**A Comparison of Tactile, Visual, and Auditory Warnings for Rear-End Collision Prevention in Simulated Driving**

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**Objective:** 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. **Background:** The proliferation of in-vehicle information and entertainment systems threatens driver attention and may increase the risk of rear-end collisions. Collision warning systems have been shown to improve inattentive and/or distracted driver response time (RT) in rear-end collision situations. However, most previous rear-end collision warning research has not directly compared auditory, visual, and tactile warnings. **Method:** Sixteen participants in a fixed-base driving simulator experienced four warning conditions: no warning, visual, auditory, and tactile. The warnings activated when the time-to-collision (TTC) reached a critical threshold of 3.0 or 5.0 s. Driver RT was captured from a warning below critical threshold to brake initiation. **Results:** Drivers with a tactile warning had the shortest mean RT. Drivers with a tactile warning had significantly shorter RT than drivers without a warning and had a significant advantage over drivers with visual warnings. **Conclusion:** Tactile warnings show promise as effective rear-end collision warnings. **Application:** The results of this study can be applied to the future design and evaluation of automotive warnings designed to reduce rear-end collisions.

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**INTRODUCTION**

More than 42,000 people are killed on U.S. roadways every year in motor vehicle crashes (National Highway Traffic Safety Administration [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 (J. D. Lee, 1997; Tijerina, Johnston, Parmer, Winterbottom, & Goodman, 2000; van Erp & van Veen, 2004). Drivers already allocate 30% to 50% of their visual attention to secondary tasks such as changing radio stations or manipulating the vehicle’s environmental settings (Hughes & Cole, 1986), spending about one third of their time looking inside the vehicle (Antin, Dingus, Hulse, & Wierwille, 1990).

But not all distractions are visual. Conversations with other passengers or via cellular telephones also demand the driver’s cognitive attention resources (Haigney, Taylor, & Westerman, 2000; Tijerina et al., 2000; Törnros & Bolling, 2005). Drivers engaged in handheld or hands-free cell phone conversations are more likely to miss critical traffic events (e.g., stop signs, traffic signals) and react more slowly to the events they do detect (Strayer & Johnston, 2001), as well as reacting more slowly to brake lights of a leading vehicle (Strayer, Drews, & Johnston, 2003).

Research is under way 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., J. D. 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 the visual resources required for detecting an impending collision (Hirst & Graham, 1997). Similarly, auditory stimuli in the driving environment may overburden the auditory system and limit the effectiveness of auditory warnings. Any attentional demand that causes the driver to look away from the road (e.g., an in-dash navigation system) or directs cognitive resources away from the road (e.g., a cell phone conversation) compromises driver situation awareness and traffic safety (Strayer & Johnston, 2001; Strayer et al., 2003; Tijerina et al., 2000; van Erp & van Veen, 2004).

Although the driver’s visual and auditory systems are engaged during driving, the sense of touch is an overlooked and underused sensory modality that has great potential to improve driver performance. Research in other domains has shown successful employment of tactile displays for navigation, situation awareness, and warnings (e.g., Rupert, 2000; Sklar & Sarter, 1999; van Erp, 2005). 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 redirect 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.

However, these previous studies did not directly compare tactile warnings with both auditory and visual warnings. Therefore, in the present research we examine the effectiveness of the tactile modality as a rear-end collision warning by comparing mean driver brake response time (RT) with a tactile warning to driver brake RT with visual and auditory warnings. Because the visual and auditory perceptual systems are more engaged in the driving task than is the tactile system, warnings in the tactile modality should produce shorter driver brake RT than visual and auditory warnings do.

The purpose of the present study was to directly compare the effectiveness of visual, tactile, and auditory rear-end collision warnings relative to a no-warning condition in a driving simulator. The effect of modality on collision warnings has been examined in previous research (e.g., Kiefer et al., 1999; J. D. Lee, McGehee, Brown, & Marshall, 2006; McGehee, LeBlanc, Kiefer, & Salinger, 2002), but in these studies warnings were multimodal (e.g., tactile plus visual) – unimodal warnings in each modality were not directly compared.

