To Go or Not to Go: Stimulus-Response Compatibility for Tactile and Auditory Pedestrian Collision Warnings

Stacie M. Straughn, Rob Gray, and Hong Z. Tan, *Senior Member*, *IEEE*

Abstract—This study examined the effect of the stimulus-response (S-R) compatibility of pedestrian collision warnings presented via different sensory modalities in a driving simulator. Despite the well-established fact that reaction times (RT) are faster under S-R compatible conditions, the majority of collision warning research has used S-R incompatible warnings (i.e., the warning comes from the direction of the obstacle to be avoided not the desired response direction). Thirty-two participants in a fixed-base driving simulator drove on a three-lane urban road in which pedestrians randomly walked from the sidewalk into the roadway. Collision warnings in two different modalities (tactile and auditory) were compared with a no warning condition. Participants were equally divided into one of four conditions representing all combinations of two levels of warning S-R compatibility (compatible and incompatible) and two levels of warning timing (early and late). For early warnings, incompatible warnings were most effective as shown by a significantly shorter steering RT and larger clearance distance. For late warnings, compatible warnings were most effective. For early warnings, RTs were significantly faster in the tactile condition. The relationship between collision warning effectiveness and S-R compatibility in driving is dependent on whether the driver has time to evaluate the situation before collision will occur. Our findings have important implications for the design of effective tactile and auditory collision warning systems. However, further research is needed to determine if these effects occur in more representative driving conditions (e.g., lower pedestrian incursion rate and unreliable warnings).

Index Terms—Attention, warnings, tactile warnings, auditory warnings, stimulus-response compatibility.

1 Introduction

Road accidents involving pedestrians are a serious problem worldwide, accounting for an estimated 65 percent of the 1.17 million yearly traffic-related deaths internationally [1]. While the frequency of pedestrian deaths in the United States is substantial (accounting for roughly 11 percent of all traffic fatalities in 2004 [2]), the problem is even worse in developing countries such as China and India where pedestrian accidents account for over 25 percent of traffic-related fatalities.

One of the main efforts to improve pedestrian safety has been the relatively recent development of Intelligent Vehicles Systems designed to detect and track pedestrians (e.g., [3]) and to use this information to deliver pedestrian collision warnings to the driver (e.g., [4]). While a great deal of effort has been put into investigating the technological aspects of pedestrian warnings (e.g., detection algorithms, computer vision systems, etc), relatively little attention has been paid to the human factor issues associated with these types of warnings [5]. In the present study, we focus on two such issues: the sensory modality used to present the warning and the stimulus-response (S-R) compatibility of the warning.

The question of which sensory modality is best for the presentation of pedestrian warnings has not been examined in previous research; however, this issue has been studied in detail for rear-end collision and lane departure warnings in driving (e.g., [6], [7]). Although previous studies showed a significant reduction of rear-end collisions for audiovisual warnings (e.g., [8], [9]) and audio warnings [8], it has been proposed that these modalities may not be optimal for driver warnings since they are already very much engaged in the driving task [10], [11], [12]. More recently, it has been suggested that tactile warnings may be more effective in preventing rear-end collisions since this sensory modality is relatively unengaged during driving [13], [14]. In field tests of tactile collision warnings, Campbell et al. [7] found that vibrational tactile displays mounted in the driver's seat can be effective but are generally not as effective as auditory warnings. In their guidelines for when to use collision warnings in different modalities, Campbell et al. [7] recommended that tactile warnings should only be used in situations where auditory warnings will be ineffective (e.g., high auditory workload and excessive noise)—otherwise, auditory warnings will be more effective and less obtrusive. Scott and Gray [15] directly compared visual, auditory, and tactile rear-end collision warnings with a no warning condition in a driving simulator and found that both auditory and tactile warnings produced significantly faster brake reaction times (RT) in response to a collision event than either no warning or the visual warning. There was no significant difference between the brake RTs to

- *S.M. Straughn and R. Gray are with the Department of Applied Psychology, Arizona State University, Santa Catalina Hall, 7291 E Sonoran Arroyo Mall, Mesa, AZ 85212. E-mail: {stacie.straughn, robgray}@asu.edu.*
- *H.Z. Tan is with the School of Electrical and Computer Engineering, Purdue University, Electrical Engineering Building, 465 Northwestern Avenue, West Lafayette, IN 47907-2035. E-mail: hongtan@purdue.edu.*

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auditory and tactile warnings. However, for conditions with a higher auditory load (simple cell phone conversations), it has been shown that tactile rear-end collision warnings are significantly more effective than auditory warnings [16]. Similar findings have been reported for lane departure warnings [17].

