Effectiveness of Lateral Auditory Collision Warnings: Should Warnings Be Toward Danger or Toward Safety?

Jing Chen, Old Dominion University, Norfolk, Virginia, USA, **Edin Šabić**, New Mexico State University, Las Cruces, USA, **Scott Mishler**, **Cody Parker**, Old Dominion University, Norfolk, Virginia, USA, and **Motonori Yamaguchi**, University of Essex, Colchester, UK

Objective: The present study investigated the design of spatially oriented auditory collision-warning signals to facilitate drivers' responses to potential collisions.

Background: Prior studies on collision warnings have mostly focused on manual driving. It is necessary to examine the design of collision warnings for safe takeover actions in semi-autonomous driving.

Method: In a video-based semi-autonomous driving scenario, participants responded to pedestrians walking across the road, with a warning tone presented in either the avoidance direction or the collision direction. The time interval between the warning tone and the potential collision was also manipulated. In Experiment 1, pedestrians always started walking from one side of the road to the other side. In Experiment 2, pedestrians appeared in the middle of the road and walked toward either side of the road.

Results: In Experiment 1, drivers reacted to the pedestrian faster with collision-direction warnings than with avoidance-direction warnings. In Experiment 2, the difference between the two warning directions became nonsignificant. In both experiments, shorter time intervals to potential collisions resulted in faster reactions but did not influence the effect of warning direction.

Conclusion: The collision-direction warnings were advantageous over the avoidance-direction warnings only when they occurred at the same lateral location as the pedestrian, indicating that this advantage was due to the capture of attention by the auditory warning signals.

Application: The present results indicate that drivers would benefit most when warnings occur at the side of potential collision objects rather than the direction of a desirable action during semi-autonomous driving.

Keywords: lateral collision warning, auditory warning, stimulus–response compatibility, semi-autonomous driving

Address correspondence to Jing Chen, Department of Psychology, Old Dominion University, 250 Mills Godwin Life Sciences Bldg, Norfolk, VA 23529, USA; e-mail: j1chen@odu.edu

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Fatal motor vehicle crashes can result from collisions with pedestrians, other motor vehicles, motorcycles, road objects, and animals. Among these collisions, pedestrian deaths accounted for 16% of all traffic fatalities in 2017 in the United States (National Center for Statistics and Analysis, 2019), with one pedestrian being killed every 88 min on average. In the last few years, many vehicles have been equipped with collision-warning systems that sense objects around a vehicle and alert the driver of a potential collision (Nedevschi et al., 2009), including the Mobileye Shield+ system (Mobileye, 2019) and the Toyota Pre-collision System (Crowe, 2013), to name a few. As more advanced sensors become integrated into modern vehicles, these systems are expected to provide more accurate information to drivers and improve road safety (Gandhi & Trivedi, 2007; Keller et al., 2011; Song et al., 2004).

However, current advanced collision-avoidance systems are not as reliable as one would hope (Jensen, 2019). A recent study by the American Automobile Association (2019) tested currently available pedestrian detection systems and showed devastating results with 60% of adult pedestrian fatalities and 89% for the child-sized dummies when tested in daylight hours at speeds of 20 mph. Indeed, tragedies have occurred when these systems were unmonitored and the human driver was uninformed about the potential danger within sufficient time (National Transportation Safety Board, 2019a, 2019b). Thus, these warning systems can be effective in reducing the risk of collision only if their design accounts for the way drivers would react to the warning signals (Hancock & Parasuraman, 1992; Spence & Ho, 2008; Wang et al., 2007).

The state-of-the-art capabilities in the current market are semiautonomous (Level 2 automation; SAE International, 2018), rather than fully automated (Level 5 full automation; SAE International, 2018). Level 2 automation allows drivers to be physically disengaged but requires them to pay attention to the road and be ready to take over control when necessary. Given that no machines are perfectly reliable, the human driver may need to manually take over control during driving even with higher levels of automation (Eriksson & Stanton, 2017). Thus, it is important for semiautonomous vehicles to communicate effectively with drivers during the transfer of control from an automated state to a manual state in safety critical situations (Banks et al., 2014; De Nicolao et al., 2007; Koo et al., 2015). Communication during the transfer of control from the semiautonomous vehicle to the human driver is essential, because semiautonomous driving has been shown to reduce vigilance and situation awareness as compared to manual driving (Campbell et al., 2018; Endsley & Garland, 2000; Kaber & Endsley, 2004).

