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

Jani Lylykangas[1*], Veikko Surakka[1], Katri Salminen[1], Ahmed Farooq[2], Roope Raisamo[2]

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

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.

Keywords

Forward collision warning
Visual orientation
Visual stimulation
Vibrotactile stimulation
Perception
Brake reaction time

---

* 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).

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 et al., 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).

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 et al., 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 and Ho, 2008). One advantage found in driving simulator studies is the faster response time to tactile stimulation compared to visual stimulation (e.g., Scott & Gray, 2008; De Rosario et al., 2010). 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., Wang, Proctor, & Pick, 2003; De Rosario et al. 2010). 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 towards 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 towards 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 towards than away from the stimulated body site (e.g., Lloyd, Bolanowski, Howard, & McGlone, 1999;

see also Forster, Cavina-Pratesi, Aglioti, & Berlucci, 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, & 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; Forster et al., 2002; Diederich & Colonius, 2004; 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 literature shows that the reaction time to visual stimuli perceived in peripheral vision is impaired (e.g., Strasburger et al., 2011) but the relationship between gaze direction and the perception of tactile stimulation seems to be more ambiguous (e.g., Lloyd et al., 1999; Forster et al., 2002). In addition, high-level S-R compatibility (e.g., Umiltá & Nicoletti, 1990) as well as multisensory enhancement effect of the stimulations (e.g., Diederich & Colonius, 2004) have been shown to facilitate reaction times. Empirical evidence on these isolated effects as a whole, however, appears relatively scarce in the context of FCW systems for the present.

The objective of this study was to assess perception of visual, tactile, and visual-tactile FCWs when the drivers' visual orientation was not distracted (i.e., observing road scene ahead) and while being distracted (i.e., observing mirrors). In order to concentrate purely in quantifying perception time of the warnings in the varying visual orientations, simple reaction time measurement was adopted as an independent variable in terms of brake response time (BRT) defined in Society of Automotive Engineers (SAE) Recommended Practice J2944 (2012).

In addition to the objective BRT measurements, also subjective experiences reflecting, for example, the S-R compatibility of the warning stimuli were investigated separately for each visual orientation. Rating scales inquired self-assessed speed of the braking reaction and assessments of the pleasantness, perceptivity, and effectiveness of the warning stimuli. Rankings and general opinions of the different FCWs were collected in a post-experimental interview. At first sight, pleasantness and preference may seem rather irrelevant features for a high priority emergency alert such as FCW. At the same time, however, overly annoying warning systems come with a risk of being rejected or disabled by the users, and therefore, a trade-off between pleasantness and urgency of the warning should also be taken into consideration (Wiese & Lee, 2004). For example, the vibrating waist belt warning in Scott & Gray (2008) turned out to be efficient in terms of response time, but at the same time 37.5% of the participants preferred it least (in comparison to visual and auditory warnings) because they did not like the vibratory sensation in their abdomen.

2. Method

2.1. Participants

Twenty voluntary participants (10 female) all having a valid driving license took part in the study (mean age 27 yrs., range 19–51 yrs.). Two of them were left-handed and one was ambidextrous by self-reports. Five participants were recruited from staff and the rest were students of the authors' University attending to an introductory course of interactive technology. The students received a course credit for their participation. All had normal or corrected to normal vision, and normal hearing and sense of touch by their own report. No-one had previous experience on FCWs. All the participants were fully informed for the purpose of the study and signed informed consents prior to the experiment.

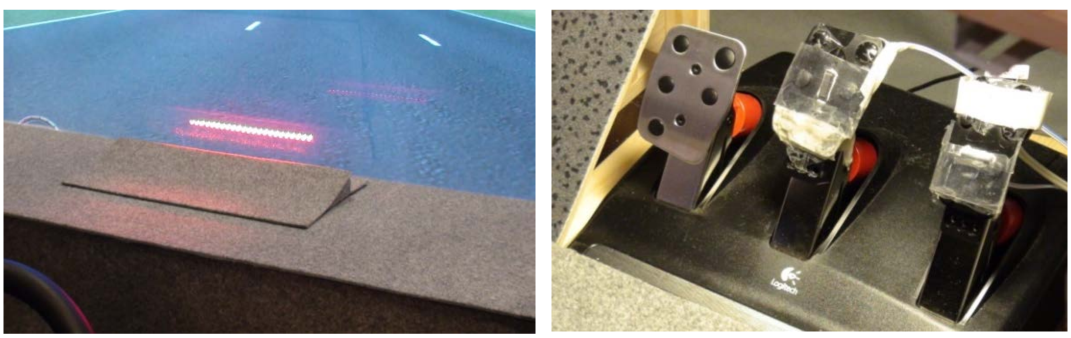
2.2. Apparatus and the experimental setup

A fixed-base driving simulator was implemented in a laboratory. A PC ran a lane change test (LCT) driving simulator software (ISO 26022, 2010) showing a simulated roadway with no other traffic. The simulator was run either on a 55" LCD display (Samsung UNES7005) or on one of a total of three 17" LCD displays (Acer LCD AL732) at medium contrast and brightness in a well-lit laboratory. The 55" display provided the on the road view for the simulator and the 17" displays provided the simulated visual orientations for two exterior mirrors and one interior mirror. A plexi-glass windscreen measuring 1200 x 800 x 4 mm (width x height x thickness) was set in about 35° angle. Simulated driving sound of the LCT was played via a Creative 3.1 speaker system through a PC soundcard at a comfortable sound level. Logitech G27 Racing Wheel and pedal pad were used to simulate the driving equipment.