Another important factor in designing a warning is how the signal will be used by the driver. For example, in the case of pedestrian warnings, is it better for the warning to indicate the direction the pedestrian is coming from or for the warning to indicate the direction the driver needs to go to avoid collision? An examination of the human factors literature suggests that the answer is quite obvious as one of the most consistent and well-known findings in this field is that responses are faster and more accurate when the stimulus locations are spatially compatible with their assigned responses; e.g., the response to a signal on the observer's right is to turn a dial to the right (reviewed in [18]). Therefore, previous research suggests drivers should react faster to a warning that indicates where they need to go to avoid a collision (S-R compatible) than a warning that indicates where the potential collide is coming from (S-R incompatible).

On the other hand, in situations when a steering avoidance response is used, most drivers seem to have learned to turn away from "naturally occurring" warning signals such as a car horn or the sound of a collision. This learning effect is perhaps the reason why S-R incompatible warnings seem more intuitive to most drivers [19] and have been adopted by the majority of directional collision warnings studied in previous driving research (e.g., [17], [20]). In their guidelines for how to make warnings compatible with driver responses, Campbell et al. [7] recommend that warnings should always be located on the same side of the vehicle as the hazard. However, to our knowledge there is no empirical data showing that S-R incompatible warnings lead to faster reaction times in driving. Wang et al. [21] investigated the effects of S-R compatibility on steering wheel responses using a nondriving task. In this study, participants were required to turn a steering wheel mounted on a desktop to the left or to the right in response to auditory tones presented through headphones. S-R compatible trials (e.g., left ear, turn left) resulted in the faster RTs both for conditions in which participants were instructed that "the tone signaled the location of a source of danger" and for conditions in which instructions were that "the tone signaled the escape direction." This finding suggests that for collision warnings to be most effective, they should be S-R compatible although as the authors concede "these results need to be verified in simulated and actual driving conditions."

The purpose of the present study was to examine the effects of the modality and S-R compatibility of pedestrian warnings on driver behavior in a simulator. Since our previous research has shown that visual warnings are significantly less effective than either tactile or auditory warnings in rear-end collision scenarios [15], we chose to only investigate the latter two modalities in the present study. Since previous research on collision warnings has shown that the timing of the warning can have a large effect on driver responses (e.g., [22]), we used both early (i.e., large value of TTC) and late warnings in the present study. Finally, to be consistent with our previous studies, in the present study, we used brake RT as the primary criterion for warning effectiveness. It should be noted that in situations with imperfect warnings (which we did not evaluate in the present study), a decreased RT may not indicate a more effective warning since it does not take into account whether or not braking was the appropriate response for the driving situation. The results of our study should shed light on the effectiveness of tactile versus auditory warnings for collision avoidance, and contribute to the vast literature on stimulus-response compatibility by employing tactile warning signals.

2 Methods

2.1 Driving Simulator and Warnings

The fixed-base driving simulator was composed of two main components: 1) a steering wheel mounted on a table top and pedals (Wingman Formula Force GP, Logitech) and 2) a 70 degree horizontal $\times$ 52 degree 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 auditory warning was a 75 dB, 5,000 Hz tone issued from a speaker on either the left or right side of the dashboard to simulate a standard sedan audio system. The speakers were laterally separated by 85 degree (center-to-center) and were 9 degree-12 degree below the driver's line-of-sight (depending on the driver's height). This warning was designed to follow the guidelines of McGhee et al. [23] which recommended a "distinctive, nonspeech 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 McGhee et al. [23] guidelines and was considerably greater than the combined intensity of the noise of simulated engine, road, traffic, and radio (approximately 60 dB). We chose 5,000 Hz for the warning because it is within the range of frequencies that produce both accurate auditory localization and low detection thresholds [24]. In pilot experiments, we found that drivers could verbally indicate the direction of the auditory warning ("left" or "right") with near-perfect accuracy.

The tactile warning was delivered via single tactors ($2.54\ \mathrm{cm} \times 1.85\ \mathrm{cm} \times 1.07\ \mathrm{cm}$ VBW32, Audiological Engineering Corp., Somerville, MA) attached to the driver's left and right biceps with Velcro straps. The warning was driven by a 290 Hz sinusoidal signal at an intensity sufficient to deliver clearly perceptible vibrotactile stimuli. The tactors were mounted in a soft housing to mask the audio output from the activated tactors. The amplitude of the tactile simulation was approximately 10.5 dB above human detection threshold for the lower abdomen [25]. When triggered (detailed below), warnings activated for 200 ms with an 800 ms pause; i.e., once per second for 200 ms.

A potential problem with directly comparing auditory and tactile warnings in this manner is that of signal intensity. It is important to rule out the possibility that differences in the effectiveness of the different modalities is not due to the fact that the particular signal to noise ratio chosen for each warning (i.e., the intensity relative to background noise in that modality) makes one signal more effective at drawing the driver's attention. We have addressed this issue in few different ways. First, as described above, the warning intensities for each modality were chosen based on the guidelines for optimal warnings developed by McGhee et al. [23]. Second, in a control experiment in which drivers were required to press a button when they detected a warning, there were no significant differences in reaction time for auditory and tactile warnings suggesting that they have similar salience [15]. Finally, neither increasing auditory noise (by adding background music [15]) nor increasing tactile noise (by adding vehicle vibration through a motion base [17]) had a significant influence on the relative effectiveness of tactile and auditory warnings in our driving experiments.

