Applied Ergonomics 58 (2017) 238–244

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Advanced driver assistance systems: Using multimodal redundant warnings to enhance road safety

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ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form
27 June 2016
Accepted 28 June 2016
Available online 16 July 2016

Keywords:
Warnings
Automation
Multimodal

ABSTRACT

This study investigated whether multimodal redundant warnings presented by advanced assistance systems reduce brake response times. Warnings presented by assistance systems are designed to assist drivers by informing them that evasive driving maneuvers are needed in order to avoid a potential accident. If these warnings are poorly designed, they may distract drivers, slow their responses, and reduce road safety. In two experiments, participants drove a simulated vehicle equipped with a forward collision avoidance system. Auditory, vibrotactile, and multimodal warnings were presented when the time to collision was shorter than five seconds. The effects of these warnings were investigated with participants performing a concurrent cell phone conversation (Exp. 1) or driving in high-density traffic (Exp. 2). Braking times and subjective workload were measured. Multimodal redundant warnings elicited faster braking reaction times. These warnings were found to be effective even when talking on a cell phone (Exp. 1) or driving in dense traffic (Exp. 2). Multimodal warnings produced higher ratings of urgency, but ratings of frustration did not increase compared to other warnings. Findings obtained in these two experiments are important given that faster braking responses may reduce the potential for a collision.

1. Introduction

Advanced Driver Assistance Systems (ADAS) are designed to assist motorists while they are operating a vehicle. These systems constantly monitor a number of parameters and when thresholds are exceeded, drivers are informed (Merat and Lee, 2012). Examples of ADAS are lane departure warning systems and forward collision avoidance systems. The former monitors the position of the vehicle within the lane whereas the latter monitors the distance between the driver's vehicle and the vehicle in front. When the vehicle moves out of its lane of travel or the time headway is too short, warnings are presented so that drivers can adjust their behavior in order to avoid potential accidents. The warnings presented by ADAS are visual, auditory and, occasionally, vibrotactile (Meng et al., 2014). Although assistance systems are designed to help drivers, poorly designed warnings may distract the driver, thus making driving less safe (Biondi et al., 2014a).

Distraction occurs when drivers are not focused on the driving task (Regan and Strayer, 2014). For example, in addition to controlling the vehicle, drivers may perform a secondary task that is unrelated to driving. Strayer et al. (2011) identified three sources distraction: visual (when eyes are not on the road), manual (when hands are not on the steering wheel), and cognitive (when attention is diverted from the driving task). Although distraction is commonly associated with executing secondary tasks such as using a cell phone (Strayer et al., 2013, 2015), a group of researchers raised the possibility that interacting with systems designed to assist drivers might in fact have unintended consequences on driving performance (Adaptive Integrated Driver-vehicle InterfacE, 2005; Kiefer et al., 2005). For example, in the study by Dijksterhuis et al. (2012), participants drove a simulated vehicle equipped with a lane departure warning system. The information about the vehicle's position within the lane was visually displayed on the

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http://dx.doi.org/10.1016/j.apergo.2016.06.016
0003-6870/

windshield via a heads-up display (HUD). Although drivers maintained a more stable lane position when using the HUD, 39% of participants reported that they tried to ignore the display as much as possible while driving. This is concerning given that the HUD was located within the area of the windshield used by drivers to scan the environment and detect potential hazards. Similarly, Rossi et al. (2013) had participants drive a simulated vehicle on a dangerous road section. Whenever the speed was too high, drivers were presented with auditory warnings and the effects of these warnings on driving behavior were observed. Although a reduction in vehicle speed was observed, a more fine-grained analysis (Biondi et al., 2014a) indicated that this effect was the consequence of a startle reaction produced in response to the abrupt onset of the warning signal. Similarly, Adell et al. (2008) had participants drive a simulated vehicle equipped with a system emitting auditory warnings when the speed exceeded a given threshold. Results showed that auditory warnings reduced driving speed but elevated the ratings of annoyance; an aspect that may lead drivers to discontinue the use of ADAS (Jamson et al., 2008). Taken together, these findings suggest that poorly designed warnings have the potential to disturb driving, distract drivers, and produce unacceptable feelings of annoyance (see Fagerlönn, 2010; Wiese and Lee, 2004). This represents an important safety issue given that warnings are presented when driving conditions are hazardous, that is, when fast corrective responses are needed.