There are three major categories of collision-avoidance systems: forward, rear-end, and lateral, with the majority of existing research focusing on forward and rear-end collision warnings (Baldwin & May, 2011; Brown et al., 2001; Kusano & Gabler, 2012; Muhrer et al., 2012; Wu et al., 2018). The present study focused on lateral collision avoidance, which is especially important to mitigate collisions with pedestrians, motorcycles, bicycles, and other vehicles invading the side of a vehicle (Song et al., 2004; Straughn et al., 2009; Wang et al., 2007). Collision-avoidance systems that provide spatial information (i.e., location or direction of potential hazards; Beattie et al., 2014) can be particularly helpful to avoid collisions. Such spatialized warning presentations have been shown to enhance drivers' gaze reactions, situation awareness, and response performance (Beattie et al., 2014; Ho & Spence, 2005; Ho et al., 2006; Plavšic et al., 2009). Studies on manual driving have been conducted to evaluate how spatialized warnings should be presented in the past two decades (Müsseler et al., 2009; Proctor et al., 2004; Wang et al., 2003a, 2007). However, further research is needed to investigate how spatialized warnings can facilitate the transition of control from an automated vehicle to a human driver in situations where potential side collisions are detected.

Imagine, for example, that a pedestrian is walking across the road from the sidewalk on the left-hand side of the driver. How should a warning system present a signal to alert the driver or the pedestrian? On the one hand, drivers may react reflexively to warning signals by steering away from them (e.g., when responding to car horns; Campbell et al., 2007), so it may be more effective if warning signals indicate the location of an object with which a collision would potentially occur. In this case, lateral warning signals should be presented on the side of the vehicle where the collision would occur (*collision direction*). On the other hand, warning signals may help drivers take avoidance actions more quickly if drivers are instead informed of the direction in which they should make the actions. If so, then lateral warning signals should be presented on the side to which an avoidance action should occur (*avoidance direction*).

It is noteworthy that the distinction between collision-detection and avoidance-direction warnings is similar to that between status and command displays in aviation (Andre & Wickens, 1992; Sarter & Schroeder, 2001; Wickens, 2003; Wickens et al., 2008). A status display informs the pilot of the current status of the plane and nearby traffic, whereas a command display indicates the action that should be taken by the pilot. The command display likely involves inferences made by the automation system based on the current status and the pilot's goals. For instance, an auditory alert of "traffic, traffic" informs the pilot of surrounding traffic that is at a high level of concern, whereas an alert of "climb, climb, climb" informs the pilot of a required maneuver (Wickens, 2003). Status and command displays support different states of decision-making and both have their own benefits and disadvantages (Andre & Wickens, 1992; Sarter & Schroeder, 2001). Status displays support the detection and diagnosis of a problem but require an extra transformation from the status information to the desired action. Command displays support the action-selection stage, which can benefit the pilot when making decisions under stress; however, these systems only instruct the pilot on what to do without providing the "why" information that is communicated by status displays. Command displays have been shown to be more effective in time-critical situations as long as the command information is highly reliable (Sarter & Schroeder, 2001).

Unlike the distinction between status and command displays, the collision-direction and avoidance-direction warnings in the current driving scenario can be opposites of each other, and there has been evidence supporting either direction (Ljungberg et al., 2012; Proctor & Vu, 2016). Evidence supporting the advantage of collision-direction warnings comes from studies that demonstrate faster processing of a target object when a cue is presented at a spatially compatible location with the target, a phenomenon known as *attention capture* (e.g., Ljungberg et al., 2012; Posner, 1980; Yantis & Jonides, 1990). When presented at the location of a colliding object, lateral warnings quickly direct the driver's attention toward the object and enhance its detection. This attention capture would theoretically allow for a faster response to the object and reduce collision risk. For the avoidance-direction warnings, supporting evidence emerges from studies that demonstrate faster responses when signals occur on the same side as the side of the required action than when they occur on the opposite side, a phenomenon known as *stimulus–response compatibility* (SRC; Fitts & Deininger, 1954; Proctor & Vu, 2006). Both attention capture and SRC are robust phenomena that have been observed numerous times in cognitive psychology research (Koelewijn et al., 2010; Kornblum & Lee, 1995; Proctor & Vu, 2016; Spence & Santangelo, 2009) and in human factors research (Janczyk et al., 2019; Kantowitz et al., 1990; Ljungberg & Parmentier, 2012; Proctor et al., 2005; Terry et al., 2008). Studies concerning attention capture focus on the relative locations of a cue and a target stimulus, whereas studies concerning SRC focus on the relative locations of the target stimulus and the response. These two phenomena provide different predictions of drivers' performance when applied to the current driving scenario.

