts [97], [103], soldiers [15], [35], [50], and/or pilots [69], [80], [99], where extensive training with any new display technology would not be a problem, car manufacturers are convinced that new tactile displays will need to be easy to use and, as a consequence, that they should not require extensive training in order for the users to be able to use them efficiently (see [93]). (Our own research in this area—see below—has involved only a minimal period of familiarization prior to testing.)

Fortunately, car accidents constitute a very rare occurrence for most drivers. This means that tactile warning signals (or any other collision avoidance warning signals for that matter) are likely to be presented very infrequently, especially if one wants to avoid the "cry wolf" phenomenon [6] (see also [4] and [18]). The rare occurrence of warning signals means that it is desirable that their meaning be immediately apparent, even if a driver has not experienced such a warning signal for a long time (see [88] on this issue). This then raises the question of whether beyond the presentation of directional cues, it is possible to present tactile messages (or icons) that are more or less instantly comprehensible, in a manner similar to the "auditory icons" favored by researchers working in the auditory domain (e.g., [11], [31], and [64]). However, as yet, there has been less work on this important topic (though see [5], [7], [8], [13], [46], [60], [62], and [96]). One thing that may be holding up progress here is simply that it is much harder to think of what tactile icons, or "tactons," might consist of than it is to generate meaningful auditory icons. However, one interesting but as yet relatively unexplored possibility involves the development of tactile displays that capture the everyday affordances of stimuli, such as the expanding pattern (and increase in intensity) observed when an auditory or visual event approaches rapidly. One might therefore wonder whether a graded expanding tactile display presented on the front of a driver's torso would be particularly effective/intuitive as a collision avoidance warning signal (cf. [56] and [93]).

Finally and again unlike many other practical domains, drivers are thought to be unwilling to attach anything to their bodies before getting into their vehicles. This means that tactile vests (cf. [50]) are out. Instead, researchers need to focus on the delivery of tactile stimuli via those surfaces of the car that the driver is already in contact with. In practice, this means that tactile stimuli can only be delivered to the driver's seat or seatbelt [38], [39], [56], via the footpedals [48], via the steering wheel (e.g., [77] and [93]), or via tactile feedback from any in-car device (or information system) that incorporates some kind of touch technology (see [59]; think only of the Immersion/BMW iDrive [17]).

Given the various costs and benefits associated with the use of tactile displays, what progress has so far actually been made in the successful design of tactile displays for drivers? Well, there are currently a number of potential uses for tactile displays in vehicular settings:

1. to arouse or awaken drowsy drivers (see [82]),
2. to alert drivers to impending danger and orient their attention using directional spatial tactile cues (see [44], [38], [39], and [78]),
3. to present more detailed information to drivers, such as navigational information [102], and
4. to reduce driver workload when interacting with in-vehicle devices by providing tactile feedback concerning a driver's actions (see [59]).

We look at the evidence concerning each of these potential applications in the sections that follow.

3 Awakening the Drowsy Driver

Perhaps the most successful commercial implementation of a tactile display in vehicles to date has come from their use in warning drivers when they cross a lane boundary. For example, in 2004, Citroën started to offer a Lane Departure Warning System (LDWS) as an optional extra in its C4 hatchback and C5 saloon cars (see [52] and [82]). This device was designed to alert potentially drowsy drivers by vibrating their buttocks should they happen to cross a lane boundary too slowly, given that such boundary crossings are likely to occur when a driver is about to fall asleep at the wheel. It has been estimated that up to a third of all crashes are caused by drivers falling asleep at the wheel, thus making drowsiness one of the leading causes of vehicular accidents (see [70]). The vibrotactile warnings implemented in these LDWSs are spatially informative in the sense that if the car veers to the right, then the right side of the seat base vibrates and vice versa when the car veers off to the left (i.e., in some sense mimicking the effect of edge-of-carriageway rumble strips; see also [63]). These tactile warning signals are typically only presented when the driver fails to indicate while travelling at speeds in excess of 50 mph.

The results of a driving simulator study conducted on 24 experienced drivers [93] showed that the vibration of the steering wheel can also be used to warn drivers about lane-departure situations. Vibrating the steering wheel, or delivering a pulselike steering torque warning signal to the steering wheel (see also [77]), was found to be more effective than an auditory tonal alert (either monaural or stereo) under conditions where the drivers had not been informed in advance about the meaning of the warning signals. In fact, the drivers reacted more than half a second faster following either the vibrating or torque warning signals than following either one of the auditory alerts when the warnings were not expected. By contrast, response latencies were pretty much identical once the participants knew the meaning of the upcoming warning signals. However, the vibrating steering wheel also resulted in the smallest lateral deviation of the driven vehicle,[3] leading Suzuki and Jansson to argue that it represented a particularly effective form of tactile LDWS. They postulated that their drivers may have "intuitively" understood (or have had an internal "mental model" in their terminology) the vibration of the steering wheel as signifying that the driven vehicle was deviating from the lane (see earlier discussion).