In a laboratory (non-driving) context, multimodal redundant targets produce faster responses compared to situations when the auditory and vibrotactile stimuli are presented separately. This is commonly referred to as the redundant target effect (Diederich and Colonius, 2004). In a non-driving study, Forster, et al. (2002) had participants respond to visual and auditory stimuli. When the two stimuli were presented concurrently, responses were faster than when just one of the stimuli was presented. In a study by Biondi et al. (2014b), participants drove a simulated vehicle and responded to the presentation of auditory and vibrotactile stimuli by pressing a button attached to their right thumb. Results showed that when these two stimuli were presented simultaneously, responses were faster than when each stimulus was presented by itself.

The aim of the current research was to determine whether the benefits associated with the presentation of multimodal stimuli can be applied to a more realistic driving context. Because Biondi et al. (2014b) used stimuli that were not associated with any particular meaning and, more importantly, relied on button presses that were unrelated to driving, it reduced the applicability of these results to the driving context (Ho et al., 2014). To address these shortcomings, we conducted two experiments in which warnings were presented by a forward collision avoidance system designed to support drivers' braking responses. We investigated the effects of multimodal warnings with participants conversing on a hands-free cell phone (Exp. 1) or driving in dense traffic (Exp. 2) because these two factors represent leading causes of collisions (NHTSA, 2007). Other studies have investigated the effects of warnings on driving, but they either considered unimodal warnings alone (Mohebbi et al., 2009) or, if multiple modalities were employed, a limited number of conditions were tested (e.g., driving and listening to the radio, Ho et al., 2007). The warnings we considered in our research were vibrotactile and auditory signals presented both together and separately. We selected auditory and tactile warnings because previous studies (Scott and Gray, 2008) found that they produced faster responses compared to other modalities.

2. Experiment 1

The first experiment investigated whether the concurrent presentation of vibrotactile and auditory warnings – i.e. a multimodal warning – could have a positive impact on braking times and subjective workload compared to when these warnings are presented separately. In addition, if benefits associated with multimodal warnings were observed, we were interested in determining whether they could also be observed when drivers were carrying out a concurrent cell phone conversation, an activity known to interfere with driving (Horrey and Wickens, 2006). When participants did not use a cell phone, we expected multimodal warnings to produce faster braking times compared to other warning conditions. However, it is possible that these benefits could be diminished when participants diverted attention to a concurrent cell phone conversation. This observation would be consistent with the research by Mohebbi et al. (2009) that showed benefits associated with auditory warnings were eliminated with complex conversation.

2.1. Method

2.1.1. Participants

Twenty-two graduate and undergraduate students (14 females) at the University of Utah participated in this experiment in exchange of class credits. They had an average age of 25 years ($SD = 6$) and possessed a valid driver license for an average of 9 years ($SD = 6$). Participants had normal or corrected-to-normal vision and reported not having hearing deficits. One participant dropped out due to simulator sickness and was replaced with another.

2.1.2. Design

We employed a two factor, within-subjects factorial design. The first factor was the type of warning and had four levels: 1-no warnings, 2-auditory, 3-vibrotactile, and 4-multimodal warnings (vibrotactile and auditory signals presented concurrently). The second factor with two levels involved cell phone use (present or absent). In the no-warning conditions, the participants drove a simulated vehicle. In the warning conditions, participants were also presented with warning signals while driving. In the cell phone condition, they were also instructed to carry on a conversation over a cell phone with a friend. Overall, eight (4 Warnings × 2 Cell Phone) different experimental conditions were considered. The order of the eight experimental conditions was randomized across participants: twenty-two different sequences (one per participant) were created. Because of the large number of experimental conditions, we did not have a fully counterbalanced experimental design across participants.