Visual warnings were provided with a HUD implemented in accordance with Lind (2007). It consisted of a stream of 23 red light emitting diodes (LEDs) (Wah Wang WW05A3SRP4-N2) spaced out over a total length of 172mm. Each LED had a relative luminance of 1.5 a.u. at 30mA and hence this was used as the base brightness parameter for the visual stimulation. The LED strip was hidden behind a cover so that only the light reflected via windscreen was visible for the participant (Fig. 1(a)). A HiWave HIAX25C10-8/HS (Tectonic TEAX09C005-8) voice coil actuator was attached to the rear of the accelerator pedal to provide the vibrotactile stimulation, whereas two linear micro switches (KW 1 21), one fitted onto both the accelerator and brake pedals provided information regarding the participant's foot movement (Fig. 1 (b)). The actuators were powered by a pulse-width modulation amplifier and a signal generator.

Physical dimensions of a cockpit in terms of relative distances between a seat, steering wheel, pedals, mirror center points, and windscreen were replicated from a left-hand drive Volvo XC60 vehicle.

A multimodal triggering and data logging software, controlled by the experimenter, provided the warning stimuli at random inter-trial intervals. The software logged the response times from the stimulus onset to brake pedal contact.



(a) (b)

Fig. 1. (a) Visual warning stimulus reflected to the windscreen and (b) pedal set with footrest. Vibrotactile actuator producing tactile warning stimulus is located behind the accelerator pedal.

2.3. Stimuli

Three types of warning stimuli were used: visual (V), tactile (T), and visual-tactile (VT). Parameters of the V warning were adopted from Lind (2007). The warning lasted for 1.2 s and it consisted of five 150 ms light flashes separated by 100 ms interval between each flash. T warning was provided by sinusoidal wave at 220 Hz and amplitude value of 18.8 V (peak to peak) and shared identical on/off timing parameters with V warning. VT warning was a synchronized combination of V and T warnings.

2.4. Procedure

In the beginning, the laboratory and the equipment were introduced to the participant. It was explained that the purpose of the experiment was to study collision warnings provided via flashing light, vibrotactile stimulation, and their combination. The experiment was carried out without shoes to enable equal conditions for vibration perception.

Before the experiment began, the seat was personally adjusted and a hearing protector headset playing pink noise was put on to mask the sound of the vibrotactile stimulation. Then the participant was introduced with the V, T, and VT warning stimuli by presenting them once without a driving task.

Next, the participant was familiarized with driving and braking task on the driving simulator. They were instructed to use their right foot for using both the accelerator and brake pedals. The left foot was held on a foot rest next to the pedals. The participant practiced by driving the simulated car accelerator pedal fully depressed at a pre-limited speed of 60 km/h and then braking until the car was completely stopped. At this point, no warning stimuli were provided. The participant practiced the braking task for at least 5 times until completing at least 3 successful brakings.

After the practice the experiment continued with four experimental blocks. In each block a different visual display was used to present the view of the driving simulator in order to control the participants' visual orientation. The 55" display in front of the participant was used as a *gaze on the road scene ahead* (On-the-road) visual orientation. Three *gaze off the road scene ahead* visual orientations were implemented by the 17" displays imitating the positions of the left mirror (L-mirror), center mirror (C-mirror), and right mirror (R-mirror). In the On-the-road block the 17" displays were turned off. In the L-, C-, and R-mirror blocks only the 17" display specific to the visual orientation showed the driving scene. The other two 17" displays were turned off and On-the-road display showed only a still image of the driving scene to provide constant background luminance conditions for the V stimulus in each block (see Fig. 2). The order of the visual orientation exposures were fully counterbalanced amongst the participants.