The SRC effect has been shown with steering-wheel responses. When responses are made with a steering wheel, turning the steering wheel toward a signal has been shown to yield quicker responses than turning away from a signal (e.g., Proctor et al., 2004; also see Yamaguchi & Proctor, 2006, for similar findings in a flight simulator). Hence, drivers may react to lateral warning signals faster when they are presented on the side to which their actions should be directed. However, the role of SRC can be ambiguous in such naturalistic scenarios and can also be dependent on task instructions (Müsseler et al., 2009; Proctor et al., 2004; Wang et al., 2003b, 2007). For example, in Proctor et al.'s first experiment, when instructions did not emphasize either hand or wheel movement, positive SRC effects were found when participants' hands were placed at the top and middle of the wheel but not when they were at the bottom of the wheel. In their second experiment using bottom-hand placement, a negative SRC effect was found when the instructions emphasized hand movement, and no SRC effect was observed when the instructions were in terms of the movement of a red tape at the top of the wheel. In Müsseler et al.'s study using a simulated driving context, when participants acted as a taxi driver, they were faster to steer away from a pedestrian stepping into the road (a condition with stimulus–response incompatibility) than steering toward a waving pedestrian calling a taxi (a condition with SRC). The results showed a reversed effect of SRC.

More specifically for warning signals, researchers have also tested the effectiveness of lateral signals in a manual driving context (Straughn et al., 2009; Wang, Pick et al., 2007). Participants in Wang et al.'s study manually operated a driving simulator while responding to side collision-avoidance warnings. The warning either indicated the location of the danger (i.e., collision direction) or the desired escape direction (i.e., avoidance direction). Participants responded more quickly to collision-direction warnings than to avoidance-direction warnings, indicating a reversed SRC effect. Similarly, Straughn et al. manipulated both the direction of the warning (collision vs. avoidance direction) and the interval between the onset of a warning and the time of a collision (*time-to-collision*, or TTC; 2 s vs. 4 s). Their results showed that the 4-s TTC warnings were more effective in the collision direction than in the avoidance direction. However, at the 2-s TTC, the avoidance-direction warnings were more effective than the collision-direction warnings. These findings are consistent with those in aviation studies that showed command displays to be more effective than status displays in time-critical situations (Sarter & Schroeder, 2001; Wickens et al., 2008). This effect of the TTC presumably reflects the urgency of reactions to a potential hazard. When the TTC is long, there is sufficient time to process the surrounding situation and signaling the direction of a potential hazard helped drivers process the collision information. When the TTC is short, however, there is insufficient time to process the information. As such, signaling the direction of the action to be taken helped drivers act quickly. Hence, the effectiveness of lateral signals appears to be time sensitive.

Although previous studies have provided useful information as to how lateral collision warnings should be designed for manual driving, these guidelines may not readily generalize to semiautomated driving scenarios. Drivers in semiautonomous vehicles are free from manual driving operations and, as such, drivers are more likely allocate their resources to nondriving tasks, leading to low situation awareness (Carsten et al., 2012; Endsley & Garland, 2000; Sibi et al., 2016). As research in many domains has shown, people detect potential incidents more slowly when monitoring the automation rather than when manually controlling the machine (de Winter et al., 2014; Kaber & Endsley, 2004). Because of these differences between manual and semiautonomous driving, the effectiveness of collision warnings may be affected by the level of automation. Thus, the previous results for manual driving may not be generalizable to semiautonomous driving; yet, little research has been conducted on lateral warnings for the latter.