2.1.3. Materials

A PatrolSim high-fidelity, fixed base simulator (L3 Communications/I-SIM) was used. The simulated vehicle was based on a Ford Crown Victoria with automatic transmission. The simulator consisted of three screens providing a horizontal visual field of approximately 180° and included simulated rear-view and side-view mirrors. The vehicle was equipped with a forward collision avoidance system. The time to collision (TTC; Lee, 1976) was calculated at 60 Hz. Participants were instructed to follow and not pass a lead vehicle (Ciuffo et al., 2012; Gipps, 1981). The lead vehicle travelled in the right-hand lane of a four-lane highway at a speed of 65 mph. The auditory warning, in accordance with ISO (2013) and SAE (2003) standards, was a 75-dB, 2000 Hz stimulus presented by two speakers. The vibrotactile warnings were delivered by two motors (20 mm diameter; 0.5 G vibration amplitude) driven by a 250 Hz sinusoidal signal and connected to the computer running the simulation via an Arduino© microprocessor; each motor was located on one of the driver's palms. Auditory, vibrotactile, and multimodal stimuli all had durations of 200 msec . We used an iPhone 5™ (Apple™ Inc.) connected to a model Era Bluetooth earpiece manufactured by Jawbone©. The cellular service was provided by Sprint©.

2.1.4. Procedure

Before the experiment, participants drove two different adaptation scenarios to become familiar with the simulator and to reduce the symptoms of simulator sickness (Draper et al., 2001). In each of the eight experimental conditions, the lead vehicle was programmed to decelerate a total of eight times. We created eight different scenarios, one per experimental condition. In each scenario, the eight deceleration events were programmed to occur at specific road sections that differed between scenarios. For these reasons, the road sections at which the lead car decelerated were unpredictable to participants. During deceleration events, the lead vehicle decreased its speed from 65 mph to 30 mph. In the simulations, the lead vehicle brake lights were disabled. Such a procedure is well-established in literature and adopted in a number of similar studies (Ho et al., 2007 Mohebbi et al., 2009; Scott and Gray, 2008) to resemble those real-life situations in which the lead car brake lights are faulty (see Great Britain Department for Transport, 2004) or not readily visible (e.g., in adverse weather conditions), the driver does not look ahead but elsewhere (e.g., on-board infotainment system), or the lead vehicle decelerates without braking. To avoid collisions, drivers must rely on other types of information, such as the looming of the lead vehicle or warnings emitted by ADAS.

During familiarization, participants drove the vehicle and were presented at random intervals with vibrotactile, auditory, or multimodal stimuli. They were instructed to respond vocally whenever they detected a stimulus. All participants correctly detected the stimuli with 100% accuracy. In the experiment, every time the lead vehicle initiated braking and TTC was less than 5 s (Mohebbi et al., 2009; Scott and Gray, 2008), warnings were presented for 200 msec every second and drivers were instructed to brake to avoid a collision. Warnings were presented as long as the TTC remained less than 5 s or a collision occurred. Whenever a collision occurred, that particular scenario concluded. In total, participants drove eight 5-min scenarios (one scenario per condition). Halfway through the one-hour experiment, participants took a 15-min break. The order in which participants drove the eight scenarios was randomized across participants. When talking on a hands-free cell phone, each participant was instructed to carry on a conversation initiated with a friend before the drive commenced. Participants were free to talk about any subject they wanted. At the end of each scenario, participants were instructed to hang up the call and answer the questions contained in the NASA TLX.

2.1.5. Dependent measures

The primary dependent measure was Braking Reaction Time (BRT). The lead car was programmed to decelerate a total of eight times and drivers were instructed to brake in response. We defined T0 as the time point at which the TTC became shorter than 5 s. We defined T1 as the time point at which the driver initiated the braking response. BRTs were therefore calculated as the difference in seconds between T1 and T0. BRTs were calculated in the same manner in both the no-warning and the warnings conditions.

The second dependent measure was subjective workload measured via an augmented version of the NASA TLX (Hart and Staveland, 1988). The NASA TLX comprises six 21-point scales: mental, physical, and temporal demand, performance, effort, and frustration. The perceived urgency of warnings (Lewis et al., 2014) was measured via a 21-point seventh scale. Although perceived urgency and frustration are often correlated, urgent warnings are not perceived as annoying in emergencies (Marshall et al., 2007). In each of the seven scales of subjective workload, 1 corresponded to “Very Low” and 21 corresponded to “Very high.”

2.2. Results and discussion

Repeated measure ANOVAs were performed on the BRTs and NASA TLX data. A Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. For pairwise comparisons, we adopted the Bonferroni correction ($\alpha = 0.008$). Reported partial η^2 values refer to within-subjects variance.