It would be particularly interesting in future research to compare the effectiveness of the directional seat vibrations currently incorporated in commercial vehicles with the vibration of the steering wheel warning signal tested in Suzuki and Jansson's [93] study. It would also be worth investigating whether the combined presentation of both of these tactile cues at the same time would lead to any enhancement of driver performance over and above that delivered by the best of the individual warning signals (cf. [72]). Finally, it would be interesting to compare these tactile warning signals with the visual and/or auditory lane departure warning signals currently in use in other vehicles (see [82]).

4 Capturing the Attention of the Distracted Driver

A second area where there has been growing interest in the development of tactile warning signals in recent years relates to the development of intelligent collision warning systems, in particular those systems designed to help drivers avoid front-to-rear-end (FTRE) collisions (e.g., [44], [38], [56], and [98]). FTRE collisions represent one of the most common causes of vehicular accidents among drivers (see [21]), and their incidence is particularly high among drivers who are distracted, such as those who use their mobile phone while driving (see [42] and [71]).

A recent series of experiments conducted in this laboratory demonstrated that spatial tactile warning signals can provide an effective means of warning drivers about an impending FTRE collision (see [42] for a review). In our original laboratory-based research [44], participants watched a video showing a car on the road ahead and another car in the rearview mirror. Participants had to depress the brake pedal whenever the lead car suddenly braked or accelerate whenever the trailing car suddenly accelerated. Spatially predictive vibrotactile warning signals were presented from the same direction as these

3. Note that a number of the participants actually reacted to the unexpected presentation of the steering torque warning signal by turning the steering wheel in the wrong direction.

"critical" driving events on 80 percent of the trials (i.e., the participant's stomach was vibrated if the lead car suddenly decelerated, while their back was vibrated if the trailing car accelerated) and from the invalid (i.e., opposite) direction on the remaining 20 percent of trials. Our results showed that participants responded approximately 66 ms faster (and somewhat more accurately) following the presentation of a directionally appropriate tactile cue than following the presentation of a spatially invalid cue.

Interestingly, the results of a second experiment showed that the magnitude of these vibrotactile cueing effects (i.e., the improved performance seen on trials where the warning signal came from the same direction as the visual driving event than when the warning signal was presented from the opposite, i.e., invalid, direction) were only slightly (but not significantly) reduced when the tactile cues were made spatially uninformative with regard to the location of the critical driving event (i.e., under conditions where the warning signal was just as likely to be presented from the participant's stomach as from their back, regardless of where the event occurred on the roadway). This latter result supports the view that tactile warning signals capture attention exogenously (and not just endogenously; see [108]). That is, participants' attention was captured by the stimulus itself, rather than necessarily by the informative content of that warning signal. It should, however, be noted that the presentation of the spatially informative vibrotactile cues in Ho et al.'s [44] study, while giving rise to a significant improvement in both the speed and accuracy of participants' braking responses, was still not quite as effective as the presentation of a spatially informative auditory icon (the sound of a car horn) examined by Ho and Spence [41] (see [45]).

Subsequent research has shed some light on the reasons behind this difference in the effectiveness of tactile and auditory spatial warning signals. While both the vibration of the driver's waist and the presentation of a car horn sound from the front carry useful spatial information, only the sound of the car horn (an auditory icon) carries an "intuitive" semantic meaning and hence can, perhaps, be understood more readily. However, an equally important reason why tactile cues are somewhat less effective in this setting is that touch is a proximal sense (i.e., we only experience touch when delivered to the body surface itself, though see [20] for evidence that tactile stimuli can also lead to distal attribution under certain conditions). We believe that tactile warning signals will tend to draw a driver's attention to their peripersonal space (i.e., to the space around the driver's body in the car itself [45]). By contrast, audition and vision are distal senses, capable of informing us both about events that are close at hand and about events occurring farther away (see [67]). Consequently, auditory and visual signals have a greater capacity to direct a driver's attention to the region of extrapersonal space outside the car where critical driving events are likely to take place (see [42] and [45]; cf. [68]). Research suggests that extrapersonal warning signals may be more efficient at directing a driver's attention to the extrapersonal space outside the vehicle than tactile signals (see [42]).