Even among the very few studies that have been conducted on lateral warnings for semiautonomous driving, findings have been mixed. Petermeijer et al. (2017) found no difference in steering-touch reaction time between the collision-direction and avoidance-direction auditory warnings at a 7-s TTC. In contrast, Cohen-Lazry et al. (2019) found faster and more accurate responses for avoidance-direction than for collision-direction tactile warnings at a 4-s TTC. Participants in both studies were required to respond to potential forward collisions by taking over control in a highly-automated vehicle. Moreover, both findings are in contradiction with prior results for manual driving (Straughn et al., 2009; Wang et al., 2007). Therefore, the effectiveness of lateral collision warnings for autonomous driving requires further investigation.

THE CURRENT STUDY

The main objective of the current study was to examine how the directionality and timing of lateral collision warnings affect drivers' detection of potential collisions and actions to avoid collisions. For the warning signals, we chose auditory warnings due to their easily manipulated directionality and wide utilization in modern vehicles. Although visual warning systems can also be used, auditory warnings appear to be most suitable because driving is already a visually demanding task (Hergeth et al., 2015; Sabic et al., 2017). Tactile warnings have been shown to yield faster response time than auditory and visual warnings (Mohebbi et al., 2009; Scott & Gray, 2008). Yet tactile systems may be affected by ambient in-vehicle vibration, the driver's posture, as well as clothes/gloves that the driver is wearing, although there are potential solutions to these issues (see Meng & Spence, 2015, for a review). In addition, it has been shown that drivers prefer auditory warnings over visual and tactile warnings for certain types of collision warnings (Scott & Gray, 2008), although it is clear that the design choice should not be solely dependent on users' preferences. As a result, we focused on auditory warnings in the current study.

In two experiments, human drivers viewed a video-based driving scene with a steering wheel available to operate as if they were in a semiautomated vehicle. The videos simulated a Level 2 semiautomated driving scenario. A pedestrian

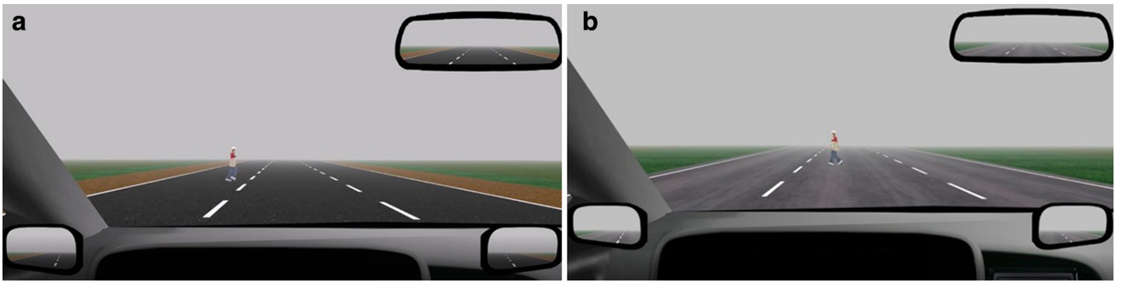

Figure 1. Examples of the driving displays at a point where time-to-collision was about 1 s: (a) Experiment 1 in which a pedestrian is walking from left edge of the road to the right; (b) Experiment 2 in which a pedestrian is walking from the middle of the road to the left.

suddenly appeared on either side of the road and walked across the road (Experiment 1; see Figure 1a) or appeared in the middle of the road and walked to either side (Experiment 2; see Figure 1b). The vehicle presented the auditory warning tone to signal the *collision direction* for half of the participants whereas presenting the auditory warning tone to signal the *avoidance direction* for the other half. The TTC was also varied across trials similar to Straughn et al. (2009) study but with more time intervals to examine whether there would be critical changes in the results between the shortest and longest TTC. The drivers were then required to turn the steering wheel in the desired direction to avoid the pedestrian as quickly and safely as possible. In both experiments, we examined participants' reaction time (RT) to the warnings.

In predicting the effectiveness of lateral warnings, we considered the two abovementioned theories of attention capture and the SRC effect. Based on the SRC effect (Fitts & Deininger, 1954; Proctor & Vu, 2006), it was expected that drivers would react more quickly for lateral warnings in the avoidance direction than in the collision direction. In contrast, based on the attention capture studies (Ljungberg et al., 2012; Posner, 1980; Yantis & Jonides, 1990) as well as prior studies on lateral warnings (Wang et al., 2007), it was expected that drivers would react more quickly when a lateral warning signals the collision direction than when it signals the avoidance direction. Further, previous research also suggested that the effectiveness of lateral warnings may depend on the TTC (Straughn et al., 2009). As such, collision-direction warnings were expected to be more effective than avoidance-direction warnings at a longer TTC, but the opposite may occur at a shorter TTC. The present study would reveal if these findings could be generalized to a context of semiautomated vehicle driving.

