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Responses to visual, tactile and visual–tactile forward collision warnings while gaze on and off the road

Jani Lylykangas [a,*], Veikko Surakka [a], Katri Salminen [a], Ahmed Farooq [b], Roope Raisamo [b]

[a] Research Group for Emotions, Sociality, and Computing (ESC), Tampere Unit for Computer-Human Interaction (TAUCHI), School of Information Sciences, University of Tampere, Finland

[b] Multimodal Interaction Research Group (MMIG), Tampere Unit for Computer-Human Interaction (TAUCHI), School of Information Sciences, University of Tampere, Finland

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ABSTRACT

The objective of the current driving simulator study ($N = 20$) was to assess brake reaction time (BRT) and subjective experiences of visual (V), tactile (T), and visual–tactile (VT) collision warnings when the drivers' visual orientation was manipulated between four locations (i.e., road and three different mirror locations). V warning was a blinking light in a windscreen, T warning was implemented by a vibrating accelerator pedal, and VT warning was their synchronous combination. The results showed that all the warning stimuli were detected in 100% accuracy in all visual orientations, but T and VT warnings produced significantly faster BRTs when compared to V warning. It was found that BRT to V warning was the slowest while observing the furthermost side mirror. However, BRTs following T and VT warnings remained unaffected by the visual orientations. Both the objective BRT measurements and subjective evaluations indicated a superiority of T and VT warnings against a sole V warning, not only in general terms, but also separately for different visual orientations.

1. Introduction

Forward collision warning (FCW) systems have been developed to prevent and reduce the seriousness of front-to-end crashes typically caused by inattentive driving and insufficient safe-headway (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). The warnings are designed to alert the driver in advance to facilitate response times to apply brakes and/or make evasive steering maneuvers. Even though the usefulness of the FCW system as such may be evident, it is not fully clear what is the most efficient way to deliver this information so that it is accurately detected and results in fast actions of the driver to avoid the potential accident (Spence & Ho, 2008).

FCW stimulation is of critical importance especially when a driver's attention is off the road scene ahead. Although there are visual FWC stimulus systems, the stimuli are typically presented in front of the driver. Following this the warnings can go unnoticed when looking at a mirror because the stimulation is in the periphery of the visual field. Even when noticed, visual stimulus in peripheral vision can be responded slower than when seen in the foveal vision (e.g., Brebner & Welford, 1980; Strasburger, Rentschler, & Jüttner, 2011).

* Corresponding author at: Research group for Emotions, Sociality, and Computing (ESC), Tampere Unit for Computer-Human Interaction (TAUCHI), School of Information Sciences, University of Tampere, Kanslerinrinne 1, 33014 Tampere, Finland. Tel.: +358 50 318 6832.

E-mail address: jani.lylykangas@uta.fi (J. Lylykangas).

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Therefore, visual FCW is typically complemented with auditory warning signal. The advantage is that auditory warning can be perceived regardless of the driver's visual orientation. Response times have also found to be inherently faster to auditory than visual stimuli (Brebner & Welford, 1980). However, similarly to visual stimuli, the efficiency of auditory warning depends on the state of the driver's situational awareness. For example, engaging secondary tasks such as a problem-solving assignment or phone conversation have been found to significantly slow down response times to a warning sound (Bueno, Fabrigoule, Ndiaye, & Fort, 2014; Mohebbi, Gray, & Tan, 2009). In the other extreme, auditory warnings can become totally useless due to hearing impairments.

Utilizing the human sense of touch (i.e., haptic modality) as a communication channel can be a functional alternative to visual and auditory modalities when the ability to process sensory information is reduced, for example, due to ageing, physical impairment, or situation (Raisamo et al., 2009). Previous research has shown that tactile stimulation (e.g., vibration) would be a potential modality to be used in FCW (e.g., Spence & Ho, 2008). One advantage found in driving simulator studies is the faster response time to tactile stimulation compared to visual stimulation (e.g., De Rosario et al., 2010; Scott & Gray, 2008). There is also evidence that in comparison to auditory stimuli, response times to tactile stimuli are less affected by driver distraction (Mohebbi et al., 2009). However, to date tactile FCWs have not been used in vehicles as frequently as visual and auditory FCWs.

