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Jeffrey J. Scott
Arizona State University

Rob Gray
Arizona State University

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COMPARISON OF DRIVER BRAKE REACTION TIMES TO MULTIMODAL REAR-END COLLISION WARNINGS

Jeffrey J. Scott^{1,2} and Rob Gray¹

¹Arizona State University

²United States Air Force

Mesa, AZ, USA

E-mail: jeffrey.j.scott@asu.edu, robgray@asu.edu

Summary: This study examined the effectiveness of rear-end collision warnings presented in different sensory modalities as a function of warning timing in a driving simulator. Drivers experienced four warning conditions: no warning, visual, auditory, and tactile. The warnings activated when the time-to-collision (TTC) reached a critical value of 3.0 or 5.0 s TTC. Driver reaction time (RT) was captured from the time the driver crossed the warning activation threshold to brake initiation. Mean driver RT data showed that the tactile warning significantly outperformed the visual warning, providing support for tactile displays as effective rear-end collision warnings.

INTRODUCTION

Over 42,000 people are killed on U.S. roadways every year in motor vehicle crashes (NHTSA, 2006). Of those crashes, 30% are reported as rear-end collisions. Of those rear-end collisions, it has been estimated that more than 60% are caused by driver inattention (Knipling et al., 1993). The proposed introduction of in-vehicle transportation information systems and entertainment technology will likely increase demands on driver visual attention (Lee, 1997; Tijerina, Johnston, Parmer, Winterbottom, & Goodman, 2000; Van Erp & Van Veen, 2004). But not all distractions are visual. Conversations with other passengers or on cellular telephones also demand the driver's cognitive attention resources (Haigney, Taylor, & Westerman, 2003; Tijerina, et al., 2000; Törnros & Bolling, 2005).

Research is underway to develop rear-end collision warnings to capture driver attention and prevent rear-end collisions. Although previous studies showed a significant reduction of rear-end collisions (e.g., Lee, McGehee, Brown, & Reyes, 2002), the collision warnings were limited to the visual and auditory modalities (see also Bhatia, 2003) and these perceptual systems are already very much engaged in the driving task. For example, drivers are likely to miss visual warnings if their attention is not forward—even when actively engaged in the driving task. Alternatively, a visual warning display may place demands on visual attention that compete with those required for the detection of an impending collision (Hirst & Graham, 1997). Similarly, auditory stimuli in the driving environment may overburden the auditory system and limit the effectiveness of such warnings.

Although the driver's visual and auditory systems are often engaged during driving situations, the sense of touch is an overlooked and underutilized sensory modality that has great potential to support driver situation awareness. Previous driving research (e.g., Ho, Reed, & Spence, 2006; Ho, Tan, & Spence, 2005; Tan, Gray, Young, & Traylor, 2003) shows promising findings for in-

vehicle tactile warning systems, because tactile stimuli seem to reliably re-direct driver visual attention forward; and for rear-end collision warnings, tactile warnings result in earlier braking responses (than without a warning) and therefore larger safety distances between vehicles.

Most previous research only compared auditory to tactile warnings or compared a tactile warning to a variation of the tactile warning. The present research directly compared mean driver brake RT with a tactile warning to driver brake RT with visual and auditory warnings. Braking RT in car-following situations has been argued to provide a robust measure of the attention and perceptual aspects of driving performance (Brookhuis, de Waard, & Mulder, 1994), so it follows that drivers with the shortest RT have the fewest rear-end collisions.

METHODS

Driving Simulator

The fixed-base driving simulator was composed of two main components: (a) a steering wheel mounted on a table top and pedals (Wingman Formula Force GP, Logitech™) and (b) a 70° horizontal x 52° vertical display of a simulated driving scene. The visual scene was rendered and updated by DriveSafety™ driving simulator software running on two PC's (Dell Optiplex GX270). The visual scene was projected onto a wall 2.4 m in front of the participant using a LCD projector (Hitachi CPX1200SER) and updated at a rate of 60 Hz. The DriveSafety™ software captured various driving performance elements at 60 Hz.

The visual warning was a 5 cm x 5 cm triangular display of red LEDs mounted in front of the driver. The display was 91.44 cm (36 in) in height and was located 9° to 12° below the driver's eye height on the simulated instrument console. The visual warning display was deliberately positioned opposite the virtual speedometer to simulate current/future in-vehicle, in-dash information displays (Ho, Reed, & Spence, 2006) and force a wider visual search like in a real driving environment. The 500-Hz auditory warning issued from three, 6.5-cm (2.56-in) diameter speakers on the fixed-base instrument console. The tactile warning issued from three tactors (2.54 x 1.85 x 1.07 cm, VBW32, Audiological Engineering Corp., Somerville, MA) mounted in a soft housing on the driver's waist belt (to muffle the audio output from the activated tactors). The tactor housing was positioned on the front-center of the driver's abdomen. When triggered, the warnings activated for 200 ms with an 800 ms pause; i.e., once per second for 200 ms.