2.2 Design and Procedure

Thirty-two drivers (ages 18-52, $\mathrm{M} = 23.6$) with 2-35 years of driving experience ($\mathrm{M} = 7.19$) 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.

Participants drove in a simulated three-lane urban environment. Each driving track was 8,000 m in length and took roughly 5-7 min to complete. Throughout the drive, pedestrians walked along the sidewalks (i.e., parallel to the roadway) on both sides of the roadway. At eight randomly selected locations during the drive, pedestrians would walk perpendicularly across the roadway at a speed of 1.3 m/s (3 mph). The pedestrian walking direction was counterbalanced within each track so that there were four instances of pedestrians walking from right-to-left across the roadway and four instances of pedestrians walking from left-to-right. Drivers were instructed to avoid pedestrians by driving in front of them (using the left or right lanes as necessary) and were instructed not to brake to avoid a collision. They were further instructed to drive in the center lane except when avoiding pedestrians and that they should always return to the center lane after an avoidance maneuver. Simulated fog was used in all conditions to make it more difficult for the driver to see the pedestrians. Participants were instructed to maintain a speed of 24.5 m/s (55 mph) throughout the drive. If their speed fell below 17.9 m/s (40 mph) the words "Speed Up!" would appear in red text on the driver's display. Driving speed was displayed in the lower left corner of the driver's display.

In the experimental sessions, the collision warnings activated when the Time-to-Collision (TTC) between the driver's vehicle and the pedestrian fell below a critical threshold of either 4.0 s (early warning condition) or 2.0 s (late warning condition). We chose these values based on previous research on rear-end collision warnings which has used warning times ranging from 2-5 sec TTC (e.g., [20]). Prior to these sessions, participants completed a practice session in which they drove one complete track in which there were no warnings on pedestrian incursions.

Each of the thirty-two participants were randomly assigned (without replacement) to one of the four experimental conditions:

1. Compatible/Early warnings,
2. Incompatible/Early warnings,
3. Compatible/Late warnings, and
4. Incompatible/Late warnings.

For the Compatible conditions, the warning was always presented on the side that the pedestrian was headed (i.e., the avoidance direction) and participants were instructed "The warnings will indicate the direction you should steer to avoid the pedestrian." For the Incompatible conditions, the warning was always presented on the side that the pedestrian was coming from and participants were instructed "The warnings will indicate the direction of pedestrians entering the roadway." Each participant completed three driving tracks corresponding to the no warning, tactile warning, and auditory warning conditions. The order was counterbalanced across participants.

2.3 Data Analysis

We used three dependent measures to quantify pedestrian avoidance performance. The first dependent variable was the steering RT; i.e., the time elapsed between the driver-pedestrian TTC falling below the warning threshold (either 2.0 or 4.0 sec) and the first steering response. Note that we used "below TTC threshold" instead of "warning on" because the latter is nonsensical for the no warning condition. A steering response was defined as follows. For each participant, we collected the standard deviation of lateral lane position for the straight road segments in the practice run ($\mathrm{SD_{lat}}$). We defined the initiation of a steering response to occur when the lateral position changed by more than $2 \times \mathrm{SD_{lat}}$. This criterion is similar to what we have used previously in studies of overtaking and passing [26], [27]. The second dependent variable was the clearance distance defined as the lateral separation between the center of the driver's car and the pedestrian at the instant the car and pedestrian were at the same longitudinal location on the roadway. The final dependent variable was the percentage of collisions with pedestrians defined as the number of collisions divided by the number of events.

3 Results

3.1 Steering Reaction Time

An initial examination of the data indicated that the drivers in our study behaved differently in the early and late warning conditions. On the one hand, in the early (4.0 s) warning conditions, drivers had not begun an avoidance maneuver at the instant the warning was activated for the majority of pedestrian incursions ($>85\%$). On the other hand, in the late (2.0 s) warning conditions, drivers had begun an avoidance maneuver at the instant the warning was activated for the majority of pedestrian incursions ($>95\%$). Therefore, we could only analyze the steering RT dependent variable for the early warning condition.