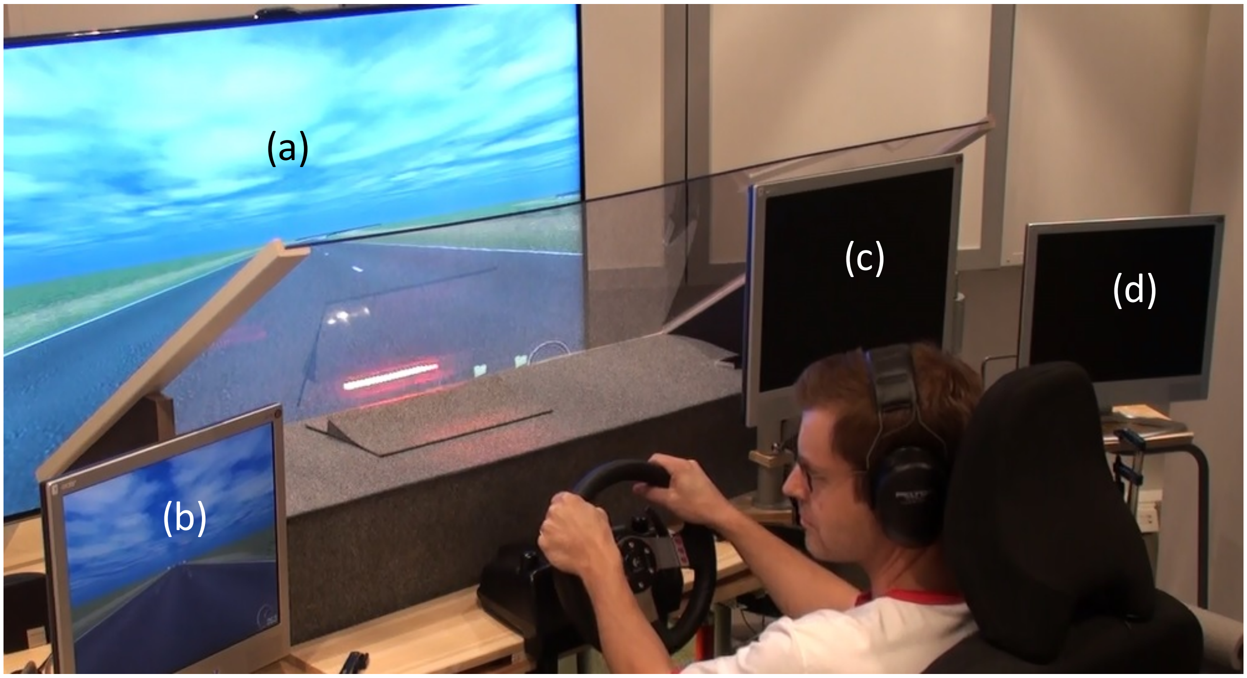


Fig. 2. Participant in the L-mirror visual orientation block. V stimulus is reflected to a lower part of the windscreen against the On-the-road display showing a still image of a driving scene. Displays used for manipulating the participant's visual orientation: (a) On-the-road, (b) L-mirror, (c) C-mirror, and (d) R-mirror.

Each visual orientation block consisted of a practice session, BRT measurement session, and subjective rating session. The purpose of the practice session was to familiarize the participant with the warnings and driving while viewing the visual orientation in question. In the practice session, V, T, and VT warning stimulus was presented once in a randomized order as follows. In the beginning of a practice trial the participant accelerated and drove a pre-limited speed of 60 km/h accelerator pedal fully depressed in a middle of a three-lane road. Then, after a randomly chosen 5–36 second interval a warning stimulus was presented. Then, the task was to release accelerator pedal and brake as quickly as possible. When the car had fully stopped, the participant was to release the brake pedal and start a new practice trial in a similar fashion. After completing the three practice trials, the participant proceeded to the actual BRT measurement session, which proceeded similarly to the practice session except that V, T, and VT warning stimuli were presented three times each in a randomized order resulting in a total of 9 experimental trials. The actual lane change task of the LCT driving simulator was omitted from the procedure.

The BRT measurement session was followed by the subjective rating session where the participants reported their experiences of the warnings with respect to the current visual orientation. For this purpose, the participant performed three additional braking tasks, one for each warning modality presented in a randomized order. Immediately after a warning stimulus was presented and the participant had completed a full braking, a questionnaire with four bi-polar, nine-point rating scales varying from 1 to 9 was given to the participant. The scales were 1) speed of the brake reaction (varying from slow to fast), 2) pleasantness of the warning (varying from unpleasant to pleasant), 3) perceptivity of the warning (varying from unnoticeable to noticeable), and 4) effectiveness (varying from ineffective to effective). On each scale a midpoint (i.e., value 5) represented a neutral experience (e.g., neither slow nor fast). After rating the V, T, and VT warnings, a new visual orientation block was initiated. This was repeated in a similar fashion until all the four visual orientation blocks were completed.

At the end of the experiment the participants were shortly interviewed. They were asked to rank which (if any) of the warnings was the most pleasant one and which (if any) they would rather have in their car. Finally, the participants were asked if they heard any sound of the T warning stimuli in order to guarantee the functionality of the hearing protection. Conducting the experiment took approximately 45 minutes.

2.5. Data analysis

BRTs were analyzed with 3 × 4 (warning modality × visual orientation) repeated measures analysis of variance (ANOVA). BRT was calculated from warning stimulus onset to the initial touch of the brake pedal according to the SAE Recommended Practice J2944 (2012). If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the *F* statistic. Pairwise Bonferroni corrected *t*-tests were used for post hoc tests. Shapiro-Wilk test of normality test suggested that the assumption of normal distribution was met regarding the BRT data S-W = .95, df = 20, $p = .43$. The subjective rating data was analyzed with Friedman tests for the effects of warning modality and visual orientation. Wilcoxon signed-ranks tests were used for pairwise comparisons. The rating scale of 1–9 was transformed to (-4)–(+4) for the Fig. 4 to illustrate the negative–positive dimensions of the bi-polar scales.

3. Results

3.1. Perception of the stimuli

Participants were able to detect and respond to all warning stimuli in each visual condition. No-one reported hearing the sound of the T warnings.