In addition, the tactile warnings in these previous studies were delivered via the accelerator pedal and/or by tactors mounted below the driver’s legs. To our knowledge, no previous research has compared the effectiveness of tactile warnings delivered via the seatbelt (that have shown promise in the work of Ho, Spence, and colleagues) relative to visual, auditory, and no warnings. Although on the surface this difference may seem minor, tactile warnings delivered via the pedal or seat may result in both attentional alerting and motor preparation (because they are stimulating the area of the body involved in the braking response – the leg/foot), whereas warnings delivered via the seatbelt would presumably have only an attentional alerting effect. Therefore, these different types of tactile warnings may differ in relative effectiveness compared with warnings in other modalities.

**METHOD**

**Driving Simulator and Warnings**

The fixed-base driving simulator was composed of two main components: (a) a steering wheel mounted on a tabletop and pedals (Wingman Formula Force GP, Logitech™) and (b) a 70-deg horizontal × 52-deg vertical display of a simulated driving scene. The visual scene was rendered and updated by DriveSafety™ driving simulator software running on two PCs (Dell Optiplex GX270). The visual scene was projected onto a wall 2.4 m in front of the participant using an 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 discrete 5 × 5-cm triangular array of nine red optoelectronic LEDs located on the simulated dashboard 9 to 12 deg below the driver’s line of sight and 6 deg to the right of his or her body midline. This warning location is roughly within the “10-deg cone of the driver’s line of sight” recommended by McGehee
et al. (2002). The warning was located 1.1 m from the driver’s eyes so that it subtended 2.6 × 2.6 deg. This triangular dashboard warning was designed to be similar to the forward collision warnings used in several commercial vehicles (Kiefer et al., 1999).

The visual warning display was deliberately positioned on the opposite of the visual field to the virtual speedometer to simulate current/future in-vehicle, in-dash information displays (Ho et al., 2006) and force a wider visual search as in a real driving environment. The luminance of the display was 45.4 cd/m². The mean road luminance was approximately 11.5 cd/m; therefore, the contrast of the visual warning (relative to the display of the simulated road) was high.

The auditory warning was a 75-dB, 2000-Hz auditory tone issued from an array of three 6.5-cm-diameter speakers (with lateral separation of 10 cm center to center) located on the simulated dashboard. The speakers were at the same height as the visual warning. The center speaker was located directly in front of the driver. This warning was designed to follow the guidelines of McGehee et al. (2002), which recommended a “distinctive, non-speech auditory warning…that emanates from the general direction of the threat” (p. 6). The 75-dB intensity of the auditory warning was also chosen based on the McGehee et al. guidelines and was considerably greater than the combined intensity of the noise of simulated engine, road, traffic, and radio (approximately 60 dB).

Design and Procedure

Sixteen drivers (ages 19–42, 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 naive to the aims of the experiment. They followed a red lead car on a rural two-lane road and were instructed to drive in their own lane and not pass the lead car. Drivers were given a 5-min practice drive without a warning to become familiar with the driving simulator. They were permitted to repeat the practice if desired. For the experimental trials, drivers were presented counterbalanced blocks of the visual, auditory, and tactile warnings plus a no-warning (baseline) condition. Trials lasted 8 to 10 min.

Drivers were instructed to maintain a 2.0-s time headway (TH) with the lead car (Ho et al., 2006; Janssen, Michon, & Harvey, 1976). If they followed too far behind the lead car, the words “Speed Up!” would appear in red text on the display. Ho et al. (2006) used a red-green-red tri-box indicator to inform the driver of the correct TH,
but a simple text message was used in this experiment so as to not confound the rear-end collision warning with a “too close” TH indication.

The collision warning was activated when the time to collision (TTC; D. N. Lee, 1976) between the driver’s vehicle and the lead car fell below a critical threshold of either 3.0 or 5.0 s (similar to Hirst & Graham, 1997). The drivers were randomly assigned equally between the 3- and 5-s warning timing conditions.

The lead car was programmed to unpredictably (to the driver) change speeds at variable intervals. The lead car traveled between 35 and 75 mph (average speed 55 mph), changing speeds between 10 and 30 s (average time 20 s).