Fig. 1 plots the mean steering RTs for the three different warning conditions in the Early (4 s) warning condition. These data only include pedestrian incursions for which the

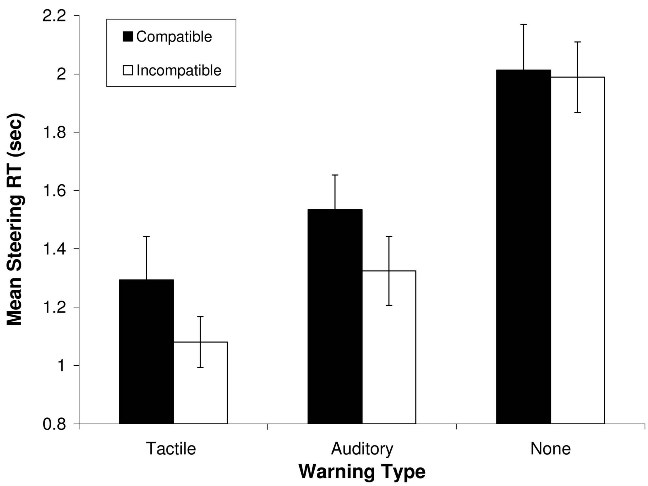
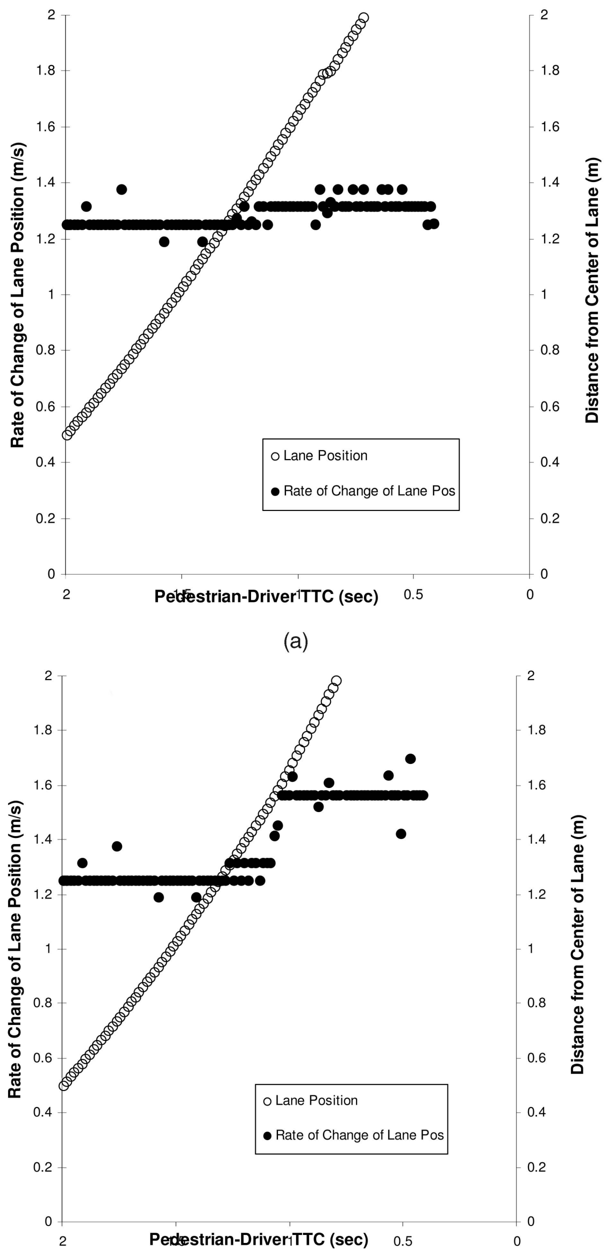


Fig. 1. Mean steering reaction times for S-R compatible and incompatible warnings for the three different warning types. Data are for the Early (4 s) warning condition only. Error bars are standard errors.

driver was not actively steering around the pedestrian at the instant the TTC fell below 4.0 s. It can be seen in Fig. 1 that both tactile and auditory warnings improved the ability of our drivers to avoid pedestrians as evidenced by shorter steering RTs. It is also evident that steering RTs were faster for S-R Incompatible warnings. These data were analyzed using a 2×3 Mixed Factor ANOVA with S-R compatibility as the between-subjects factor and warning type as the within-subject factor. This analysis revealed a significant main effect of S-R Compatibility $[\mathrm{F}(1,14) = 16.0, \mathrm{p} < 0.001]$ and a significant main effect of Warning Type $[\mathrm{F}(2,28) = 182.2.0, \mathrm{p} < 0.001]$. The S-R Compatibility $\times$ Warning Type interaction was not significant. Posthoc comparisons revealed that the steering RT for Tactile warnings was significantly shorter than the steering RT for Auditory warnings for both the Compatible $[\mathrm{t}(7) = -5.2,\ \mathrm{p} < 0.01]$ and Incompatible $[\mathrm{t}(7) = -6.2,\ \mathrm{p} < 0.001]$ conditions.