Ho et al. [38] conducted a study in a high-fidelity driving simulator. In this study, drivers had to follow a lead vehicle around an urban road layout while keeping a fixed distance from the lead vehicle. The participants monitored an in-car visual display that informed them whether they were travelling at the right distance from the lead vehicle or not. This display was designed to mimic the attentional demands of a typical piece of in-car technology (or in-vehicle information system) such as a satellite navigation (SatNav) system (see [1]). The lead vehicle would periodically brake, and the participants had to brake in order to avoid a potential FTRE collision. Ho et al. compared participants' braking responses on those trials where no warning signal was presented (i.e., the typical situation in the majority of cars today) to that seen when a vibrotactile warning signal was presented at the moment that the lead vehicle started to decelerate. The presentation of the tactile warning signal from the appropriate direction (i.e., on the participant's stomach) led to a significant improvement in participants' braking responses of more than 400 ms.

One potentially important limitation with regards to the practical implications of this research concerns the fact that the vibrotactile warning signals were presented as soon as the lead vehicle started to brake. Presumably, however, any actual in-car collision avoidance system would take a certain amount of time to detect the braking of the lead vehicle and to determine whether or not to present a tactile warning signal (see [10] and [42]). It will therefore be an interesting question for future research to determine just how effective vibrotactile collision avoidance warning signals are when they are presented at varying delays after the onset of braking by a lead vehicle (see [37], [57], and [78]).

To date, the majority of research on tactile FTRE collision warnings has considered the delivery of abrupt single-stage warning signals. However, simulator research conducted by Lee et al. [56] has shown that graded tactile warning signals may in fact be preferable under certain circumstances. Their research suggested that drivers trust graded tactile warning signals (where the intensity and frequency of the seat vibration increased as the warning level became more severe) more than single-stage abrupt warnings. Lee et al. also found that graded warning signals were perceived as less annoying and more appropriate than single-stage warnings. Finally, graded tactile warnings led to greater safety margins and to a lower incidence of inappropriate responses to nuisance warnings in this simulator study.

Ho et al. [39] reported a driving simulator study that highlighted the potential benefit associated with multisensory warning signals. The study involved the presentation of multisensory warning signals (consisting of auditory and tactile warning signals presented simultaneously from the same direction) as compared to conditions when the auditory warnings and tactile warnings were presented alone. The effectiveness of these warning signals in improving a driver's responses to potential FTRE collisions was assessed. When taken together, the results of Ho et al.'s research suggest that the presentation of multisensory warning signals can lead to an improvement in a driver's braking responses of as much as 600 ms (see [86]). This compares very favorably with the 500-ms reduction in braking reaction times (RTs) that Suetomi and Kido [92] estimated would be sufficient to lead to a 60 percent reduction in FTRE collisions (the most common form of car accident, especially among distracted drivers). Of course, further research will be needed, given that the warning signals were presented far more frequently in Ho and her colleagues laboratory- and simulator-based work (approximately once every minute on average) than would be expected in any realistic situation (cf. [58]): Researchers will need to confirm that the benefits in braking RTs documented thus far hold up under more realistic warning signal presentation schedules (cf. [42], [100], and [101]). It will also be important to assess the effect of different levels of false alarms given the "cry wolf" phenomenon (cf. [4]).

One final concern here relates to the issue of risk compensation [22]. As has been seen previously in the case of the introduction of other safety technologies in vehicles, initial safety gains can sometimes be offset by the apparent risk compensation that many drivers engage in [106] (though see [54]). That is, it seems as though many drivers actually try to maintain a certain acceptable perceived level of risk. In the present context, the danger might be that the drivers of vehicles fitted with such multisensory collision avoidance warning signals would simply take their eyes off the road more often (perhaps to check their email or SatNav), "safe" in the knowledge that their in-car technology will (or at least should) alert them should they need to return their attention to the road ahead!

5 Reducing the Workload of the Overloaded Driver

Van Erp and Van Veen [102] reported a study in which they investigated whether it would be possible to present navigational information to car drivers via the sense of touch, via a visual display, or by the combined use of vision and touch. Navigational messages consisting of the distance to the next waypoint and the direction (left/right) to turn were presented to experienced drivers in a driving simulator setting. The transfer of information was achieved via tactors embedded in the driver's seat (tactile) or visually via simple symbols displayed on a contemporary in-car navigation display. While tactile information was presented to the driver's thigh, visual information was presented from a display situated away from the driver's body (i.e., the visual and tactile information were presented from very different spatial positions—they were not colocalized; see [42]). Van Erp and van Veen found that drivers responded rapidly following navigational messages presented in a bimodal (tactile and visual) display than when the messages were presented unimodally. However, the lowest subjective mental workload ratings occurred in the touch-only condition, as compared to when the drivers used the visual-only or bimodal (i.e., multisensory) displays.