In addition, the lead car was programmed to make 11 unpredictable (to the driver) full stops at a –6 m/s² deceleration rate. The unpredictable behavior of the lead car made it very difficult for the driver to predict when the lead car would speed up, slow down, or stop, creating multiple possible rear-end collision situations. The critical 3- or 5-s TTC warning activation threshold was updated and monitored at 60 Hz, so the warning activation distance between the two cars would shift depending on their relative velocities. This warning activation window would continuously adjust for the constantly changing speeds of the two cars, triggering multiple and unpredictable rear-end collision warning activations.

To more closely simulate real-world rural driving conditions, drivers listened to background music of their preference at 60 dB to engage the auditory system (Hughes & Cole, 1986), and intermittent opposing roadway traffic was included to engage the visual system (Ho et al., 2006).

**Dependent Variable**

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 driver brake RT was the main dependent variable in this analysis. Driver brake RT was captured from the time the TTC between the two vehicles fell below the critical warning threshold to driver brake onset. An analysis of variance (ANOVA) was accomplished with warning timing as a between-drivers variable. In addition, Tukey pairwise comparisons (α = .05) were accomplished to compare each warning condition against the others.

**RESULTS**

It was established prior to data collection that we would not include potential collision events if the participants followed too far behind the lead car (i.e., failed to maintain the directed 2-s time headway) at the onset of the collision event. In many of these cases, the lead car was obviously slowing and/or stopped, and the driver was already braking before the driver reached the 3.0- or 5.0-s TTC warning activation criterion.

Although rear-end collision warnings should alert inattentive drivers to stopped vehicles, the drivers in this experiment were fully attending to the lead car and could easily see when the lead car slowed and stopped, thereby rendering the warning to a stopped car an unnecessary nuisance alarm. Consequently, 9.1% of scripted collision events were not evaluated (consistent with Ho et al., 2006) if the driver’s TH with the lead car was greater than 2 s when the collision warning activated.

**Effect of Modality**

Figure 1a shows mean driver RT. As can be seen in this figure, driver RT was the lowest with the tactile warning and the highest in the no-warning condition. ANOVA revealed significant main effects of modality, \( F(3, 42) = 17.16, p \leq .001 \). Tukey comparisons showed that all warning modalities were significantly different from the no-warning condition (visual: \( q = 4.344 \); auditory: \( q = 6.977 \); tactile: \( q = 9.808 \)) and that the tactile warning was significantly different from the visual warning condition, \( q = 5.465 \).

**Effect of Warning Timing**

Figure 1b shows mean driver RT decomposed by warning timing. Solid bars show mean driver RT for the 5-s TTC warning, and open bars show mean driver RT for the 3-s TTC warning. ANOVA revealed significant main effects of warning timing, \( F(1, 14) = 47.865, p < .001 \).

**Modality × Warning Timing Interaction**

ANOVA revealed a significant Modality × Warning Timing interaction, \( F(3, 42) = 5.498, p = .003 \). 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 as well as between the visual and tactile warnings.
There were no significant findings in the late warning condition.

Recall that the DriveSafety™ driving simulator software provided data at 60 Hz – providing a very discrete resolution of driver braking behavior for post hoc analysis. Therefore, driver braking behavior was decomposed into two mutually exclusive segments for examination: warning below threshold to accelerator release (labeled BT2R) and accelerator release to brake onset (R2B).

In the early warning condition of the BT2R segment, Tukey comparisons revealed significant differences ($q = 4.670$) between the no-warning ($M = 0.471$ s) and audio warning ($M = 0.338$ s) conditions and significant differences ($q = 4.160$) between the no-warning and tactile warning ($M = 0.332$ s) conditions. In the early warning condition of the R2B segment, Tukey comparisons revealed a significant ($q = 3.935$) difference between the no-warning ($M = 0.757$ s) and the tactile warning ($M = 0.475$ s) conditions. There were no significant findings in the late warning condition for either segment. Table 1 provides a snapshot overview of the significant findings.

### Effect of Driver State

There were collision events as the driver was both on the accelerator and not on the accelerator (i.e., coasting). Figure 2 shows mean driver RT separated into these different states.