3.2 Clearance Distance

Because in most cases our drivers were engaged in an avoidance maneuver at the instant the late (2.0 s) warning was activated, this dependent variable was also analyzed differently than planned. Fig. 2a plots the lateral position (open circles) and rate of change of lateral position (solid circles) of the driver's car as a function of pedestrian-car TTC for one maneuver in the No Warning Condition. Fig. 2b plots the same two variables for a maneuver made in the Late/Tactile Warning condition. Relative to Fig. 2a, it appears that the driver adjusted his/her ongoing steering execution in response to the warning (as evidenced by the jump in rate of change of lane position). For the clearance distance analysis, we included all pedestrian incursions in the 2 s warning condition for which there was a discontinuity in rate of change of position (with a magnitude greater than 5 m/s) like that shown in Fig. 2b. The number of such events ranged between two and five per condition; therefore, we decided to combine data from the tactile and auditory warnings so that the mean for each participant was based on a minimum of four events. We chose not to compare the timing of this steering adjustment to the steering RTs described above



(b)

Fig. 2. Lane position and rate of change of lane position as a function of TTC for single pedestrian avoidance maneuvers. (a) No warning. (b) Late (2 sec) warning.

because it has been shown that RTs for the adjustment of an ongoing movement are significantly shorter than RTs for the initiation of a new movement [28] so these values would be difficult to compare.

Fig. 3 plots the mean clearance distance (averaged for the tactile and auditory conditions) for the Early and Late warnings as a function of S-R compatibility. These data were analyzed using a 2×2 between subjects ANOVA with Warning Time and S-R compatibility as factors. This analysis revealed a significant main effect of Warning Time $[\mathrm{F}(1,28) = 33.9,\ \mathrm{p}\ < 0.001]$ as Early warnings produced a significantly larger clearance distance than Late warnings. There was also a significant Warning Time $\times$ S-R compatibility interaction

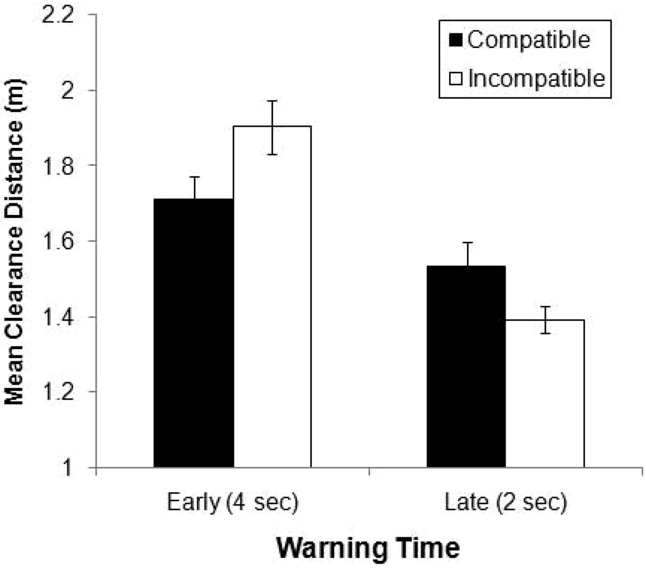


Fig. 3. Mean pedestrian clearance distance for the Early and Late warnings as a function of S-R compatibility. Data for tactile and auditory warnings were combined. Error bars are standard errors.

$[F(1, 28) = 7.9,\ p < 0.01]$ as the mean clearance distance was larger for Compatible warnings than for Incompatible warnings in the Late warning condition while the opposite pattern of results was found in the Early warning conditions. The main effect of S-R compatibility was not significant.

For comparison, we also calculated the mean clearance distance for all trials for which an avoidance maneuver was made but there was no discontinuity in rate of change of position (i.e., the warning appeared to have no effect on steering as shown in Fig. 3). The mean clearance distance for these "no discontinuity" conditions $(M = 1.32\ m)$ was significantly smaller than the overall mean for the "discontinuity present" conditions $(M = 1.6\ m):\ t(31) = 3.1,\ p < 0.01$.

One of our underlying assumptions when using clearance distance as a dependent measure was that a larger distance between the vehicle and pedestrian equates to a higher degree of safety. However, as one anonymous reviewer suggested a clearance distance that is too large could be indicative of an overcorrection (e.g., the driver losing control of the vehicle, veering into oncoming traffic, or driving off the roadway). Was the additional clearance distance evoked by the late warning signal actually beneficial to driving safety? To address this question we analyzed a fourth dependent measure: road departures. A road departure was defined as a trial in which the driver's vehicle crossed either the left-hand boundary of the left lane or the right-hand boundary of the right lane during an avoidance maneuver (i.e., they went off the simulated three-lane/one-way road). The mean number (averaged across participants) of road departures for all "discontinuity present" trials $(M = 0.91)$ was not significantly different than the mean number of road departures for the "no discontinuity" trials $(M = 0.85):\ t(31) = 0.51, p > 0.5$. This result together with the clearance distance data discussed above indicates that when drivers responded to the late warning by altering their steering (i.e., "discontinuity present" trials), there was a larger margin for error when they passed the pedestrian (e.g., in case of misestimation or a change in the pedestrian's walking speed) without an associated loss of vehicle control. We would argue that this is indicative of safer driving behavior.