3.2. Brake response times

Mean ratings and standard error of the means (*S.E.M.s)* for BRTs are presented in Fig. 3. A two-way 3 × 4 (warning modality × visual orientation) ANOVA showed a statistically significant main effect of the warning modality $F(1.40, 26.56) = 365.37$, $p < .001$, $\mu^2 = .74$, and visual orientation

$F(3, 57) = 4.27$, $p = .009$, $\mu^2 = .01$. In addition, the interaction of the main effects was statistically significant, $F(2.60, 49.26) = 4.85$, $p = .007$, $\mu_p{}^2 = 0.20$.

To further analyze the interaction of the main effects, four one-way ANOVAs were performed to study the effect of warning modality separately in each visual orientation. ANOVAs showed that the modality affected to BRTs in all visual orientations as follows: On-the-road $F(1.54, 29.21) = 147.88$, $p < .001$, $\mu^2 = .81$, L-mirror, $F(1.41, 26.79) = 66.94$, $p < .001$, $\mu^2 = .68$, C-mirror $F(2, 38) = 203.64$, $p < .001$, $\mu^2 = .87$, and R-mirror, $F(1.21, 23.12) = 94.82$, $p < .001$, $\mu^2 = .77$. Post hoc pairwise comparisons showed that participants braked significantly faster after T than V warnings in all visual orientations: On-the-road, *MD* = 81 ms, $p < .001$, $r = .94$, L-mirror, *MD* = 83 ms, $p < .001$, $r = .89$, C-mirror, *MD* = 83 ms, $p < .001$, $r = .97$, and R-mirror, *MD* = 122 ms, $p < .001$, $r = .91$. The participants also braked significantly faster after VT than V warnings in all visual orientations: On-the-road, *MD* = 88 ms, $p < .001$, $r = .97$, L-mirror, *MD* = 86 ms, $p < .001$, $r = .90$, C-mirror, *MD* = 88 ms, $p < .001$, $r = .97$, and R-mirror, *MD* = 129 ms, $p < .001$, $r = .93$. The difference between T and VT warnings was not statistically significant in any of the visual orientations.

To further investigate the interaction, three one-way ANOVAs were performed to analyze the effect of visual orientation within each warning modality. The ANOVAs revealed that the interaction was due to the fact that visual orientation affected to BRT for V warnings, $F(1.92, 36.40) = 5.87$, $p = .007$, $\mu^2 = .18$, whereas no significant effect was found for T and VT warnings. Post hoc pairwise comparisons showed that the BRT was significantly slower to V warnings in R-mirror orientation than when orienting to On-the-road, *MD* = 41 ms, $p = .011$, $r = .64$ and C-mirror, *MD* = 39 ms, $p = .038$, $r = .58$. The other pairwise comparisons were not statistically significant.

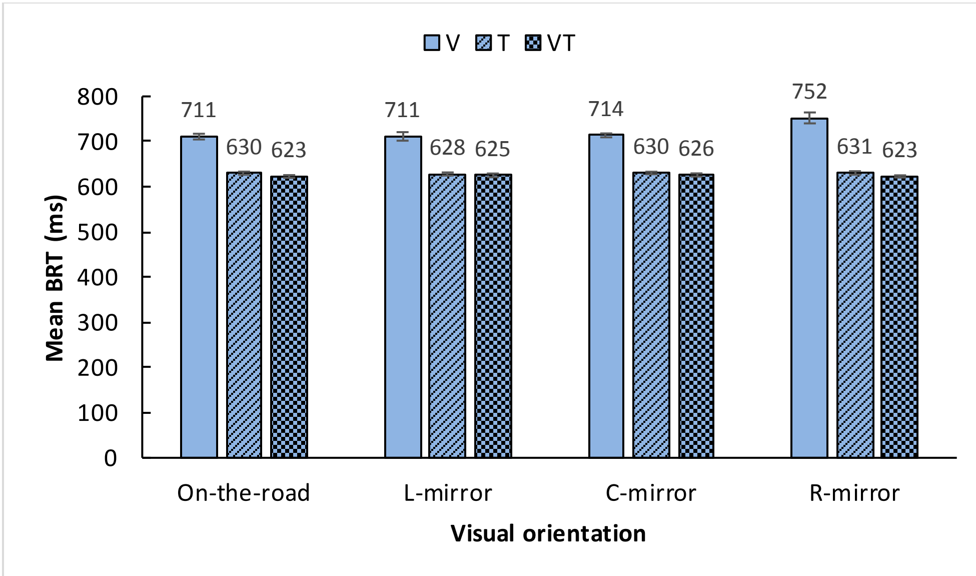


Fig. 3. Mean BRTs by warning modality and visual orientation. Error bars represent *S.E.M.s*. Note: V = visual; T = tactile; VT = visual-tactile.

3.3. Subjective ratings

Fig. 4 shows an overview of the subjective ratings averaged over the visual orientation conditions. Results of more detailed, scale-specific analysis are presented in the following sections.

