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Tactile warning signals for in-vehicle systems

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ABSTRACT

The last few years have seen growing interest in the design of tactile warning signals to direct driver attention to potentially dangerous road situations (e.g. an impending crash) so that they can initiate an avoidance maneuver in a timely manner. In this review, we highlight the potential uses of such warning signals for future collision warning systems and compare them with more traditional visual and auditory warnings. Basic tactile warning signals are capable of promoting driver alertness, which has been demonstrated to be beneficial for forward collision avoidance (when compared to a no warning baseline condition). However, beyond their basic alerting function, directional tactile warning signals are now increasingly being utilized to shift the attention of the driver toward locations of interest, and thus to further facilitate their speeded responses to potential collision events. Currently, many researchers are focusing their efforts on the development of meaningful (iconic) tactile warning signals. For instance, dynamic tactile warnings (varying in their intensity and/or location) can potentially be used to convey meaningful information to drivers. Finally, we highlight the future research that will be needed in order to explore how to present multiple directional warnings using dynamic tactile cues, thus forming an integrated collision avoidance system for future in-vehicle use.

1. Introduction

Over the last decade or two, there has been a rapid growth of interest in the development of collision avoidance systems (CASs) designed to direct a driver's attention to an impending crash so that they can initiate an avoidance maneuver in a manner that is both timely and appropriate (Dingus et al., 1997; Fitch et al., 2011 see Campbell et al., 2007, for a review). The hope is that the various components of CASs, such as forward collision warning systems (FCWSs), lane departure warning systems (LDWSs), blind spot detection systems (BSDSs), and lane changing warning systems (LCWSs), will help to prevent a substantial number of rear-end collisions, roadway departures, and crashes attributable to drivers changing lanes inappropriately (see Kim et al., 2010; Fitch et al., 2011). Such systems may, in the future, present a viable solution to help significantly reduce the number and severity of collisions on our roads (e.g. see Yonas et al., 1977; Kiefer et al., 1999; Tijerina et al., 2000).

One important question that has arisen in the design of CASs concerns the optimal means of presenting a collision warning signal to the driver (Kaufmann et al., 2008; Mohebbi et al., 2009; Fitch et al., 2011). While related research has demonstrated the potential benefits associated with the presentation of visual, auditory, tactile, and even multisensory warning signals in terms of alerting the driver and rapidly orienting their spatial attention in the direction of potential danger (for a review, see Spence and Ho, 2008a; Ho and Spence, 2013; Haas and Van Erp, 2014; see also Lee et al., 2002, 2004; Ho et al., 2005a,c; Spence and Ho, 2008b,c; Gray, 2011,b; Baldwin et al., 2012a,b; Liu and Jhuang, 2012), research interest in the utilization of tactile warning signals in vehicles has only really emerged more recently (e.g. see Gallace and Spence, 2014; Spence and Ho, 2008a).

The sense of touch (on our body surface) compromises those sensations elicited by the stimulation of the skin, such as pressure, temperature, pain, and vibration (Deatherage, 1972; Gemperle et al., 2003; McGlone and Spence, 2010). Embedded within our skin are many different classes of sensory receptors, each capable of receiving (or transducing) different kinds of sensory inputs (Geldard, 1957). The majority of the tactile warning signals covered in this review involve only a small number of tactile receptors for vibration presented by stimulators capable of stimulating various body surfaces (also including the force feedback from foot pedals) or else torque delivered by the jerking of the steering wheel. Knowledge concerning how to communicate information via the

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skin is still, relatively-speaking, fairly limited, at least when compared to what is known about visual or auditory communication (e.g. Geldard, 1957; Lerner, 1996). However, several commercial tactile warning systems are already available in the marketplace, for example, the LDWS in certain models of Citroen and BMW cars (Spence and Ho, 2008a) and a pre-collision advanced vehicle safety management (AVSM) in Kia cars (see López, 2012). We are therefore now starting to see a transition from tactile stimulation as an optional extra to it becoming a standard feature on at least certain models of car.

Therefore, a critical review of what is currently known in terms of the design of tactile warning signals for safe driving may help to highlight a number of potentially important implications for the future design of in-vehicle tactile warnings. This review starts by discussing visual, auditory, tactile, and even olfactory warning signals, before highlighting the potential promise as well as the limitations inherent in the implementation of various types of in-vehicle tactile warning displays. In the sections that follow, we attempt to classify the literature on tactile warning signals. Specifically, a distinction is made between non-directional tactile warnings (basic tactile alerts), directional tactile warnings, and meaningful tactile warnings. Finally, we conclude by highlighting what we see as the most pressing questions that will need to be addressed by future research in this area, specifically related to resolving the challenges associated with the implementation of multi-tactile alert systems.