3.3 Percentage of Collisions

The mean percentage of collisions for the early warning were as follows: Tactile/Comp: $3.1\ (SE = 1.2)\%$; Tactile/InComp: $1.9\ (SE = 1.5)\%$; Audio/Comp: $4.5\ (SE = 1.6)\%$; Audio/InComp: $2.4\ (SE = 1.9)\%$; None: $6.2\ (SE = 1.8)\%$. The mean percentage of collisions for the late warning were as follows: Tactile/Comp: $3.5\ (SE = 0.9)\%$; Tactile/InComp: $4.8\ (SE = 1.7)\%$; Audio/Comp: $4.1\ (SE = 1.8)\%$; Audio/InComp: $5.7\ (SE = 1.9)\%$; None: $7.1\ (SE = 2.0)\%$. The pattern of results for this dependent variable was consistent with the variables described above. However, a logistic regression performed on these data revealed that none of the independent variables nor combinations of these variables explained a significant amount of variance in the regression model. This is not surprising given that collision percentage has proven not to be a sensitive measure of performance in previous driver warning studies (e.g., [15], [16]).

4 Discussion

The results of the present study indicate that the relationship between S-R compatibility and collision warning effectiveness in driving is dependent on the timing of the warnings. We propose that this effect occurs because warnings presented at different values of time to collision elicit very different responses by the driver. On the one hand, when a warning is presented at a very short TTC and the driver does not have time to shift their attention to the location of potential collision, then the only effective means of utilizing the warning is to generate a reactive motor response (e.g., auditory warning on the $left = turn$ the wheel to the left). This situation is identical to most laboratory experiments on S-R compatibility where the participant is instructed to make a directional response as quickly as possible after detecting the signal (e.g., [21]). Therefore, it is not surprising that in the late warning condition of the present study, the results were consistent with these previous experiments: S-R compatible collision warnings are more effective. On the other hand, when a collision warning is presented at a larger value of TTC, the driver may have time to shift their attention to the location of the potential collision, evaluate the situation (e.g., the direction and speed of the moving pedestrian), and then decide what action is needed (e.g., no response, large steering response, hard braking, etc.). In this situation, we would expect S-R compatible warnings to lead to slower responses as compared to S-R incompatible warnings, since, in the former case, the driver would presumably shift their attention in the direction of the warning signal and then redirect it to the location of the potential collision. Therefore, as found in the present study, early S-R incompatible collision warnings should be more effective than early S-R compatible collision warnings.

In comparing the effects of S-R compatibility as a function of timing, it is important to point out that the warning signals were likely qualitatively different in our early and late conditions. On the one hand, because in the majority of cases, drivers had initiated an avoidance maneuver before receiving the signal in the late warning condition, it might be better to consider it as "guidance support" rather than a "warning." In other words, the signal indicated whether or not their maneuver was in the correct direction rather than warning drivers of an impending hazard and seems to have encouraged them to increase the magnitude of the steering maneuver. On the other hand, the early warning seems to have led to the initiation of a steering correction. It will be important for future research to examine warning times between the 2 and 4 second TTC values used in the present study to determine whether the significant S-R $\mathrm{Compatibility} \times \mathrm{Warning}$ Time interaction observed in the present study was primarily due to qualitative differences in the early and late warnings.

Turning to the question of which modality is best for pedestrian collision warnings, the present finding that tactile warnings elicit faster driver RTs than auditory warnings is consistent with our previous findings for rear-end collision warnings [15], [16]. However, because we presented the tactile warnings to the driver's arms, the present findings may have not been solely a modality effect. Previous research on lane departure warnings [29] has found that warnings that selectively stimulate the muscles involved in the warning response (asymmetric oscillation of the steering wheel) lead to shorter duration recovery maneuvers from a lane departure and greater steering wheel acceleration as compared to warnings that do not selectively stimulate particular muscles (vibrating symmetric oscillation of the steering wheel). There was no significant effect on steering reaction time. The significant effects have been explained in terms of motor priming, i.e., stimulation of the muscles that are needed for the subsequent response leads to faster initiation of the movement. Therefore, future research using tactile pedestrian collision warnings on other body locations (e.g., the torso) are needed to determine the exact reason for the faster steering RTs for tactile warnings found in the present study.

The findings of the present experiment were limited by certain constraints imposed through the simulation paradigm. For one, the drivers in the present experiment were fully expecting pedestrians to enter the roadway and rate of incursion was unnaturally high, so driver responses recorded in this simulation were likely faster than can be expected in a real driving situation. Furthermore, the simulated pedestrians walked at a constant speed and had a constant heading so that their motion was much more predictable than would occur in real driving. Finally, drivers were required to make a steering avoidance response for every incursion event. In real driving, it has been shown that drivers are more likely to make a braking response even in situations where steering would have been more effective in avoiding a collision [30]. Future research is needed to verify the present findings in a more representative driving environment that takes into account these limitations.