Procedure

Sixteen drivers ages 19 to 42 ($M = 27.6$, $SD = 8.4$) with 2 to 24 years of driving experience ($M = 10.2$, $SD = 7.6$) participated in the study. All drivers completed an informed consent and were compensated for their participation. The drivers were naïve to the aims of the experiment. The drivers followed a red lead car on a rural, two-lane road and were instructed to maintain a 2.0 s time headway with the lead car (Ho, Reed, & Spence, 2006; Janssen, Michon, & Harvey, 1976). If the drivers followed too far behind the lead car, the words "Speed Up!" would appear in red text on the driver's display. The lead car was programmed to travel at speeds between 35 and 75 mph and unpredictably (to the driver) accelerate, decelerate, and brake to a full stop (-6 m/s^2

deceleration rate), creating multiple potential rear-end collision situations. Drivers were directed to drive in their lane and not change lanes.

To more closely simulate real-world rural driving conditions, drivers listened to background music via streaming audio of their preference to engage the auditory system (Hughes & Cole, 1986), while intermittent opposing roadway traffic was included to engage the visual system (Ho, Reed, & Spence, 2006).

After a short practice session without a warning, drivers were presented counterbalanced blocks of the visual, auditory, and tactile warnings, plus a no-warning condition. The collision warning activated when the Time-to-Collision ([TTC] Lee, 1976) between the driver's vehicle and the lead car reached a critical threshold of either 3.0 or 5.0 s TTC (similar to Hirst & Graham, 1997). The drivers were randomly assigned equally between the 3.0 s and 5.0 s warning timing conditions. Driver RT was calculated from the time the driver crossed the critical warning threshold to brake initiation. Data was analyzed by Analysis of Variance (ANOVA) and Tukey pairwise comparison tests ($\alpha = .05$).

RESULTS AND DISCUSSION

Effect of Modality

As seen in Figure 1, the tactile warning produced the shortest mean driver RT. ANOVA revealed a significant main effect of Modality ($F(3,42) = 17.16, p < .001$). Tukey comparisons showed all warning modalities produced significantly shorter driver RT than the no-warning condition (visual: $q = 4.344$; auditory: $q = 6.977$; tactile: $q = 9.808$). These findings are consistent with Ho, Tan, and Spence's (2005) findings that any warning was better than no warning. Furthermore, the tactile warning produced significantly shorter driver RT than the visual warning ($q = 5.465$), suggesting a tactile warning may be superior to visual warnings in rear-end collision situations.

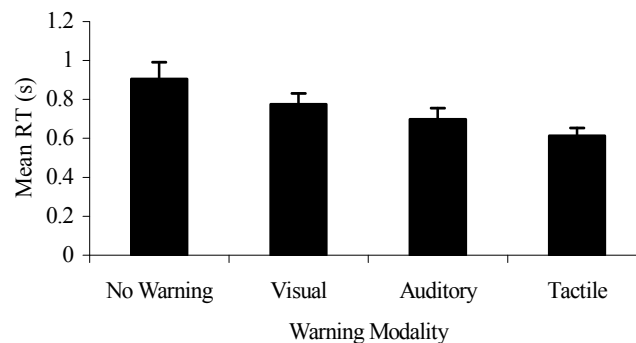


Figure 1. Mean driver RT across the warning modalities
(Error bars represent standard errors)

Effect of Warning Timing

As seen in Figure 2, the tactile warning again produced the shortest mean driver RT in both timing conditions. ANOVA revealed a significant main effect of Warning Timing ($F(1,14) = 47.865, p < .001$). This significance was most likely a result of the experimental methodology;

i.e., the 5.0 s TTC warning activation window opened earlier than the 3.0 s TTC envelope so drivers had more time to react to the warning stimuli and probably decided to coast and close with the lead car before applying brakes. Previous research substantiates this conclusion (Abe & Richardson, 2004; Muttart, 2005).

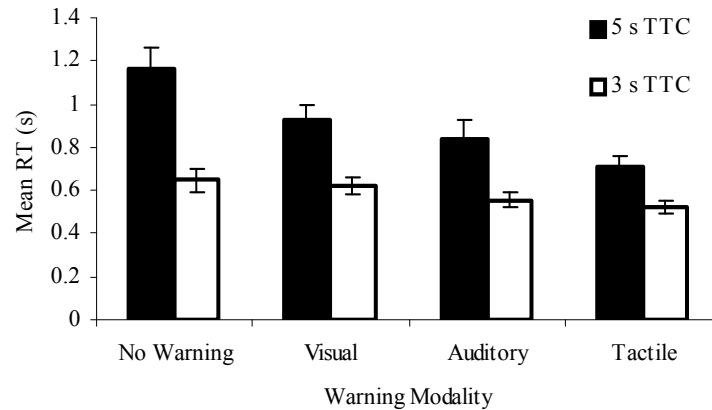


Figure 2. Mean driver RT decomposed into early and late warning timing conditions across the warning modalities. (Error bars represent standard errors.)