BRTs. Data were normally distributed (Pastore et al., 2008; Shapiro et al., 1968). Fig. 1 presents the BRT data. A 2 (Cell Phone: no cell phone, cell phone) x 4 (Warnings: no warnings, auditory, vibrotactile, multimodal) repeated measures ANOVA was performed. Mauchly’s test indicated that the assumption of sphericity was violated for cell phone (χ^2 (0) = 0, p < n/a, $\varepsilon = 1$), warnings (χ^2 (4) = 45.2, $p < 0.001$, $\varepsilon = 0.45$) and interaction (χ^2 (5) = 24.3, $p < 0.001$, $\varepsilon = 0.56$). We used the Greenhouse-Geisser correction and p-values were adjusted accordingly. However, as common in literature (McKeown and Isherwood, 2007), reported degrees of freedom are uncorrected to facilitate the interpretation of the data. Significant main effects of cell phone, $F(1, 21) = 20.01$, $p < 0.05$, partial $\eta^2 = 0.48$, and warnings, $F(3, 63) = 134.41$, $p < 0.05$, partial $\eta^2 = 0.86$, were found. BRTs were slower in the cell phone ($M = 1.10$ s) compared to the no-cell phone ($M = 0.94$ s) condition. The Cell Phone × Warnings interaction was not significant ($p > 0.05$). Comparisons of the estimated marginal means revealed that BRTs to multimodal warnings ($M = 0.63$ s) were significantly faster than those recorded in the no-warning ($M = 1.77$ s, $p < 0.008$), auditory ($M = 0.80$ s; $p < 0.008$) and vibrotactile ($M = 0.88$ s; $p < 0.008$) warning conditions. No significant difference between BRTs to auditory and vibrotactile warnings was found ($p > 0.05$).

Multimodal redundant warnings produced faster responses compared to auditory and vibrotactile warnings presented separately. This finding represents one of the first studies (see also Ho et al., 2007 with participants listening to the radio; Spence and Ho, 2008a, 2008b for reviews) in which the benefits associated with redundant warnings were observed within the driving context. The significant main effect of warnings suggests that benefits of multimodal warnings occur even when participants were engaged in a cell phone conversation. Consequently, multimodal warnings have positive effects on driving even when drivers are distracted and their response times are usually prolonged (Rossi et al., 2012). Compared to unimodal warnings, multimodal warnings reduced braking times by up to ms. According to NHTSA

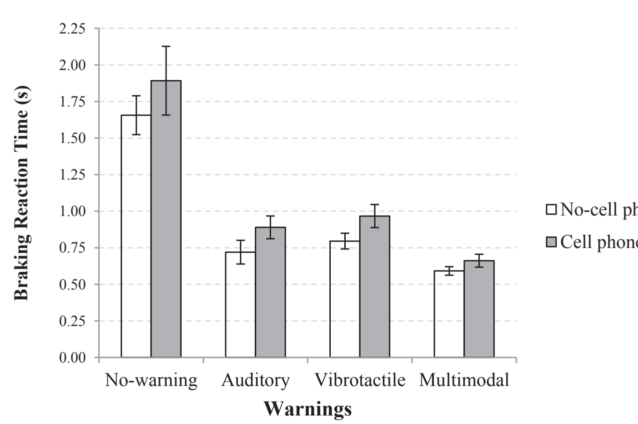

Fig. 1. Mean braking reaction times and 95% confidence intervals in seconds across warnings and cell phone conditions.

(2013), rear-end collisions account for 28% of the total number of on-road crashes and it is estimated that ADAS may reduce these collisions by 40%. For these reasons, employing signals capable of producing faster braking responses should reduce the likelihood of collisions (Brown et al., 2001). The absence of the significant interaction between cell phone and warning is discussed in more detail in the General Discussion section.