When accelerating, modality ($F[3, 42] = 6.611$, $p = .001$) and warning timing ($F[1, 14] = 35.719$, $p < .001$) were significant. Tukey comparisons showed that the auditory ($q = 4.686$) and tactile ($q = 6.001$) warnings were significantly different from the no-warning condition. When coasting, modality ($F[3, 42] = 7.829$, $p < .001$), warning timing ($F[1, 14] = 6.082$, $p = 0.27$), and Modality × Warning Timing ($F[3, 42] = 4.371$, $p = .009$) were significant. Tukey comparisons showed that the no-warning condition was significantly different from all warnings (visual: $q = 4.170$; auditory: $q = 5.399$; and tactile: $q = 6.334$).
Warning timing decomposition revealed significant differences in the early (5-s TTC) warning condition only. While accelerating, the no-warning condition was different from both the auditory ($q = 4.460$) and tactile ($q = 5.586$) warning modality conditions. While coasting, the no-warning condition was significantly different from all warning conditions (visual: $q = 5.573$; auditory: $q = 6.126$; tactile: $q = 6.926$). There were no significant findings in the late warning condition. Table 2 shows a snapshot overview of significant findings per driver state.

### Number of Collisions

A collision event was recorded when the driver got close enough to the lead car to activate the collision warning (or, in the case of the no-warning condition, when the driver reached the critical TTC warning activation threshold). A collision was recorded when the driver collided with the lead car. Figure 3 shows the mean number of collision events and mean number of collisions per warning modality.

There was no significant effect of modality on either the number of collision events or number of collisions. Tukey comparisons did not reveal any further significance. However, drivers without a warning had the highest percentage of collisions per number of collision events (12.95%) compared with drivers with the visual (10.14%), auditory (7.8%), or tactile (5.1%) warnings.

### Driver Preferences

Figure 4 shows drivers’ preferred warning condition as self-reported in a postdrive questionnaire.

### Warning Detectability Control Study

A control study was completed to determine if

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**TABLE 1: Overview of Significant Findings**

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<thead>
<tr>
<th>Modality</th>
<th>Overall $^a$</th>
<th>Early $^b$</th>
<th>Late $^b$</th>
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<td>V</td>
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<td>No warning vs. auditory</td>
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<td>No warning vs. tactile</td>
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<td>Visual vs. auditory</td>
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<td>Auditory vs. tactile</td>
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Note. The letters in the cells represent the warning modality conditions that produced the shorter mean driver response time (RT). For example, in the Overall column, No warning vs. tactile row, the tactile warning produced a significantly shorter driver RT than the no-warning condition. Blank cells represent no significant differences between conditions.

$^a$Overall significant effect of modality. $^b$Significant effect of Modality $\times$ Warning Timing interaction.

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*Figure 2. Mean driver response time (RT) per driver state for both warning timing conditions across the warning modalities. Error bars represent standard errors. Solid bars show mean driver RT while accelerating and open bars show mean driver RT while coasting.*
the warning stimuli used in this experiment differed in conspicuity. Ten participants sat at the controls of the fixed-base simulator used in the present experiment and responded to blocked, counterbalanced presentations of the visual, auditory, and tactile stimuli used in the present experiment. Each modality was presented 15 times with a randomized 0.5- to 2.0-s interval between activation. The participants responded via computer mouse click when they perceived the warning stimulus.

Mean RT was recorded for analysis (visual: $M = 0.287$ s, $SD = 0.026$; audio: $M = 0.315$ s, $SD = 0.039$; tactile: $M = 0.309$ s, $SD = 0.044$). A one-way ANOVA revealed no significant differences across warning modalities. We used Cohen’s $d$ as a measure of effect size and found a $d = 0.27$, which is considered to be a small effect size (Cohen, 1988).

**No Radio Control Study**

As suggested by an anonymous reviewer, it may have been unfair to compare an auditory warning that was presented with a mask (the radio noise) versus unmasked visual and tactile warnings. To address this concern, we conducted

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<th>Modality</th>
<th>Accelerating</th>
<th>Coasting</th>
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<td></td>
<td>Overall$^a$</td>
<td>Early</td>
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<td>No warning vs. visual</td>
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<td>Auditory vs. tactile</td>
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*Overall significant effect of modality. $^b$Significant effect of Modality × Warning Timing interaction.