Meanwhile, Lee and Spence [59] recently conducted a study in which drivers had to avoid potential accidents on the roadway ahead while at the same time trying to operate a touch-screen device (a mobile phone). The results showed that drivers reacted more rapidly to the movements of the car in front when given trimodal feedback (consisting of tactile feedback from the touch screen, together with visual feedback from the screen and auditory feedback from a loudspeaker placed just behind the screen, i.e., when all feedback was presented from the *same* spatial location) than when given either unimodal visual or bimodal (visuotactile or audiovisual) feedback in response to their button presses. The participants also rated their subjective mental workload as being significantly lower (as measured by the NASA-TLX) in the multisensory feedback condition as compared to the unimodal feedback condition (see also [15]).

Surprisingly, many of the applied studies published to date have failed to demonstrate any particular benefit of multisensory over unisensory tactile information displays or warning signals (e.g., [24], [57], and [102]). It is critical to note, however, that the various unisensory components of the multisensory signals used in these studies were always presented from different locations. Cognitive neuroscience research suggests that such conditions can actually lead to multisensory suppression rather than multisensory facilitation (see [91] for a review). It is particularly interesting that those studies that have demonstrated a significant advantage of multisensory over unisensory tactile displays, showing that multisensory displays and warning signals can significantly reduce both braking latencies [39] and subjective workload [59], presented the stimuli from the different sensory modalities from the *same* direction or position in space.

Santangelo et al. [72] recently manipulated the spatial correspondence of the auditory and tactile components of warning signals (or cues). They observed multisensory facilitation *only* when both the auditory and tactile cues came from the same direction (either on the left or on the right) but not when one signal was presented from the side while the other signal was presented from straight ahead. These findings highlight the potential importance of spatial correspondence for multisensory interface design (see also [83] and [89]). Santangelo et al. argued that it might be sufficient for the unisensory components of a multisensory warning signal to be presented from the same direction, not necessarily from the same location, to give rise to multisensory facilitation effects [42].

6 Advanced Tactile Information Displays for Drivers

Given that tactile and/or multisensory displays for drivers appear to be here to stay, one might ask what the future holds for in-vehicle display design. One important issue here relates to the limitations on information transfer via the skin. That is, just how much information can be transmitted to the "visually overloaded" driver (see [87]) by means of tactile, auditory, and/or multisensory displays? While there have been some interesting developments in this area recently (e.g., see [34], [50], and [107]), research from our laboratory has shown that at least in the absence of prolonged training (once again, not a practical option for normal drivers), tactile information processing across the body surface is quite limited (see [27] for a recent review). For example, without extensive training, people simply cannot count more than two or three tactile stimuli when presented simultaneously across their body surface (or hands; see [25] and [28]). What is more, the sudden presentation of a visual (or, for that matter, tactile) stimulus can also make people effectively "blind" to any changes taking place in the pattern of tactile stimulation presented across their body (or hands; see [26], [29], [2], and [3]). Even unambiguous directional tactile signals (such as those elicited by the movement of a tactile stimulus across the skin) can be overridden by the simultaneous presentation of visual or auditory stimuli if they happen to be moving in a different direction [61].

Given these fairly severe limitations on tactile (and, more importantly, multisensory) information processing (see [85], for a review), we remain unconvinced of the utility of complex tactile displays (at least for use in a vehicular setting),[4] as was perhaps envisioned in the early days when researchers discussed such possibilities as "tactile television" [16] and the possibility of businessmen and women soon receiving the latest stock market figures from an array of vibrating stimulators around their waists (see [35]). That said, some researchers have recently started to report that meaningful tactile icons can be used to convey more complex information to an interface operator, when they had been given sufficient training (see also [13], [60], [62], and [96]).