NASA TLX. Table 1 presents the NASA TLX and urgency data. A 2 (Cell Phone: no cell phone, cell phone) x 4 (warnings: no-warnings, auditory, vibrotactile, multimodal) within-subjects multivariate ANOVA with cell phone and warnings as independent variables and NASA TLX scales (6 levels: mental, physical, temporal, performance, effort, frustration) as dependent variables was performed. The perceived urgency scale was not included in this analysis and was analyzed separately. Cell phone and warnings were treated as within-subject factors and NASA TLX scales as levels of the multivariate factor; separate ANOVA were then conducted for scales for which significant differences were found. Multivariate tests revealed significant main effects of cell phone, Wilks' lambda = 0.60, $F(6, 152) = 5.91$, $p< 0.001$, partial $\eta^2 = 0.20$, and warnings, Wilks' lambda = 0.35, $F(18, 496) = 15.32$, $p < 0.001$, partial $\eta^2 = 0.32$. No significant Cell Phone × Warnings interaction was found ($p > 0.05$). A subsequent ANOVA revealed a significant effect of cell phone for the mental workload scale, Wilks' lambda = 0.341, $F(1, 168) = 27.95$, $p < 0.001$, partial $\eta^2 = 0.14$, with driving and talking on a cell phone ($M = 8.5$) being more mentally demanding than the no-cell phone condition ($M = 6.2$). No significant effect of Cell Phone was found for the other TLX scales. For warnings, a subsequent ANOVA revealed a significant effect of warning only for the frustration scale, Wilks' lambda = 0.532, $F(3, 168) = 3.04$, $p < 0.05$, partial $\eta^2 = 0.05$. Bonferroni-corrected pairwise comparisons between different warnings revealed that, although multimodal warnings produced a higher feeling of frustration compared to the no-warning condition ($p < 0.008$), no significant differences between warnings were found ($p > 0.05$).

For perceived urgency, a repeated measure ANOVA with Cell Phone (2 levels) and Warnings (3 levels: auditory, vibrotactile, multimodal) as within-subject factors revealed a significant main effect of warnings, $F(2, 42) = 7.36$, $p < 0.05$, partial η^2.26, with auditory ($M = 9.1$) and multimodal warnings ($M = 9.9$) producing higher perceived urgency than vibrotactile warnings ($M = 7.9$), $p < 0.008$. There were no significant differences between multimodal and auditory warnings, $p > 0.05$.

When compared to vibrotactile and auditory warnings presented separately, multimodal warnings did not produce a significant increase in the level of frustration. This is important given that one main issue of warnings is the elevated reports of frustration associated with them (Adell et al., 2008; Fagerlönn, 2010).

3. Experiment 2

Most rear-end collisions occur in urban areas (NHTSA, 2007) where, among other things, traffic density is usually greater than in rural areas. In the second experiment, we investigated whether multimodal redundant warnings were effective while driving in high- and low-density traffic conditions.

3.1. Procedure and methods

Participants. Twenty-two students (16 females) at the University of Utah participated in this experiment. They had an average age of 27 years ($SD = 8.9$) and possessed a valid driver license for an average of 10 years ($SD = 8.7$). They had normal or corrected-to-normal vision and reported not having hearing deficits. One participant dropped out due to simulator sickness and was replaced with another. Participants from this sample did not participate in Experiment 1.

3.1.1. Design and materials

We employed a 2 × 4 within-subjects factorial design. The first factor was the traffic density: low-vs. High-density traffic. As in the first experiment, the second factor was warnings. Driving simulator, warnings, and lead vehicle's behavior were the same as those of the first experiment.

3.1.2. Procedure

Procedure and instructions were the same as in Exp. 1. To manipulate traffic density we adopted a procedure similar to that of Strayer et al. (2003). In the low-traffic density condition, only the lead vehicle and that driven by participants were on the road. In the high-density traffic condition, twenty other vehicles drove in the left lane between 5% and 10% faster than the lead vehicle. Although neither the lead vehicle nor other vehicles changed lane at any time during the drive, this manipulation was expected to increase the level of driving demand. Having other vehicles moving on the road may increase the likelihood that drivers look at them and become distracted (Stutts et al., 2003). As in the previous experiment, we considered two main dependent measures: BRTs and subjective workload.

4. Results and discussion

Repeated measure ANOVAs were performed on BRTs and NASA TLX data. A Greenhouse-Geisser correction was applied when sphericity assumption was violated. For pairwise comparisons, we adopted the Bonferroni correction ($\alpha = 0.008$). Reported partial η^2 values refer to within-subjects variance.

Table 1
Mean scores (M) and standard errors (SE) for each of the seven scales of the augmented version of the NASA TLX across warnings and cell phone conditions.