Note. The letters in the cells represent the warning modality conditions that produced the shorter mean driver response time (RT). For example, in the Accelerating Overall column, No warning vs. tactile row, the tactile warning produced a significantly shorter driver RT than the no-warning condition. Blank cells represent no significant differences between conditions.

![Figure 3](image.png)

*Figure 3.* Mean number of collision events and mean number of collisions across warning modalities. Triangle icons identify percentage of the mean number of collisions per the mean number of collision events per warning modality across all subjects.
one control study in which the radio was turned off with eight participants who did not complete the experiments described earlier. For this experiment, only the early (i.e., 5.0-s TTC) warning activation criterion was used. Mean reaction times (SE in parentheses) averaged across the eight drivers were 0.918 s (0.07), 0.896 s (0.08), 0.741 s (0.06), and 0.681 s (0.05) for the no-warning, visual, auditory, and tactile conditions, respectively.

Tukey tests revealed the similar pattern of results as found for the radio-on condition described earlier – namely, the auditory warning ($q = 3.98$) and the tactile warning ($q = 4.16$) were significantly different from the no-warning condition, and the tactile warning was significantly different from the visual warning condition ($q = 3.88$).

**Driver Demographics Correlations**

There were no significant correlations between driver grand mean RT (calculated across all warning modalities) and driver gender or years of licensed driving experience.

**DISCUSSION**

**Effect of Modality**

The significant effect of modality is consistent with Ho et al.’s (2005) earlier findings that any warning was better than no warning. Furthermore, Tukey comparisons showed that drivers had significantly shorter RT with the tactile warning than with the visual warning, suggesting that tactile warnings produce faster driver responses than visual warnings in rear-end collision situations.

The lack of significance between the auditory and tactile warnings may be a result of unrepresentative audio loading. Although the volume of the background audio was clearly audible over the simulated roadway noise (yet less than the auditory warning), three drivers reported that they were so engaged in the driving simulation that they paid little attention to the background music. In a real driving situation – in which the novelty, constraints, and challenges of the driving simulation experiment are absent and drivers are comfortable and confident in their own automobiles – the auditory system may potentially be engaged with music louder than vehicle/roadway noise, passenger/cellular phone conversations, and/or in-vehicle information/entertainment systems. Further research should include such conditions to more closely simulate present-day, real-world driving distractions.

**Effect of Warning Timing**

As seen in Figure 1b, the significant effect of warning timing occurred because the recorded times for the 3-s TTC warning were shorter than those for the 5-s TTC warning. This significance was most likely a result of the experimental methodology (i.e., the 5-s TTC warning activated earlier than the 3-s TTC warning). Therefore, drivers had more time to evaluate the evolving collision situation and probably decided to coast and close with the lead car before applying the brakes.
Previous research substantiates this conclusion. Abe and Richardson (2004) concluded that drivers with early warnings were able to recognize imminent collision situations faster than with late warnings and thus apply brakes as necessary to prevent collisions. Similarly, Muttart (2005) argued that at TTCs of 5 s or greater, the collision situation is becoming less and less of an immediate emergency, so drivers have more time to make decisions.

**Modality × Warning Timing Interaction**

With a late warning, there was no statistically significant advantage of the visual, auditory, or tactile warning over the no-warning condition, nor was there an advantage of one modality over another. This finding makes sense because drivers have little time to react to late warnings, regardless of warning type, and most likely reflexively release the accelerator and quickly transition to the brake.

With an early warning, Tukey comparisons showed that all warning modalities produced significantly shorter driver RT than the no-warning condition. These statistics suggest that any modality with an early warning is suitable to improve driver RT in rear-end collision situations, even without a warning. In addition, drivers with an early warning exhibited significantly shorter RT with a tactile warning than with a visual warning. This finding suggests that early tactile warnings may be more effective than early visual warnings to improve driver braking responses.

When driver braking behavior in the early warning condition was decomposed and examined from the warning below threshold to accelerator release (BT2R), Tukey comparisons showed that driver RT with auditory and tactile warnings was significantly shorter than driver RT without a warning, suggesting that early tactile and auditory warnings may prompt drivers to release the accelerator earlier than they would normally (i.e., without a warning), thus creating more separation between the two vehicles. When examining the accelerator release to brake (R2B) component, only the tactile warning produced significantly faster driver responses than the no-warning condition. This finding suggests that even with sufficient time to evaluate the evolving collision situation, drivers with a tactile warning transition to the brake more quickly than with visual or auditory warnings, resulting in less closure with the lead vehicle and therefore a greater safety margin between the two vehicles.