7 Warning Signals for the Aging Driver

Older drivers now constitute the most rapidly growing section of the driving population (see [104]). In fact, it has been estimated that there will be more than a billion people over the age of 60 years by 2020 [86]. This is particularly worrying given the significant increased accident risk in drivers once they reach the age of 55 years. We believe that ergonomists will therefore need to start focusing more of their research efforts on the design of multisensory interfaces targeted specifically at the elderly driver. One recent finding that holds particular promise with regard to the slowing of responses that is often seen in elderly drivers comes from the work of Laurienti et al. [53]. They found that while elderly participants (mean age of 71 years) responded to auditory and visual targets significantly more slowly than did a group of younger participants (mean age of 28 years), they were nevertheless able to respond to multisensory targets (consisting of the simultaneous presentation of the auditory and visual targets) as rapidly as the younger participants responded to either of the unimodal targets. Laurienti et al.'s results therefore suggest that multisensory warning signals and displays may represent a particularly effective means of supporting safe driving in older drivers. Given the findings reported earlier [39] (see also [73]), it will be particularly interesting to determine whether older drivers also benefit more from the presentation of spatially colocalized audiotactile warning signals.

8 Conclusions and Questions for Future Research

In this brief review of the literature on tactile and multisensory interface design, we have tried to highlight the relevance of the latest cognitive neuroscience research to contemporary interface design, in particular as it related to the design of in-vehicle warning signals and information displays. We are convinced that developments in the field of cognitive neuroscience, particularly those related to the topic of attention, will have an increasingly important impact on the design of multimodal (or multisensory) interfaces in the next few years (e.g., [23] and [83]). In fact, the first cognitive neuroscience-inspired design principles for interface, and warning signal, design are already upon us [42], [68], [87] (cf. [76] and [90]).

That said, it is also clear that much more research will be needed in order to better understand the potential trade-off between graded warning signals (which may be less annoying but at the same time less immediate than abrupt onset signals) and the fast reactions that are typically required in response to such warning signals. Additionally, given the specific constraints of the commercial vehicular setting, another important question concerns whether more "intuitive" tactile icons can be developed that somehow convey their meaning without the need for extensive training (one limitation of working with tactile displays for regular road users). One way to achieve this might be through the incorporation of everyday affordances into the design of the tactile stimulus itself. However, future research will also need to assess the extent to which the whole-body vibration experienced by drivers on the road will interfere with their ability to process tactile displays/warning signals. More information is also needed regarding how the issue of compliance versus reliance (see [18]), or the "cry wolf" phenomenon (associated with the presentation of signals that are perceived as false alarms [6]), influences the effectiveness of tactile and/or multisensory warning signals.

Having discovered which signals work most effectively when presented both with a high reliability and very frequently in the driving simulator research outlined here, we need to follow up with additional research to ensure that those signals still deliver genuine performance/safety benefits to drivers when they are not always reliable [4] and when they are presented infrequently (as would be the case for any actual in-car warning system). Given the very limited number of on-road studies that have involved the presentation of tactile or multisensory warning signals, this will also be another area for future research. However, one should not forget the potential ethical implications of what would happen should a participant/driver have an accident while on the road in such a study. Given that it is currently unclear who would be responsible in such a situation, researchers have argued that high-fidelity simulator studies may currently offer the best and most appropriate environment in which to evaluate any new tactile or multisensory driver technology [42].

One other final important research area concerns the presentation of multisensory (i.e., audiotactile and/or audiovisual) warning signals and information displays. However, further research is needed to determine whether there may be certain regions of the body (or certain regions of the space surrounding the body) where tactile/multisensory warning signals are especially effective (see [42], [68], and [88]). The latest research suggests that audiotactile multisensory interactions are qualitatively different in the region close to the back of the head than they are elsewhere (see, e.g., [51]). However, currently, we do not know whether these findings (from the cognitive neuroscience research laboratory) also predict how people will respond in a more applied setting (is it the case, for example, that the space

4. See Jones and Sarter [49] and Nagel et al. [66] for exciting developments in other domains of tactile interface design where the extensive training of participants does not represent such a problem.

immediately behind a driver's head is also dealt with in a special way while they are driving?). Researchers will also need to determine just how important spatial coincidence and temporal synchrony of the individual sensory signals are to determining the effectiveness of real-world multisensory displays. Just how similar does the position/direction from which unisensory stimuli are presented need to be in order to deliver significant benefits from the utilization of a multisensory warning signal? It is still an open question as to whether it might (counterintuitively) be the case that slightly desynchronized multisensory warning signals are actually more effective than synchronized ones (see [14] and [84] on this issue). Finally, more research is needed to determine how to design tactile (and multisensory) warning signals that can help the growing population of aging drivers to drive safely.

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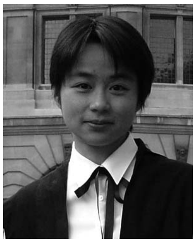

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