Warning	Scale													
	Mental		Physical		Temporal		Performance		Effort		Frustration		Urgency	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
No-cell phone														
None	5.1	0.8	5.1	0.5	3.1	0.3	17.2	0.9	5.3	0.9	3.0	0.3	–	–
Auditory	6.6	0.5	6.6	0.2	4.5	0.4	17.5	0.5	5.6	0.6	4.4	0.5	9.3	0.8
Vibrotactile	6.3	0.5	6.3	0.4	4.2	0.3	18.2	0.4	5.1	0.5	4.2	0.4	7.9	1.0
Multimodal	7.2	0.5	7.2	0.4	4.8	0.5	17.5	0.6	6.2	0.8	4.8	0.4	10.1	0.7
Cell														
None	7.3	0.7	3.8	0.5	3.8	0.4	16.5	0.8	4.9	0.7	3.6	0.4	–	–
Auditory	9.2	0.5	3.8	0.3	4.5	0.3	16.6	0.4	6.8	0.6	4.4	0.4	8.8	0.8
Vibrotactile	8.5	0.5	4.6	0.5	4.5	0.4	16.4	0.8	5.9	0.7	4.7	0.5	8.0	0.8
Multimodal	9.0	0.6	4.5	0.4	4.9	0.4	17.0	0.6	6.2	0.7	4.8	0.5	9.9	0.8

BRTs. Preliminary normality tests revealed that BRT data were normally distributed. Data are presented in Fig. 2. A 2 (Traffic: high density, low density) x 4 (Warnings: no-warning, auditory, vibrotactile, multimodal) repeated-measures ANOVA was performed. Mauchly's test indicated that the assumption of sphericity was violated for traffic (χ^2 (2) = 27.4, $p < 0.001$, $\varepsilon = 1$), warnings ($\chi^2(5) = 31.6$, $p < 0.001$, $\varepsilon = 0.51$), and the interaction (5) = 117, $p < 0.001$, $\varepsilon = 0.71$); degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Significant main effects of traffic, $F(1, 21) = 22.67$, $p < 0.05$, partial $\eta^2 = 0.52$, warnings, $F(3, 63) = 122.38$, $p < 0.05$, partial $\eta^2 = 0.85$ and a significant interaction, $F(3, 63) = 4.73$, $p < 0.05$, partial $\eta^2 = 0.18$, were found. BRTs in high-density traffic in the no-warning ($M = 1.72$ s), auditory ($M = 0.81$ s), and vibrotactile ($M = 0.90$ s) warning conditions were significantly slower than those in low-density traffic (respectively, $M = 1.49$ s, $M = 0.64$ s, $M = 0.72$ s; $p < 0.008$). No significant effect of traffic was found for multimodal warnings ($p > 0.05$).

Presenting multimodal warnings ($M = 0.57$ s) produced significantly faster BRTs compared to the no-warning ($M = 1.61$ s), auditory ($M = 0.72$ s; $p < 0.008$) and vibrotactile ($M = 0.81$ s; $p < 0.008$) conditions in both traffic densities. BRTs for auditory warnings did not differ from those for vibrotactile warnings ($p > 0.05$). The significant main effect of traffic suggested that driving in high-density traffic increased BRT in the no-warning, auditory, and vibrotactile warning conditions ($p < 0.008$), but not in the multimodal warning conditions in which BRTs with dense traffic were as fast as those with low-density traffic ($p = 0.86$). In high density traffic, Bonferroni-corrected pairwise comparisons revealed that BRT to multimodal warnings were significantly faster compared to vibrotactile, $t(21) = 7.8$, $p < 0.001$, and to auditory, $t(21) = 4.2$, $p < 0.001$, warnings. Differences in BRT between the multimodal condition and the no-warning, auditory, and vibrotactile warnings conditions were greater in high- (1.16 s, 0.25 s, 0.34 s) than in low-density traffic (0.92 s, 0.07 s, 0.15 s), respectively.