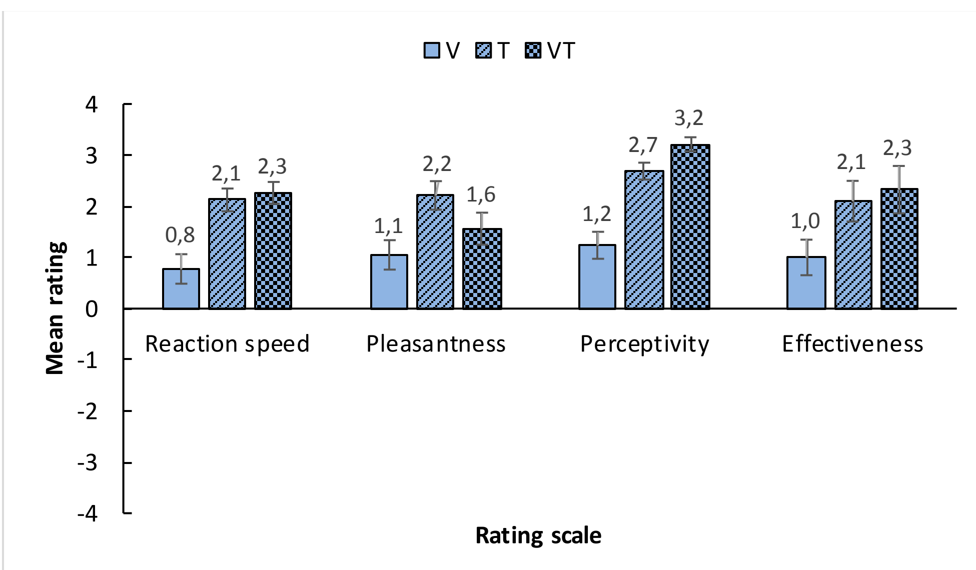


Fig. 4. Mean ratings averaged over visual orientations by warning modality and rating scale. Error bars indicate *S.E.M.*s. Note: V = visual; T = tactile; VT = visual-tactile.

3.3.1. Reaction speed

Friedman tests showed that warning modality had a statistically significant effect to the reaction speed ratings in all visual orientation conditions as follows: On-the-road, $\chi^2 = 15.39$, $p < .001$, L-mirror, $\chi^2 = 27.91$, $p < .001$, C-mirror, $\chi^2 = 27.03$, $p < .001$, and R-mirror, $\chi^2 = 15.74$, $p < .001$. Results of Wilcoxon signed-ranks tests are in Table 1.

Table 1
Wilcoxon *Z* test statistics for the pairwise comparisons of the warning modalities by visual orientation. Modality rated to produce faster reaction is indicated by bolded abbreviation.

Visual orientation	Faster reacted modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** (*Z* = 3.18)***	**VT** (*Z* = 2.87)**	*ns*
L-mirror	**T** (*Z* = 3.36)***	**VT** (*Z* = 3.77)***	*ns*
C-mirror	**T** (*Z* = 3.57)***	**VT** (*Z* = 3.77)***	*ns*
R-mirror	**T** (*Z* = 3.15)**	**VT** (*Z* = 2.97)**	*ns*

**p* ≤ .05, ***p* ≤ .01, ****p* ≤ .001, and *ns* = *p* > .05

Friedman tests did not reveal statistically significant effect of visual orientation to the reaction speed ratings for any warning modality.

3.3.2. Pleasantness

Friedman tests revealed that warning modality affected significantly to the pleasantness ratings in all visual orientation conditions: On-the-road, $\chi^2 = 16.75$, $p < .001$, L-mirror, $\chi^2 = 8.28$, $p = .016$, C-mirror, $\chi^2 = 7.32$, $p = .026$, and R-mirror, $\chi^2 = 8.79$, $p = .012$. Results of Wilcoxon signed-ranks tests can be seen in Table 2.

Table 2
Wilcoxon *Z* test statistics for the pairwise comparisons of each warning modality in all visual orientation. Modality rated as more pleasant is indicated by bolded abbreviation.

Visual orientation	More pleasant modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** (*Z* = 2.93)**	**VT** (*Z* = 2.31)*	**T** (*Z* = 2.35)*
L-mirror	**T** (*Z* = 2.76)**	**VT** (*Z* = 1.98)*	**T** (*Z* = 2.20)*
C-mirror	**T** (*Z* = 2.03)*	*ns*	**T** (*Z* = 1.99)*
R-mirror	**T** (*Z* = 2.59)**	*ns*	*ns*

**p* ≤ .05, ***p* ≤ .01, ****p* ≤ .001, and *ns* = *p* > .05

Friedman tests did not show statistically significant effect of visual orientation to the pleasantness ratings for any warning modality.

3.3.3. Perceptivity

Friedman tests showed that warning modality affected the perceptivity ratings in all visual orientation conditions: On-the-road, $\chi^2 = 18.00$, $p < .001$, L-mirror, $\chi^2 = 29.43$, $p < .001$, C-mirror, $\chi^2 = 28.73$, $p < .001$, R-mirror, and $\chi^2 = 28.48$, $p < .001$. Table 3 shows results of Wilcoxon signed-ranks tests.

Table 3
Wilcoxon *Z* test statistics for the pairwise comparisons of the warning modalities for each visual orientation. Modality rated as more noticeable is indicated by bolded abbreviation.