2. Do tactile cues provide a good solution (modality) for in-vehicle warnings?

Previously, visual and auditory warnings have been trialed extensively in the design of CASs (e.g. Ben-Yaacov et al., 2002; Shinar and Schechtman, 2002; Lee et al., 2004 Scott and Gray, 2008; Bueno et al., 2013). A few researchers have even considered the possibility of using olfactory warnings (Baron and Kalsher, 1998; Ho and Spence, 2005; Raudenbush et al., 2005; Schuler and Raudenbush, 2005 see Spence and Ho, 2008c, for a review). For instance, Grayhem et al. reported that the presentation of both cinnamon and peppermint odour led to improved alertness while driving (Grayhem et al., 2005). Meanwhile, others have reported that 'unpleasant' smells, such as (synthetic) body odour, might be even more effective in terms of alerting people than pleasant odours (Chen et al., 2006). Such results would appear to hint at the promise of olfactory cues as a novel and potentially subtle means of keeping the drowsy driver alert (Baron and Kalsher, 1998; Schuler and Raudenbush, 2005; Spence and Ho, 2008c; Susami et al., 2011). Ambient odours (no matter whether they are pleasant or unpleasant) can also be used to reduce people's reaction times (RTs) to visual or auditory stimuli (e.g. Millot et al., 2002), and give rise to an increased accuracy of responding to tactile stimuli (Ho and Spence, 2005). However, given the fact that olfactory stimuli are difficult to perceive in a timely manner, at least when compared to visual, auditory, or even tactile cues (Spence and Squire, 2003), they do not really represent a plausible alternative for time-critical collision avoidance situations. Hence, olfactory warning signals will not be elaborated on further within the scope of the present review.

As shown in Table 1, visual warning signals are typically relatively straightforward and can be used to convey various signals by including symbolic information and colour (or colour change; Laughery et al., 1993; Braun and Silver, 1995; Baldwin et al., 2012a,b). However, as a complicated sensorimotor task, driving undoubtedly involves a relatively high visual workload (Senders et al., 1967; Chun et al., 2013). Indeed, it has been estimated that as much as 95% of the information received while driving is identified visually (Shinar and Schieber, 1991 though also see Sivak, 1996 and Spence and Ho 2008b, for a critical assessment of the empirical evidence in support of this particular statistic). Visual warnings may therefore be expected to have to compete for access to the visual resources required for effective vehicular control (Horberry et al., 2006; Scott and Gray, 2008). More worrying still is the fact that the drivers are likely to miss visual warnings when driving (Hirst and Graham, 1997; Fitch et al., 2007) or when distracted by a secondary visual task in vehicle, such as operating the entertainment system, checking email, or dealing with navigation messages (Ashley, 2001; Harms and Patten, 2003; Horberry et al., 2006; Clark, 2013). These practical limitations mean that visual warnings run the risk of becoming ineffective in terms of increasing the margin of safety for the driver.

As audition is considered to be intimately connected with the brain's arousal and activation systems, auditory warnings usually produce faster responses than do visual warnings (see Jones and Furner, 1989). Additionally, verbal warnings, as one class of auditory warning signal, can undoubtedly also convey spatial

Table 1
The comparison among olfactory, visual, auditory and tactile warnings for in-vehicle warning systems.

Modality	Advantages	Disadvantages
Olfactory	• Improving alertness while driving • Reducing reaction times to visual or auditory stimuli	• Not suitable for time-critical collision avoidance situations
Visual	• Straightforward means of conveying information	• Competing with the visual resources for vehicle control • Can easily be missed while driving
Auditory	• Easy to convey spatial information by verbal signals • Perception of auditory stimuli is "gaze-free"	• To be easily masked by background noise or be interfered with by secondary tasks • Can be difficult to localize the spatial direction from which auditory warning signals presented • Some drivers suffer from a hearing impairment • The phenomenon of "inattentional deafness"
Tactile	• Less central to driving • Its utilization not expected to increase visual or auditory workload • Less interfered with by secondary tasks while driving	• Can only be delivered from seat, pedal and seat belt • Some drivers use only one hand while driving, thick clothing/gloves, not to mention in-vehicle vibration might impair effectiveness • The phenomenon of "change numbness"