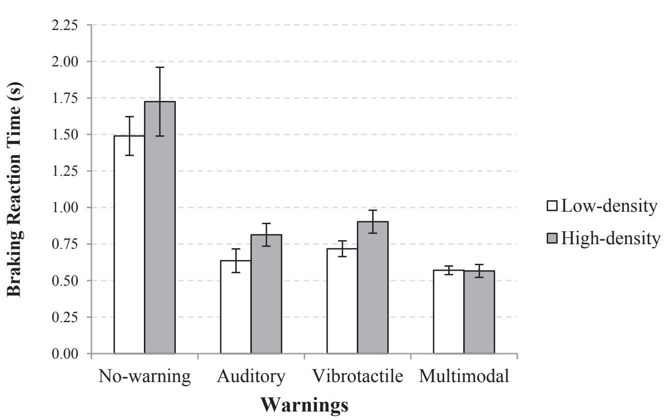

Fig. 2. Mean braking reaction times and 95% confidence intervals in seconds across warnings and traffic densities.

Results suggested that drivers benefit from using multimodal warnings in both low- and high-density traffic conditions. Multimodal warnings in high-density traffic produced faster braking responses than with unimodal warnings. Further, multimodal warnings were observed to be as effective in high-density traffic condition as they were when traffic was less dense.

NASA TLX. Table 2 presents the NASA TLX and urgency data. The same procedure adopted in Exp. 1 was considered in Exp. 2. A 2 (Traffic: high density, low low density) x 4 (Warnings: no-warning, auditory, vibrotactile, multimodal) within-subject multivariate ANOVA with traffic and warnings as independent variables and NASA TLX scales (6 levels: mental, physical, temporal, performance, effort, frustration) as dependent variables was performed. Traffic and warnings were treated as within-subject factors and NASA TLX scales as levels of the multivariate factor. Separate ANOVAs were then conducted for scales for which significant differences were found. Multivariate tests revealed significant main effects of traffic, Wilks' lambda = 0.32, $F(6, 152) = 7.31$, $p < 0.001$, partial $\eta^2 = 0.24$. Neither a significant main effect of warnings nor the interaction between warnings and traffic density were found. For Traffic, a subsequent ANOVA revealed a significant effect of traffic density only for the mental workload scale, Wilks' lambda = 0.456, $F(1, 168) = 6.21$, $p < 0.05$, partial $\eta^2 = 0.04$, with driving in high-density traffic ($M = 7.36$) being more mentally demanding than driving in low-density traffic ($M = 5.78$).

For the perceived urgency scale, a repeated measures ANOVA with Traffic (2 levels) x Warnings (3 levels: auditory, vibrotactile, multimodal) as within-subject factors revealed a significant effect of warnings, $F(2, 42) = 4.1$, $p < 0.05$, partial $\eta^2 = 0.16$, with multimodal warnings ($M = 9.18$) producing higher ratings of perceived urgency compared to vibrotactile warnings ($M = 7.25$; $p < 0.008$).

Ratings of subjective workload found in Exp. 2 were similar to those of Exp. 1. Multimodal warnings produced no significant increases in frustration compared to the other three conditions but produced higher feelings of urgency compared to the vibrotactile warning. Presenting multimodal, redundant warnings led to faster braking by drivers. Compared to unimodal auditory or vibrotactile warnings, multimodal warnings produced significant reductions in BRTs without increasing reported levels of annoyance (Adell et al., 2008). This finding is important given that warnings were presented when a collision was imminent.

Table 2
Mean scores and standard errors for each of the seven scales of the augmented version of the NASA TLX across warnings and traffic densities.

Scale														
Warning	Mental		Physical		Temporal		Performance		Effort		Frustration		Urgency	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Low-density														
None	5.3	0.7	3.3	0.4	3.8	0.5	18.0	0.5	5.4	0.7	4.3	0.9	–	–
Auditory	5.7	0.9	3.2	0.4	4.8	0.6	17.5	0.5	5.4	0.8	5.9	0.9	7.4	1.2
Vibrotactile	5.9	0.7	4.1	0.5	4.4	0.6	17.4	0.4	4.2	0.7	6.3	1.2	7.0	1.0
Multimodal	6.1	0.8	3.8	0.5	5.1	0.7	17.9	0.6	5.9	0.8	5.6	1.1	9.1	0.9
High-density														
None	7.4	1.1	3.7	0.5	4.9	0.6	16.5	0.8	5.4	0.9	5.8	1.1	–	–
Auditory	7.3	1.0	3.4	0.4	5.7	0.8	17.6	0.6	6.4	0.9	5.6	0.8	9.1	1.2
Vibrotactile	6.7	0.8	4.1	0.5	5.6	0.6	17.7	0.5	6.3	0.8	5.8	0.9	7.5	1.0
Multimodal	7.9	1.0	4.1	0.5	5.3	0.7	17.7	0.6	6.4	0.8	5.9	0.9	9.3	0.8