An alternative explanation for the significantly shorter driver RT to tactile warnings may be that drivers hit the brake as quickly as possible to terminate the tactile warning. In a postexperiment questionnaire, 37.5% of drivers reported that they least preferred the tactile system, expressing that the tactile belt was “annoying,” “distracting,” and/or “stressful” (Figure 4). These drivers explained that they did not like the sensation the tactors made on their abdomens. The placement of the tactile display on the front-center of a waist belt was selected because (a) it was easy to don, (b) it simulated a vehicle’s seat restraint, and (c) it capitalized on the directionality benefit of tactile displays. Perhaps adjusting the placement of the tactors 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.

For example, J. D. Lee, Hoffman, and Hayes (2004) used a tactile seat to compare graded and imminent auditory and tactile collision warnings in a driving simulator. They found that graded alerts led to a greater safety margin than did imminent warnings and reported – contradictory to the present findings – that tactile warnings were perceived as less annoying than auditory warnings. Likewise, Ferris, Penfold, Hameed, and Sarter (2006) used a single tactor strapped to the outside of each upper arm in a cross-modal cueing experiment in a driving simulator and reported that most of their participants rated the tactile cue as most effective and the auditory cue as most annoying. Their tactors were deliberately positioned on the upper arm to cue drivers left and right. The upper arm usually has less body mass to disturb than the abdomen, and therefore Ferris et al.’s participants were probably not as annoyed by the single tactor’s vibration as were the drivers in the present experiment, who had tactors strapped around their abdomens.

However, 31.25% of drivers in the present study reported that they preferred the tactile warning system to the other warning modalities. The findings in this study, along with previous research (e.g., Ferris et al., 2006; J. D. Lee et al., 2004), support tactile warnings over visual and
auditory warnings for rear-end collision prevention. Some drivers may not have preferred the tactile warnings, but they worked the best to decrease driver RT!

**Effect of Driver State**

Modality had a significant effect on driver RT both when accelerating and coasting. Tukey comparisons again showed significantly shorter driver RT with the tactile and auditory warnings than without a warning for both accelerating and coasting driving states. These findings were also observed only in the early warning Modality × Warning Timing interaction, providing support for earlier – rather than later – rear-end collision warnings. More on warning timing is discussed later.

The visual warning was significantly different from the no-warning condition only while coasting (again observed only in the early warning timing condition). This finding suggests that drivers do not benefit from a visual warning while accelerating. Perhaps drivers do not observe the visual warning while accelerating because they are attending to other visual phenomena (e.g., optic flow, speedometer) and therefore do not have the visual attention resources to spare on visual warnings. This conclusion is consistent with Hirst and Graham’s (1997) position that drivers are likely to miss visual warnings even when actively engaged in the driving task and that visual warnings may compete with resources necessary for vehicle control.

**Number of Collisions**

Even though there was no significant effect of modality on either the number of collision events or the number of collisions, there was a decreasing trend in the percentage of collisions per collision events across warning modalities. For example, in the no-warning condition, drivers had an average of 1.8 collisions per 14 events (i.e., 12.95% of collision events resulted in a collision) compared with the tactile warning condition in which drivers averaged only about 0.6 collisions per 12 events (5.1%). This roughly 8% drop in collision percentage adds more observable evidence to support tactile displays as effective rear-end collision warnings.

**Absent Background Music**

The lack of differences in braking behavior between drivers listening to music and those not listening to music validates the observational and anecdotal remarks that the drivers listening to music were so engaged in the driving simulation that they disregarded the background music to concentrate on the driving task. This finding suggests that drivers need to be more comfortable driving the simulator in order to attend to background music, or the auditory loading needs to be more aggressive (cell phones, in-vehicle information/entertainment systems, etc.).

