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

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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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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