In order to enhance the efficiency of warning signals, investigating a stimulus–response (S–R) compatibility between the warning and its expected consequence is of essence (e.g., De Rosario et al., 2010; Wang, Proctor, & Pick, 2003). S–R compatibility has been long studied in psychology, and in general it refers to the fact that some S–R pairings are easier to use than others (Umiltá & Nicoletti, 1990). High level S–R connection has been shown to facilitate speed and accuracy of a performed task in comparison to those with lower level S–R connection.

More specifically, a spatial type of S–R compatibility occurs when the position of the stimulus indicates the position of the required response (Umiltá & Nicoletti, 1990). According to this, visual FCW implemented by a head-up display (HUD) in a windscreen (e.g., Lind, 2007) would appear to have a high spatial S–R compatibility by orienting a driver's vision toward the direction of a threat. Visual orienting to unexpectedly occurring salient cue such as blinking warning light is reflexive by its nature and, thus, it happens automatically and can be resilient to other concurrent visual information (Jonides, 1981; Müller & Rabbitt, 1989). Following this analogy, FCW presented down in a cluster panel, for example, would be spatially incompatible by prompting the driver's attention toward an inappropriate location in respect to the threatening event. Evidence pro this was reported by Lind (2007) who found that the HUD warning had the highest detection rate, resulted in shortest brake response time, and was also the most preferred in comparison to other visual warnings located either in cluster panel or steering wheel. So, when studying visual FCWs it seems that HUD would be a rational starting point to be adopted in the experimental design.

Tactile stimulation and motor response can also have high spatial compatibility as exemplified by an automatic reaction to quickly withdraw a limb away from unexpected touch sensation such as static electricity shock. Regarding an FCW provided in tactile modality the spatially congruent S–R association would suggest that stimulation should be presented to the body location that is primarily required for the response (De Rosario et al., 2010). Right foot is typically used for the accelerator and brake pedals and hence it would seem rational to stimulate that area for an FCW. As compared to vibrational warnings applied by waist belt (e.g., Scott & Gray, 2008), seat (e.g., Higuchi & Raksincharoensak, 2010), or steering wheel (e.g., Chun et al., 2012), a vibrating accelerator pedal would seem to have a stronger S–R compatibility. This is because apart from a sole attentional alarming effect it may also result in motor preparation for a quick release of the foot from the vibrating accelerator and applying brakes (Scott & Gray, 2008).

Another central factor that affects to the detection of warning signals relates to the focus of attention. The drivers' visual attention is concentrated diversely between on the road scene and other locations both inside and outside the vehicle. As mentioned earlier, this behavior makes the perceptivity of visual warnings highly dependent on the situation. Additionally, there is evidence that gaze direction can influence the perception of tactile stimuli as well. For example, reaction time to tactile stimulation has been found to be faster when looking toward than away from the stimulated body site (e.g., Lloyd, Bolanowski, Howard, & McGlone, 1999; see also Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002 for contradictory results). Nevertheless, the effect of variation in the visual focus (gaze on vs. off the road) to a perception time of visual and tactile FCWs has not been systematically investigated. Ho, Gray, and Spence (2014) found that response time to vibrotactile warning signal applied in the waist was significantly faster when looking forward than when head was turned either left or right for looking back. However, possible differences in the actual perception times between the head position conditions remained unclear. This is because the longer response time in the head turn conditions probably cumulated due to an additional visual discrimination task and the fact that the participants had to turn their head forward before giving the response, whereas neither of these tasks was involved in the forward looking condition.

Including concurrently presented bimodal visual–tactile warning becomes highly reasonable in the light of earlier laboratory studies showing proof on behalf of a facilitation effect known as multisensory enhancement (Diederich & Colonius, 2004). It has been found that multimodal stimuli can produce faster reaction times than unimodal stimuli (e.g., Burke et al., 2006; Diederich & Colonius, 2004; Forster et al., 2002; Higuchi & Raksincharoensak, 2010), which would naturally be an advantageous feature for an imminent warning signal such as FCW. However, possible sensorimotor facilitation effects of visual–tactile warnings in the varying driving conditions are still largely unstudied.

In summary, the earlier studies indicate the potential of tactile warning modality either alone or when combined with visual and/or auditory modalities (e.g., Spence & Ho, 2008). Touch-based stimulation seems to be especially advantageous when participants are exposed to some type of distraction (e.g., Bueno et al., 2014; Mohebbi et al., 2009). A large body of