**More on Warning Timing**

Hirst and Graham (1997) were unable to conclude if earlier (e.g., 5-s TTC) warnings were more appropriate than later (e.g., 3-s TTC) warnings. Hirst and Graham compared only variations of visual and auditory warnings. The inclusion of tactile warnings helps elucidate some differences. For example, in all segments, driver RT in the early warning condition was significantly shorter than driver RT in the no-warning condition, providing support for earlier tactile warnings. Although earlier warnings may prompt earlier braking and thus prevent more collisions (Hirst & Graham, 1997), they will also likely increase the number of nuisance, false alarms (Abe & Richardson, 2004), which may be unacceptable to drivers. In fact, long-term exposure (i.e., everyday driving) to nuisance alarms could potentially undermine any safety benefits of collision warnings (J. D. Lee et al., 2002). Therefore, the evidence supporting early tactile warnings must be balanced against the fact that they may annoy or frustrate the driver. More research on tactile warning timing is necessary for real-world applications.

The present experiment eschewed any speed penalty as recommended by Hirst and Graham (1997) and used a simple dichotomy for the early and late warning timing criteria. The simple collision warning timing algorithm used here may not be suitable for practical applications; therefore, more sophisticated collision algorithms – such as the three-zone warning algorithm used by Brown, Lee, and McGehee (2001) or the stop-distance algorithm used by Abe and Richardson (2004) – may be more realistic and reveal further differences in driver RT with tactile warnings. Warning timing is a crucial factor for determining warning effectiveness (Janssen & Nilsson, as cited in Abe & Richardson, 2004), so future tactile warning research should include more sophisticated collision warning algorithms.
Other factors inextricably linked to warning timing are warning reliability and driver trust. Abe and Richardson (2004) argued that warning timing influences drivers’ perception of warning validity or reliability, with consequent effects on system acceptance and effectiveness. Their rear-end collision warning research established that early warnings result in a prompt braking response and increased trust. Late warnings may not actually help drivers avoid collision situations because some drivers may start braking before the activation of the warning (Abe & Richardson, 2005), leading to decreased trust, which may negatively affect collision warning system effectiveness.

Therefore, early warnings may play an important role in maintaining driver trust at appropriate levels despite the fact that these warnings do not always lead to improved driver performance (Abe & Richardson, 2005). Wickens and Flach (1988) argued that any evaluation of detection tasks (in this case, warning detection) must include a proper study of reliability. Future tactile collision warning research should include a study of warning reliability.

The findings of the present experiment are limited by the simulation paradigm. Although driving simulation is safer and allows a researcher to investigate a wider range of driving scenarios, it lacks the complexity and workload of a real driving situation. Therefore, the present findings may not faithfully translate to the real world. For example, the drivers in the present experiment were undistracted and fully expecting the lead car to suddenly stop, so driver responses recorded in this simulation are likely 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 – that is, tactile warnings should still produce faster driver braking responses relative to visual and auditory warnings in the real world. This needs to be tested empirically.

It was also the case that the frequency of warnings in our experiment was much higher than would occur in real driving, and it is possible that this high warning frequency could lead to unnatural driving behavior (see J. D. Lee et al., 2002). Future research is needed in which warnings occur at a much lower frequency. In addition, future tactile rear-end collision warning research should include more realistic and complex driving conditions, such as increased audio loading (e.g., cell phones and in-vehicle information/entertainment systems), and more sophisticated collision warning algorithms. In this experiment we did not examine multisensory warnings (e.g., audio and tactile); therefore, more research is needed.

CONCLUSION

Driver inattention is a major contributor in rear-end collision accidents. Research is under way to design warnings that most effectively capture driver attention to prevent rear-end collisions. Previous research in other domains has shown that the tactile modality is an effective way to present warning information to a user; however, most previous research compared only auditory warnings with tactile warnings or variations of tactile warnings.

In the present research we directly compared a tactile rear-end collision warning with auditory and visual rear-end collision warnings. Driver brake RT was captured for analysis. The timing of the warning was also varied between subjects by early (5-s TTC) and late (3-s TTC) warning timing conditions. The findings show that tactile warnings improved aware, expectant, and undistracted driver braking responses better than did visual or auditory warnings.

More research is necessary to determine the most effective way to present tactile warnings to the driver, but these findings provide support for tactile warnings as effective rear-end collision warnings.

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