EXPERIMENT 1

Method

Participants. Forty-two undergraduate students (25 females) at New Mexico State University participated in the experiment for course credit. Participants were on average 20.26 years old (*SD* = 3.58). Four participants reported having less than 1 year of driving experience, 11 participants had 1 to 2 years of driving experience, and 27 participants had more than 2 years of driving experience. This experiment complied with the American Psychological Association (APA) Code of Ethics and was approved by the Institutional Review Board (IRB) at New Mexico State University.

Apparatus and stimuli. The apparatus consisted of a personal computer (Dell OptiPlex 7020) with a 19-in LCD monitor, a steering wheel (Logitech Driving Force G920), and headphones (Audio-Technica ATH-M30X). Each participant was seated in an individual testing room. The collision warning was an 1100 Hz tone, the same as used in Wang, Pick et al. (2007), which was presented monaurally to either side of the ears through the headphones. The volume of the audio system was kept constant at 30% for all participants to avoid the potential impact of differing sound intensity levels on RT across participants. All participants were able to identify the direction of warning tones accurately at this volume level (see "Procedure"). The experiment was programmed with E-Prime 2.0 software (www.pstnet.com), which presented video clips and logged steering-wheel responses.

Pedestrian video clips were created by recording an automated-driving scenario from a STISIM Driving Simulator (http://stisimdrive.com/). The self-driving video clips consisted of a car driving at a constant speed (50 mph, or about 80 kph) in the central lane of a three-lane road in a rural area (Figure 1a). A heavy fog was applied to the driving scene to reduce the visibility to approximately 300 ft (see Greenlee et al., 2018, for a similar setting) but still allow the pedestrian to be visible and gradually fade into the scene. The pedestrian appeared after every 20–30 s after the driving started. This range of 20–30 s was chosen to prevent the participants predicting when the pedestrian could occur but still allow for repeated response data collected from each participant. The video clips were manipulated in E-Prime so that the pedestrian was at different distances from the participant's car at onset, yielding different values of TTC (2, 2.5, 3, 3.5, and 4 s). The shortest and longest TTC were chosen based on Straughn et al.'s (2009) study, and the additional levels of TTC were included to understand the dynamics of how the TTC may affect the effectiveness of the lateral warnings. Within each TTC condition, half of the videos consisted of a pedestrian walking from the right side of the vehicle across the road toward the left, and the other half consisted of a pedestrian walking from the left side toward the right. A tone was presented concurrently with the pedestrian in the collision or the avoidance direction.

Experimental design. The independent variables included the TTC (2, 2.5, 3, 3.5, and 4 s) and warning direction (collision vs. avoidance direction). The TTC was randomized within each block to avoid any order effects. Warning direction was manipulated between-subjects to avoid possible confusion about the meaning of the warning signals. The dependent variables included RT and accuracy of the participant's responses. RT was defined as the interval between onset of the pedestrian (and the warning tone) and when the steering wheel was rotated approximately 15 degrees from the resting position. This criterion of 15 degrees was determined based on the pilot testing, taking into consideration the sensitivity of the wheel used.

Procedure. Participants completed a demographics survey and were then briefed on the structure of the experiment. Participants were randomly and evenly assigned to either the collision-direction warning group or the avoidance-direction warning group. Participants were informed about the semiautonomous nature of the simulated driving scene. The instructions stated, "Throughout this experiment you will be asked to imagine that you are in a semiautonomous vehicle that is usually in self-driving mode. However, sometimes the vehicle will not know what to do in certain scenarios, such as when a pedestrian is crossing the street, and will require you to make a response." Before the test trials, participants were presented with three warning tones to ensure that they were able to identify each of the tone's direction. All participants were able to identify the tone direction with a 100% accuracy when required to report the direction of each tone. A practice block showed one scene of a pedestrian walking across the road and participants were asked to turn the wheel to avoid the pedestrian.