Visual orientation	More noticeable modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** (*Z* = 2.39)*	**VT** (*Z* = 3.33)***	**VT** (*Z* = 2.72)**
L-mirror	**T** (*Z* = 3.23)***	**VT** (*Z* = 3.76)***	**VT** (*Z* = 2.81)*
C-mirror	**T** (*Z* = 3.32)***	**VT** (*Z* = 3.75)***	**VT** (*Z* = 2.49)*
R-mirror	**T** (*Z* = 3.66)***	**VT** (*Z* = 3.67)***	*ns*

$^*p \le .05$, $^{**}p \le .01$, $^{***}p \le .001$, and *ns* = $p > .05$

Friedman tests did not show statistically significant effect of visual orientation to the perceptivity ratings for any warning modality.

3.3.4. Effectiveness

Friedman tests showed that warning modality affected the effectiveness ratings significantly in all visual orientation conditions: On-the-road, $\chi^2 = 19.58$, $p < .001$, L-mirror, $\chi^2 = 20.80$, $p < .001$, C-mirror, $\chi^2 = 15.27$, $p < .001$, R-mirror, $\chi^2 = 14.40$, $p = .001$. Results of Wilcoxon signed-ranks tests are shown in Table 4.

Table 4
Wilcoxon *Z* test statistics for the pairwise comparisons of the warning modalities by visual orientation. Modality rated as more effective is indicated by bolded abbreviation.

Visual orientation	More effective modality		
	V vs. T	V vs. VT	T vs. VT
On-the-road	**T** (*Z* = 2.98)**	**VT** (*Z* = 3.45)***	**VT** (*Z* = 2.24)*
L-mirror	**T** (*Z* = 3.17)**	**VT** (*Z* = 3.45)***	*ns*
C-mirror	**T** (*Z* = 2.47)*	**VT** (*Z* = 2.32)**	*ns*
R-mirror	**T** (*Z* = 3.07)**	**VT** (*Z* = 3.12)**	*ns*

$^*p \le .05$, $^{**}p \le .01$, $^{***}p \le .001$, and *ns* = $p > .05$

Friedman tests did not yield significant effect of visual orientation to the effectiveness ratings for any warning modality.

3.4. Warning modality rankings

Post-experimental interviews revealed that 11 participants considered T warning as the most pleasant, 6 voted for VT, 1 found V warning as the most pleasant, and 2 could not decide. Typical reasoning included a clear association between T warning and braking, and complains of V warning being distracting or too vigorous especially when presented alone.

Ten participants considered that they would rather use T warning while driving, 8 would prefer VT, 1 would use V warning, and 1 could not decide. When asked why, the participants considered that T and VT warning was able to catch the attention efficiently. In addition, they found that vibration reflected the needed reaction (i.e., clear association for lifting the leg from the pedal) well. Similarly to the pleasantness ratings the excessive intensity of V warning was the most frequent reason for its low popularity.

4. Discussion

In general, the 100% detection accuracy showed that the FCW stimuli were functional in capturing attention in all the currently used visual orientations. Statistical analysis revealed significant differences between the responses to different warning modalities by showing that responses to T and VT warnings were significantly (i.e., 81–122 and 86–129 ms, respectively) faster as compared to V warnings throughout all visual orientations. Theoretically, when driving at a speed of 100 km/h this would enable an advantage to react about 2.3–3.6 m earlier in comparison to V only warnings. Moreover, the participants' subjective ratings of their reaction speed supported the BRT results. The objective BRT results concurred with earlier studies showing that tactile collision warning stimulus can be responded significantly faster as compared to visual stimulus (e.g., Scott & Gray, 2008; De Rosario et al., 2010). Significant multisensory enhancement effect of VT stimuli producing faster reactions than T stimuli found in earlier laboratory studies (e.g., Forster et al., 2002; Diederich & Colonius, 2004) was not obtained. However, Fig. 3 shows that BRTs to VT warnings were systematically, yet not significantly, shorter compared to T warnings. This tendency can also be considered as somewhat consistent with subjective data showing that VT warnings were rated as more noticeable and efficient than T warnings in some visual orientations.

The found effect of visual orientation provided new and more detailed insights regarding the perceptivity of FCWs in different visual orientation conditions. Fig. 3 clearly shows that BRTs to V warnings were slower in R-mirror orientation as compared to the other visual orientations, whereas BRTs to T and TV warnings remained intact. This can be explained by the fact that in the R-mirror condition the participant was exposed to the largest angular change between the visual orientation and the visual stimulus location. A body of earlier research has shown that perception of visual stimulus typically slows down as a function of increased visual angle (e.g., Strasburger et al., 2011). Concentrating gaze on L- and C-mirrors spatially closer to the visual stimulus did not lead to significantly different BRTs as compared to On-the-road orientation. This result indicates that the HUD implementation of V warning was perceived equally efficiently within the range of angular displacement of the On-the-road as well as L-mirror, and C-mirror orientations.