5 Conclusion

Our findings have important implications for the design of effective pedestrian collision warning systems involving tactile signals. Road accidents involving pedestrians are a serious problem worldwide and pedestrian warning systems are one of the main efforts toward addressing this problem. But while substantial effort has been put forth toward investigating the technological aspects of these systems, relatively little research has examined related human factor issues. The present study examined the effects of the sensory modality, S-R compatibility, and timing of pedestrian warnings on driver behavior. For early (large TTC) warnings, S-R incompatible warnings (signaling the direction of the pedestrian) were most effective, while for late (short TTC) warnings, S-R compatible warnings (signaling the escape direction) were most effective. These effects appear to be determined by whether or not the driver has time to evaluate the situation before responding. In addition, tactile warnings produced significantly faster steering reaction times than auditory warnings for early warnings. These findings are expected to hold for other directional warnings in driving (e.g., lane departure and blind-spot warnings).

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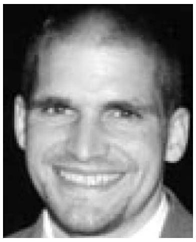
References

[1] World Bank, http://www.worldbank.org/html/fpd/transport/roads/safety.htm, 2006.
[2] Nat'l Highway Traffic Safety Administration (NHTSA), "Traffic safety facts 2006: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System," NHTSA Publication no. DOT-HS-810-818, US Dept. of Transportation, 2008.
[3] D.M. Gavrila, "Sensor-Based Pedestrian Protection," *IEEE Intelligent Systems,* vol. 16, no. 6, pp. 77-81, Nov./Dec. 2001.
[4] G.D. Nicolao, A. Ferrara, and L. Giacomini, "Onboard Sensor-Based Collision Risk Assessment to Improve Pedestrians' Safety," *IEEE Trans. Vehicular Technology,* vol. 56, no. 5, pp. 2405-2413, Sept. 2007.
[5] T. Gandhi and M.M. Trivedi, "Pedestrian Protection Systems: Issues, Survey, and Challenges," *IEEE Trans. Intelligent Transportation Systems,* vol. 8, no. 3, pp. 413-430, Sept. 2007.
[6] R. Kiefer, D. LeBlanc, M. Palmer, J. Salinger, R. Deering, and M. Shulman, "Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems," NHTSA Publication no. DOT HS 808 964, Nat'l Highway Transportation Safety Administration, 1999.
[7] J.L. Campbell, C.M. Richard, J.L. Brown, and M. McCallum, "Crash Warning System Interfaces: Human Factors Insights and Lessons Learned," DOT HS 810 697, Nat'l Highway Transportation Safety Administration, 2007.
[8] J.D. Lee, D.V. McGehee, T.L Brown, and M.L. Reyes, "Collision Warning Timing, Driver Distraction, and Driver Response to Imminent Rear-End Collisions in a High-Fidelity Driving Simulator," *Human Factors,* vol. 44, pp. 314-334, 2002.
[9] P. Bhatia, "Vehicle Technologies to Improve Performance and Safety," UCTC Publication no. 622, Univ. of California, 2003.
[10] G. Abe and J. Richardson, "The Effect of Alarm Timing on Driver Behaviour: An Investigation of Differences in Driver Trust and Response to Alarms According to Alarm Timing," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 7, pp. 307-322, 2004.
[11] S.M. Belz, G.S. Robinson, and J.G. Casali, "A New Class of Auditory Warning Signals for Complex Systems: Auditory Icons," *Human Factors,* vol. 41, pp. 608-618, 1999.