Each participant performed two experimental blocks consisting of 60 trials each, with the starting location of the pedestrian (left vs. right) and the TTC (2–4 s) being randomized within each block. After the first block, participants took a break for up to 5 min to reduce fatigue. At the beginning of each trial, participants were asked to ensure the steering wheel was centered by placing the cursor in a blue square located in the center of the screen. Each driving scene lasted between 20 and 30 s before a pedestrian appeared and started walking across the road. Participants were told to monitor the simulated driving scene and steer away from the pedestrian to avoid a collision. A tone was presented concurrently with the pedestrian in the collision direction or the avoidance direction. Each trial ended with a text image stating "correct" for the trials in which participants successfully avoided the pedestrian, or a crash scene with shattered glass for the trials in which participants turned the wheel in the wrong direction. The feedback was to simulate the consequences of the drivers' actions in the real world, and was also included in the practice block. The next trial started after the 1500 ms visual feedback. At the end of the experiment, participants were asked about their previous driving experience, measured in years. The whole experiment session took about 50 min.

Results

Response accuracy and mean RT for correct responses were computed for each participant. Trials were excluded if the RT was above or below 3 *SD*s from the participant's mean in each condition (2.0% of all trials). The RT and accuracy were analyzed using 5 (TTC: 2.0, 2.5, 3.0, 3.5, 4.0 s; within-subjects) × 2 (warning direction: avoidance vs. collision; between-subjects) analyses of variance (ANOVAs). To assess whether driving experience impacted participants' performance during the task, we included driving experience as a covariate by creating a group for those with less than 2 years of driving experience ($n = 15$) and those with more than 2 years of driving experience ($n = 27$). The covariate did not significantly interact with either factor across any analyses. As a result, we excluded the covariate from final analyses. The Greenhouse–Geisser correction was used when the sphericity assumption was violated. In this and the next experiments, the statistical significance level was set at 0.05.

For the RT, there was a significant main effect of warning direction, $F(1, 40) = 11.80$, $p = .001$, $\eta_p^2 = .23$. Responses were faster for the collision-direction group ($M = 767$ ms) than the avoidance-direction group ($M = 964$ ms). There was also a main effect of the TTC, $F(1.70, 67.94) = 61.50$, $p < .001$, $\eta_p^2 = .61$. Responses were faster for a shorter TTC (*M*s = 767, 806, 869, 900, and 987 ms from 2 to 4 s TTCs, respectively). Pairwise comparisons (Šidak) showed that each level of the TTC was significantly different from every other level, *p*s <.05, except for the 3.0 and 3.5 s TTC, which differ only marginally ($p = .07$). There was also a significant interaction between the TTC and warning direction, $F(1.70, 67.94) = 6.74$, $p = .003$, $\eta_p^2 = .14$. The advantage (i.e., faster responses) of the collision-warning group increased as the TTC increased (Figure 2a).

The RT data showed that drivers responded faster for the shorter TTC. Note that the shorter TTC meant that the driver's vehicle was closer to the pedestrian at the time the warning signal was presented. Thus, it was not immediately clear whether the drivers reacted faster for the shorter TTC than for the longer TTC because they did not respond until their vehicle approached the pedestrians to a certain distance. This question is of practical importance because it tells us whether a more advanced warning (i.e., a longer TTC) would ensure earlier reactions of the drivers to increase safety. Consequently, we also computed the distances to the pedestrian at the time when the drivers made responses: *Response Distance* = (*TTC* – *RT*) × *Driving Speed*. An ANOVA was conducted on the response distance data as a function of the TTC and warning direction, which showed a significant main effect of the TTC (*M*s = 27.6 m, 37.9 m, 47.6 m, 58.1 m, and 67.4 m from 2 to 4 s TTC, respectively), $F(1.70, 67.94) = 4192.26$, $p < .001$, $\eta_p^2 = .99$. Therefore, for both groups, drivers responded earlier when warning signals occurred earlier, indicating that drivers did not wait to make responses until they approached the pedestrians to a certain distance. The ANOVA also showed a main effect of warning direction (*M*s = 45.5 m vs. 49.9 m for avoidance- and collision-direction warnings, respectively), $F(1, 40) = 11.80$, $p = .001$, $\eta_p^2 = .23$, as well as the interaction between the TTC and warning direction (see Figure 2b), $F(1.70, 67.94) = 6.74$, $p = .003$, $\eta_p^2 = .14$, which were consistent with RT and require no further elaboration.