The fact that BRTs were unaffected by visual orientation when tactile warning modality was involved demonstrates the potential of T and VT warnings especially when visual attention is concentrated off the road scene ahead, that is, in situations when FCW is typically with the utmost urgency. Given that reduced visual field is common especially amongst elderly drivers it is also noted that the ability to perceive a unimodal V warning in the off the road visual orientations would probably be deteriorated in the average driving population as compared to the current sample consisting of relatively young participants with normal peripheral vision, typically around 180° wide horizontally. As an example, the minimum requirement of about 100–120° wide horizontal visual field is a precondition for a driving license in many countries (Bron et al., 2010). This visual field would probably have been insufficient for perceiving the currently used V warning stimulus in the R-mirror orientation in the current study. Actually, narrowed visual field has been found to be a key factor explaining proclivity for traffic accidents by elderly drivers (e.g., Ball et al., 1993). Thus, it is possible that the potential benefits of tactile FCW would turn out to be especially significant amongst the elderly drivers.

Fig. 4 shows that subjective ratings as a whole were favorable regarding each warning modality yet intermodal differences were also found. T modality was clearly more preferred than V in all visual orientations, but in the other modalitywise comparisons visual orientation had a significant effect on the pleasantness ratings. For example, T and VT were rated equally pleasant in R-mirror orientation, but in the other spatially closer visual orientations T was experienced as more pleasant. Post-experimental interviews revealed one possible explanation for this result by showing that many participants considered the V warning being too intense. The intensity of the V warning probably diminished to a more acceptable level in the R-mirror orientation due to large angular displacement; V stimulus seen in peripheral visual field possibly made the stimulus appear less intense and thus more pleasant. Pleasantness ratings of V and VT warnings were similar in the C-and R-mirror visual orientations. Interestingly, however, in the spatially closer On-the-road as well as in L-mirror orientations VT was rated as more pleasant than sole V warning. This may indicate that the unpleasant experience of the excessive intensity of the visual stimulation was attenuated by the concurrent tactile stimulation. In the post experimental interviews nobody reported any discomfort of the vibrating accelerator pedal. This result is contradictory to Scott & Gray (2008) where unpleasant experiences of the vibrating waist belt warning were frequently complained.

In the S-R compatibility frame of reference both the objective and subjective results suggest that T and VT stimuli were more compatible with the braking response than a sole V stimulus in the varied gaze directions. However, it is noted that in a realistic driving situation the cognitive processes taking place between a warning stimulus and brake response can be more complex than in the current study, particularly when gaze is off the road. In addition to the motor reaction of lifting a foot from the accelerator, a natural reaction would include a visual shift towards the road scene ahead before hitting the brakes. The visual confirmation prior to a brake response is needed for making a decision whether to brake and/or steer to avoid collision, or perhaps do neither, for example, in case of a false alarm. Thus, despite the fact that the results of T and VT warnings were much alike, it would seem rational to rather use VT stimulation to enable a more optimum S-R compatibility for an FCW; The tactile component of the bimodal warning would enable quick foot response whilst the concurrent visual component would prompt visual attention towards the windscreen. Otherwise it might be possible that a sole T warning would actually shift the driver’s gaze inappropriately towards the pedals.

Being aware of the constraints of the controlled experimental setups virtually always present in the automotive domain (e.g., Aust, Engström, & Viström, 2013), we chose to first concentrate on plain perception times of the warning modalities by means of simple reaction time measured using a standard of BRT. This approach will also allow to relate the current results to other studies using the same standardized performance measures (Green, 2012). Our results obtained in the four visual orientations can serve as a basis for further investigations to substantiate the promising feasibility of the foot vibrating warnings in more applied fashion and against other vibration locations such as seat and seatbelt.

Intelligent safety technologies advance and emerge rapidly in the automotive domain, and in addition to FCWs also fully automated braking systems able to take control over the driver in near-to-collision situations are already available. However, their impact on driving safety has been found twofold; On one hand they can prevent accidents, but on the other hand there is evidence that situational awareness and driving performance may actually decline along with increased level of automation, for example, due to overreliance on the technology (Young & Stanton 2007; Strand, Nilsson, Karlsson, & Nilsson, 2014). This suggests that as long as the human operator in the vehicle is in response of the driving safety, there is still a need for investigations and development of more efficient, yet not overly annoying warning methods that rather assist than replace the driver in hazardous situations.

Acknowledgments

This research was supported by the HapticAuto project funded by the Finnish Funding Agency for Technology and Innovation (Tekes), decision number 40289/11. In addition, the research was supported by Doctoral Programme in User-Centered Information Technology (UCIT).

References

Aust, M. L., Engström, J., & Viström, M. (2013). Effects of forward collision warning and repeated event exposure on emergency braking. *Transportation Research Part F: Traffic Psychology and Behaviour, 18*, 34–46.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology & Visual Science, 34*(11), 3110–3123.

Brebner, J. M. T. & Welford A. T. (1980). Introduction: An historical background sketch. In A. T. Welford (Eds.), *Reaction Times* (pp. 1–23). New York: Academic Press.

Bron, A. M., Viswanathan, A. C., Thelen, U., de Natale, R., Ferreras, A., Gundgaard, J., Schwartz, G., & Buchholz, P. (2010). International vision requirements for driver licensing and disability pensions: using a milestone approach in characterization of progressive eye disease. *Clinical Ophthalmology, 4*, 1361–1369.