Modality x Warning Timing Interaction

ANOVA revealed a significant Modality x Warning Timing interaction ($F(3,42) = 5.498, p = .007$) (Figure 2). Tukey comparisons of the early warning condition revealed significant differences between the no-warning and visual ($q = 4.935$), audio ($q = 6.820$), and tactile ($q = 9.611$) warnings. These statistics suggest that any modality with an early warning is suitable to improve driver RT in rear-end collision situations over situations without a warning. However, there is also a significant difference between the visual and tactile warnings ($q = 4.670$), suggesting that early tactile warnings may be more effective than early visual warnings, resulting in faster brake application and a larger safety margin between the two vehicles. There were no significant differences in the late warning condition; however, the tactile warning still elicited the fastest responses, and even a small decrease in RT can result in a significant decrease in rear-end collisions (Brown, Lee, & McGehee, 2001).

Driver Preferences

An alternate explanation for the significantly shorter RT to tactile warnings may be that drivers hit the brake as soon as the warning activated simply to terminate the tactile warning. In a post-experiment questionnaire, 37.5% of drivers (Figure 3) reported that they least preferred the tactile system, expressing that the tactile belt was “annoying,” “distracting,” and/or “stressful.” Conversely, 31.25% of drivers reported that they preferred the tactile warning system to all other warning conditions. The drivers that disliked the tactile warning explained that they did not like the sensation the tactors made on their abdomen. The placement of the tactile display on the front-center of a waist belt was selected to (a) simulate a vehicle’s seat restraint, (b) because it was easy to don, and (c) to capitalize on the directionality benefit of tactile displays (e.g., Van Erp, 2005). Perhaps adjusting the placement of the tactile display would eliminate or minimize

the annoyance (e.g., on the shoulder harness of a vehicle's seat restraint). More research is necessary to determine the most effective placement, presentation, number, and intensity of a tactile display for rear-end collision warnings. Regardless of driver preference, the present findings, along with previous research (e.g., Lee, Hoffman, & Hayes, 2004; Ferris, Penfold, Hameed, & Sarter, 2006), support tactile warnings over visual and audio warnings for rear-end collision avoidance—some drivers may not have preferred the tactile warnings, but they worked the best to improve brake RT!

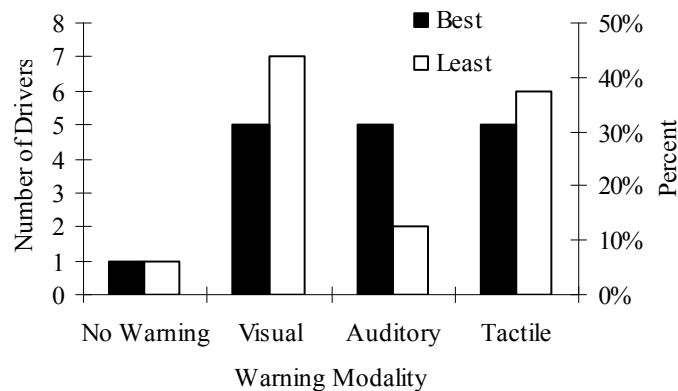


Figure 3. Driver's preference ratings of warning stimulus modality

Interestingly, there is a near-even split between drivers that prefer visual warnings and those that prefer tactile warnings. Of the five drivers that preferred the visual warning, four of them (80%) least preferred the tactile warning. Conversely, five of six drivers (83%) that preferred the tactile warning least preferred the visual warning. The most recurring comment from drivers in each camp was that their least preferred warning was too distracting. Perhaps those drivers that were uncomfortable or annoyed with the tactile warning simply selected as their most preferred the warning modality that they perceived was the least intrusive or alarming (in this case, the visual warning). Conversely, those drivers that preferred the alarming nature of the tactile warning selected the warning that they perceived was the least alarming (again, the visual warning).

LIMITING FACTORS

The present findings are limited by the simulation paradigm. For example, mean driver RT recorded in this simulation may be shorter than can be expected in a real driving situation. However, it is reasonable to expect that the relative effectiveness of the different modalities will be the same in real driving; i.e., tactile warnings should still produce shorter driver brake RT relative to visual and auditory warnings in the real world. This needs to be tested empirically. Additionally, future tactile rear-end collision warning experiments should examine (a) the effectiveness of the tactile warning when the lead car's brake lights are enabled, (b) the number, placement, and intensity of tactile displays, (c) tactile warning reliability and driver trust issues, as well as incorporate more realistic and complex driving conditions such as (d) increased audio loading (e.g., cell phones) and (e) more sophisticated collision warning algorithms.

CONCLUSION

Driver inattention is a major contributor in rear-end collision accidents. Research is underway to design warnings that most effectively capture driver attention to prevent rear-end collisions. Previous research in other domains has shown the tactile modality is an effective way to present warning information to a user. The present research directly compared driver brake RT to tactile warnings to driver brake RT to visual and auditory warnings in a driving simulator. Regardless of driver preferences, the findings show that tactile warnings produced the shortest driver RT, suggesting that tactile warnings capture driver attention more effectively than visual or auditory warnings and thus result in less closure and a larger safety margin between two vehicles traveling in the same direction on the roadway. These findings provide support for tactile warnings as effective rear-end collision warnings.

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