[12] J.D. Lee, J.D. Hoffman, and E. Hayes, "Collision Warning Design to Mitigate Driver Distraction," *Proc. ACM SIGCHI Conf. Human Factors in Computing Systems,* vol. 6, pp. 65-72, 2004.
[13] J.B.F. Van Erp, "Presenting Directions with a Vibrotactile Torso Display," *Ergonomics,* vol. 48, pp. 302-313, 2005.
[14] C. Ho, H.Z. Tan, and C. Spence, "Using Spatial Vibrotactile Cues to Direct Visual Attention in Driving Scenes," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 8, pp. 397-412, 2005.
[15] J.J. Scott and R. Gray, "Comparison of Visual, Auditory and Tactile Warnings for Rear-End Collision Prevention in Driving," *Human Factors,* vol. 50, pp. 264-275, 2008.
[16] R. Mohebbi, R. Gray, and H.Z. Tan, "Driver Reaction Time to Tactile and Auditory Rear-End Collision Warnings While Talking on a Cell Phone," *Human Factors,* vol. 51, pp. 102-110, 2009.
[17] K. Suzuki and H. Jansson, "An Analysis of Driver's Steering Behaviour During Auditory or Haptic Warnings for the Designing of Lane Departure Warning System," *JSAE Rev.,* vol. 24, pp. 65-70, 2003.
[18] *Stimulus-Response Compatibility: An Integrated Perspective,* R.W. Proctor and T.G. Reeve, eds. North-Holland, 1990.
[19] J.L. Campbell, B.L. Hooey, C. Camey, R.J. Hanowiski, B.F. Gore, B.H. Kantowitz, and E. Mitchell "Investigation of Alternative Displays for Side Collision Avoidance Systems," technical report, US Dept. of Transportation, Nat'l Highway Traffic Safety Administration, Dec. 1996.
[20] D.P. Jenkins, N.A. Stanton, G.H. Walker, and M.S. Young, "A New Approach to Designing Lateral Collision Warning Systems," *Int'l J. Vehicle Design,* vol. 45, pp. 379-396, 2007.
[21] D.-Y. Wang, R.W. Proctor, and D.F. Pick, "Stimulus-Response Compatibilitiy Effects for Warning Signals and Steering Responses," *Proc. Second Int'l Driving Symp. Human Factors in Driver Assessment, Training and Vehicle Design,* pp. 226-230, 2003.
[22] S. Hirst and R. Graham, "The Format and Presentation of Collision Warnings," *Ergonomics and Safety of Intelligent Driver Interfaces,* Y.I. Noy, ed., pp. 203-219, Lawrence Erlbaum, 1997.
[23] D.V. McGehee, D.J. LeBlanc, R.J. Kiefer, and J. Salinger, "Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements," no. J2400, Soc. of Automotive Engineers, 2002.
[24] E.B. Goldstein, *Sensation and Perception.* Wadsworth Publishing, 2006.
[25] S.J. Bolanowski, G.A. Gescheider, R.T. Verrillo, and C.M. Checkosky, "Four Channels Mediate the Mechanical Aspects of Touch," *J. Acoustical Soc. of America,* vol. 84, pp. 1680-1694, 1988.
[26] R. Gray and D. Regan, "Risky Driving Behavior: A Consequence of Motion Adaptation for Visually Guided Action," *J. Experimental Psychology: Human Perception and Performance,* vol. 26, pp. 1721-1732, 2000.
[27] R. Gray and D. Regan, "Perceptual Processes Used by Drivers During Overtaking in a Driving Simulator," *Human Factors,* vol. 47, pp. 394-417, 2005.
[28] E. Brenner and J.B.J. Smeets, "Fast Responses of the Human Hand to Changes in Target Position," *J. Motor Behavior,* vol. 29, pp. 297-310, 1997.
[29] J. Navarro, F. Mars, and J.M. Hoc, "Lateral Control Assistance for Car Drivers: A Comparison of Motor Priming and Warning Systems," *Human Factors,* vol. 49, pp. 950-960, 2007.
[30] L.D. Adams, "Review of the Literature an Obstacle Avoidance Maneuvers: Braking versus Steering," Report no. UMTRI-94-19, Transportation Research Inst., Univ. of Michigan, 1994.

Stacie M. Straughn received the MS degree in applied psychology from Arizona State University in 2008.



Rob Gray received the BA degree in psychology from Queens University in 1993, and the MS and PhD degrees in psychology from York University, Canada, in 1995 and 1998, respectively. He was a research scientist with Nissan Cambridge Basic Research from 1998 to 2001. Since 2001, he has been with Arizona State University, where he is currently an associate professor and head of the Applied Psychology Program. Since 2005, he has been a part-time research psychologist with the Mesa Air Force Research Laboratory. He is the author of more than 50 published refereed journal articles and chapters. He serves as a consulting editor for the *Journal of Experimental Psychology: Human Perception and Performance* and is an editorial board member for *Human Factors*. In 2007, he was awarded the Distinguished Scientific Award for early career contribution to psychology from the American Psychological Association.

Hong Z. Tan received the bachelor's degree in biomedical engineering in 1986 from Shanghai Jiao Tong University, and the master's and doctorate degrees in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT), in 1988 and 1996, respectively. She was a research scientist at the MIT Media Lab from 1996 to 1998 before joining the faculty at Purdue University. She is currently an associate professor of electrical and computer engineering, with courtesy appointments in the School of Mechanical Engineering and the Department of Psychological Sciences. She is an associate editor of *Presence*, the *ACM Transactions on Applied Perception*, and the *IEEE Transactions on Haptics*. She was a co-organizer (with Blake Hannaford) of the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems from 2003 to 2005. She served as the founding chair of the IEEE Technical Committee on Haptics, a home for the international interdisciplinary haptics research community, from 2006 to 2008. She was a recipient of the US National Science Foundation CAREER award from 2000 to 2004, and a coauthor of "Haptic Feedback Enhances Force Skill Learning" that won the Best Paper Award at the 2007 World Haptics Conference. She has published more than 110 peer-reviewed articles in journals and conference proceedings and two book chapters. Her research focuses on haptic human-machine interfaces in the areas of haptic perception, rendering, and multimodal performance. She is a senior member of the IEEE and a member of the Psychonomic Society.