Bueno, M., Fabrigoule, C., Ndiaye, D., & Fort, A. (2014). Behavioural adaptation and effectiveness of a Forward Collision Warning System depending on a secondary cognitive task. *Transportation Research Part F: Traffic Psychology and Behaviour, 24,* 158–168.

Burke, J. L., Prewett, M. S., Gray, A. A., Yang, L., Stilson, F. R. B., Coovert, M. D., Elliot, L. R., & Redden, E. (2006). Comparing the effects of visual-auditory and visual-tactile feedback on user performance: a meta-analysis. In *Proceedings of the 8th international conference on Multimodal interfaces (ICMI '06)*. ACM, New York, NY, USA, 108–117.

Chun, J., Han, S. H., Park, G., Seo, J., Iee, I., & Choi, S. (2012). Evaluation of Vibrotactile Feedback for Forward Collision Warning on the Steering Wheel and Seatbelt. *International Journal of Industrial Ergonomics, 42*(5), 443–448.

De Rosario, H., Louredo, M., Díaz, I., Soler, A., Gil, J. J., Solaz, J. S., & Jornet, J. (2010). Efficacy and feeling of a vibrotactile frontal collision warning implemented in a haptic pedal. *Transportation Research Part F: Traffic Psychology and Behaviour, 13*, 80–91.

Diederich, A. & Colonius, H. (2004). Bimodal and trimodal multisensory enhancement: Effects of stimulus onset and intensity on reaction time. *Perception & Psychophysics, 66*(8), 1388-1404.

Forster, B., Cavina-Pratesi, C., Aglioti, S. M., & Berlucchi, G. (2002). Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time. *Experimental Brain Research, 143*(4), 480–487.

Green, P. (2012). Using standards to improve the replicability and applicability of driver interface research. In *Proceedings of the 4th international conference on automotive user interfaces and interactive vehicular applications (AutomotiveUI '12).* ACM, New York, NY, USA.

Higuchi, M. & Raksincharoensak, M. (2010). Seat vibrotactile warning interface for forward vehicle collision avoidance. In Proceedings of the Society of instrument and control engineers annual conference (SICE 2010). IEEE, 1370–1373.

Ho, C., Gray, R., & Spence, C. (2014). Reorienting driver attention with dynamic tactile cues. *IEEE Transactions on Haptics, 7*(1), 86–94.

ISO 26022 (2010). Road vehicles - Ergonomic aspects of transport information and control systems - Simulated lane change test to assess in-vehicle secondary task demand.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). The impact on driver inattention on near-crash/crash risk: an analysis using the 100-car naturalistic driving study data (Report No. DOT HS 810 594). Washington, DC: National Highway Traffic Safety Administration.

Lind, H. (2007). An efficient visual forward collision warning display for vehicles (SAE Technical Paper 2007-01-1105). *Society of Automotive Engineers World Congress*, Detroit, MI.

Lloyd, D. M., Bolanowski, S. J. Jr, Howard, L., & McGlone, F. (1999). Mechanisms of attention in touch. *Somatosensory & Motor Research, 16*(1), 3–10.

Mohebbi, R., Gray, R., & Tan, H. Z. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors, 51*(1), 102–110.

Müller, H. J. & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*(2), 315–330.

Raisamo, R., Surakka, V., Raisamo, J., Rantala, J., Lylykangas, J., & Salminen, K. (2009). Haptic interaction becomes reality. *Journal of Ambient Intelligence and Smart Environments, 1*(1), 33–37.

Scott, J. J. & Gray, R. (2008). A comparison of tactile, visual, and auditory warnings for rear-end collision prevention in simulated driving. *Human Factors, 50*(2), 264–275.

Society of Automotive Engineers. (2012). *Operational Definitions of Driving Performance Measures and Statistics* (draft SAE Recommended Practice J2944), Warrendale, PA: Society of Automotive Engineers.

Spence, C. & Ho, C. (2008). Multisensory warning signals for event perception and safe driving. *Theoretical Issues in Ergonomics Science, 9*(6), 523–554.

Strand, N., Nilsson, J., Karlsson, I. C. M, & Nilsson, L. (2014). Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F: Traffic Psychology and Behaviour, 27,* 218–228.

Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: a review. *Journal of Vision, 11*(5):13, 1–82.

Umiltà, C. & Nicoletti, R. (1990). Spatial stimulus-response compatibility. In R.W Proctor & T.G. Reeve (Eds.), *Stimulus-response compatibility: an integrated perspective* (pp. 89–116). Amsterdam: North-Holland.

Wang, D.-Y., Proctor, R. W., & Pick, D. F. (2003). Stimulus-response compatibility effects for warning signals and steering responses. In *Proceedings of the 2nd international driving symposium on human factors in driver assessment, training and vehicle design.* Park City, Utah.

Wiese, E. E. & Lee, J. D. (2004). Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance. *Ergonomics, 47*(9), 965–986.

Young, M. S. & Stanton, N. A. (2007). Back to the future: Brake reaction times for manual and automated vehicles. *Ergonomics, 50*(1), 46–58.