For response accuracy (Table 1), there was no significant main effect of warning direction, $F(1, 40) = 2.27$, $p = .140$, $\eta_p^2 = .05$, or of the TTC, $F(1.89, 75.62) = 1.18$, $p = .311$, $\eta_p^2 = .03$. The interaction between the TTC and warning direction was not significant either, $F(1.89, 75.62) = 1.46$, $p = .238$, $\eta_p^2 = .04$.

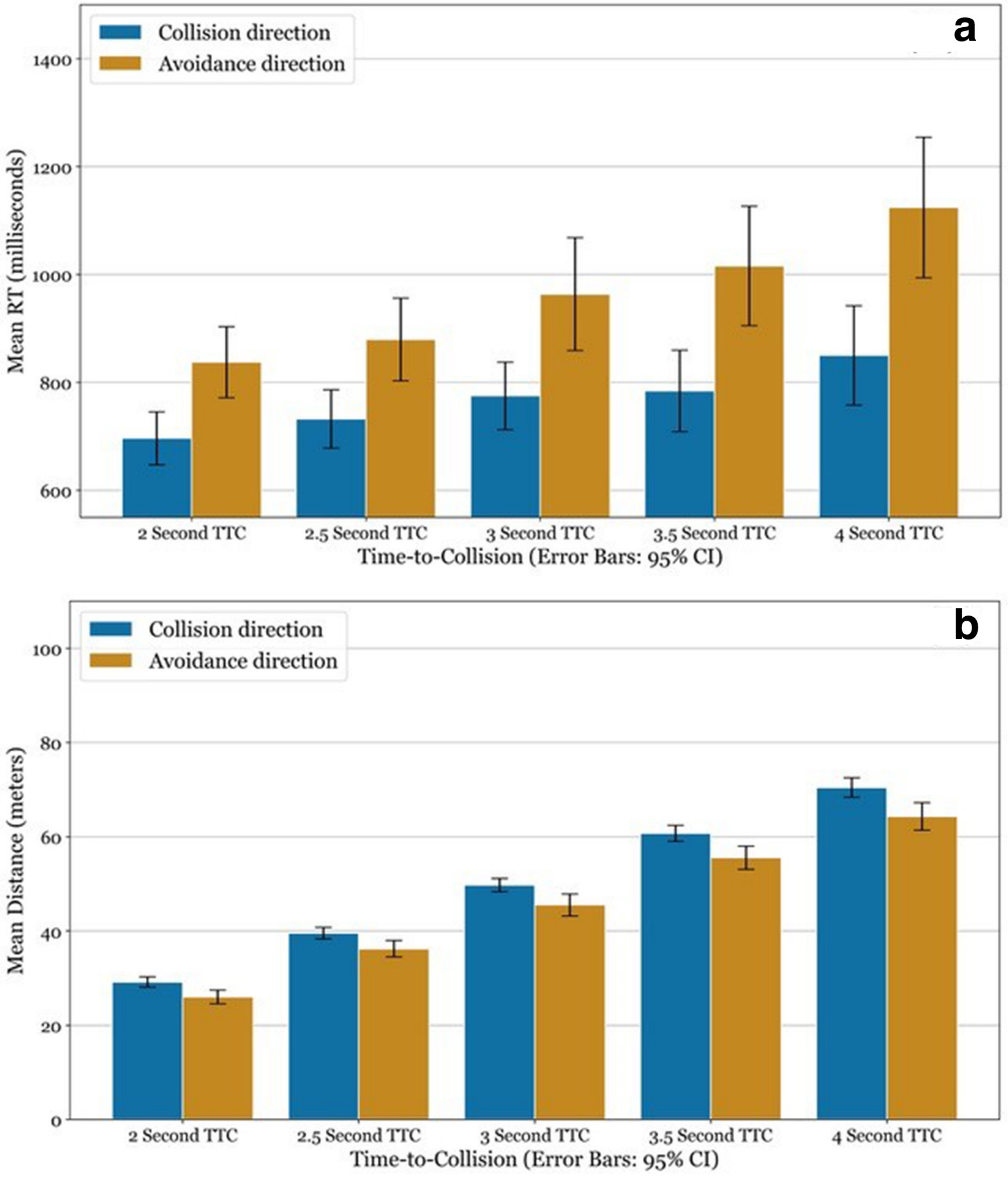

Figure 2. (a) Mean reaction time (RT) and (b) response distance across different time-to-collision (TTC) conditions for the avoidance-direction and collision-direction groups in Experiment 1.