5. General discussion

Multimodal redundant warnings were effective even when drivers were talking on a cell phone (Exp. 1) or were driving in dense traffic (Exp. 2). These findings extend the literature on warnings since previous studies either considered unimodal warnings alone (Mohebbi et al., 2009) or tested the effects of multimodal warnings in a limited driving context (e.g., driving and listening to the radio, Ho et al., 2007). However, it is worth noting that, while multimodal warnings eliminated the cost associated with driving in dense traffic (Exp. 2), the same phenomenon was not observed with participants talking on a cell phone (Exp. 1). An explanation may be found in the theory of Strayer et al. (2011): Talking on a cell phone requires drivers to listen to the message produced by another speaker, process it, and produce a vocal response (Mulatti et al., 2010). Although the final stage involves motor activation, the core of the task is cognitive in nature (Rossi et al., 2012). Driving in the traffic, on the other hand, is associated with a significant amount of visual workload. Indeed, dense traffic may cause drivers to divert their eyes from the forward roadway (Stutts et al., 2003).

In a preliminary study, we (Biondi et al., 2014b) had participants perform two tasks using a dual-task paradigm (Pashler, 1994). Although multimodal stimuli for the first task reduced the interference produced by executing the two tasks concurrently (i.e., dual-task cost), these stimuli were never able to eliminate the interference completely. We interpreted these data within a dual-task context in which presenting multimodal stimuli may have a facilitatory effect at the perceptual stage of processing but not at the cognitive stage, given that the cost was never eliminated. From this perspective, the results obtained in Exp. 1 may be accounted for as a consequence of the inability of multimodal warnings to circumvent the cognitive bottleneck (Rossi et al., 2012) produced by the cell phone conversation. On the other hand, since driving in dense traffic is associated with a significant visual demand, presenting (non-visual) multimodal warnings may have successfully reduced the perceptual component of the dual-task cost, a hypothesis in accordance with multiple resource theories (Wickens, 1980, 1984).

Talking on a cell phone has been widely observed to slow braking times (Strayer and Drews, 2004) and increase the likelihood of getting into accidents (Redelmeier and Tibshirani, 1997), especially when traffic is congested. Because multimodal warnings speeded braking responses and elevated the feeling of urgency, we suggest that the benefit associated with these warnings may be maximized in emergency situations when severe collisions are about to occur if no appropriate maneuvers are executed (Marshall et al., 2007).

One limitation of that the current research is that it was performed in a driving simulator and drivers may have expected the warnings and lead vehicle's braking. By creating eight different driving scenarios with warnings presented at different locations, we attempted to make the signals unpredictable. However, even if participants could anticipate the presentation of signals, the relative differences across warnings and, more importantly, the benefits associated with multimodal warnings obtained in our studies may hold in more realistic conditions. Furthermore, the high frequency of deceleration events are similar to stop-and-go rush hour traffic.

A main concern associated with warnings is that if there are too many warnings across ADAS, and/or if the warnings are poorly-designed, they may likely be distracting. Everyday examples of such situations are found in intensive care units in hospitals (Edworthy and Hellier, 2006). For this reason, instead of assisting, they may impair safety (Schmid et al., 2011). In surface transportation, a plausible solution to avoiding distracting or annoying warnings is to employ adaptive warnings that are easier to interpret and faster to respond to. Adaptive warnings are warnings whose characteristics (e.g., pitch for auditory or vibration frequency for vibrotactile warnings) vary depending on, for instance, the type of hazard (a bicycle vs. a truck; see Biondi and Skrypchuk, 2016), the age of the driver (teen vs. elderly drivers) or the level of emergency (low fuel level vs. collision system). Given the high ratings of perceived urgency associated with multimodal warnings, we suggest that they be only presented in emergency situations requiring the execution of fast driving maneuvers to avoid accidents.

Acknowledgments

The authors acknowledge the technical contribution of Joel M. Cooper, Ph.D. (Precision Driving Research, Salt Lake City, Utah).

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