Discussion

The results showed that responses were faster and yielded a greater distance from the pedestrian when an auditory warning was presented in the collision direction than when it was presented in the avoidance direction. This result is consistent with the attention capture (Ljungberg et al., 2012; Posner, 1980; Yantis & Jonides, 1990) prediction, rather than the SRC (Fitts & Deininger, 1954; Proctor & Vu,

TABLE 1: Mean Response Accuracy (%) in Experiments 1 and 2 (Values in the Parentheses Represent Standard Errors of the Mean)

	Experiment 1					Experiment 2				
Time-to-collision	2 s	2.5 s	3 s	3.5 s	4 s	1.5 s	2 s	2.5 s	3 s	3.5 s
Collision direction	99.8 (0.9)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	99.8 (0.9)	98.7 (2.3)	98.9 (2.9)	99.6 (1.3)	98.8 (3.2)	99.6 (1.2)
Avoidance direction	99.4 (2.0)	98.8 (3.8)	99.4 (1.5)	100.0 (0.0)	99.4 (2.0)	99.3 (1.6)	98.9 (1.9)	99.2 (2.3)	99.1 (1.8)	98.7 (3.2)

2006) prediction. It indicates that the collision-direction warning directed participants' attention to that direction and facilitated responses to the pedestrian. Moreover, this attention capture benefit of the collision-direction warnings is greater than the potential faster responses resulting from the SRC between the avoidance-direction warnings and the responses.

For the effect of the TTC, participants responded faster for a shorter TTC than a longer TTC, and the advantage (i.e., faster responses) of collision-direction warnings over the avoidance-direction warnings increased as the TTC increased. In the previous study by Straughn et al. (2009), there was a similar interaction between the TTC and warning direction; they found an advantage of avoidance-direction warnings with a 2-s TTC, but it turned to an advantage of collision-direction warnings with a 4-s TTC. Although the trend was in the same direction as the previous study, there was little indication that the avoidance-direction warnings yielded any advantage in the present study even for the shortest TTC. This result may be due to the difference in the mode of driving (manual vs. semiautomated driving). Drivers in the current experiment did not manually drive the vehicle until a signal occurred, and thus they were able to react to the signal more quickly. As a result, shorter TTCs were sufficient for participants in the current experiment to plan avoidance actions, which might have excluded the advantage of the avoidance-direction warnings. On a more technical side, the advantage of warning in the collision direction is inconsistent with SRC (Müsseler et al., 2009), which would instead predict that presenting a tone in the avoidance direction would be compatible with the required actions and should yield a benefit. Instead, the observed advantage of the collision-direction warnings is consistent with the prediction that warnings that direct attention toward the potential collision allow for quicker pedestrian detection and quicker avoidance maneuvers. This advantage caused by attention capture was largely due to the same relative location of the warning and the pedestrian in the collision-direction condition.

EXPERIMENT 2

In Experiment 1, a warning signal and the appearance of the pedestrian occurred simultaneously, and the advantage of the collision-direction warnings could be explained by attention capture. However, the same result could also be explained by a phenomenon called *stimulus–stimulus congruence* (SSC), which states that the processing of two stimuli is facilitated when they have similar features than when they have dissimilar features (e.g., De Houwer, 2003; Kornblum et al., 1990). Hence, drivers may react more quickly to lateral warning signals when they are presented on the same side as a pedestrian because it facilitates processing of both the warning signal and the pedestrian. The main difference of SSC from attention capture is that it is not necessarily about location, but any similar features could produce an advantage of congruence.

In Experiment 2, warning signals occurred on the left or right to indicate the collision direction or the avoidance direction as in Experiment 1. However, pedestrians always appeared in the middle of the road and walked toward either side (Figure 1b). This scenario of pedestrians suddenly appearing in the middle of the road is possible in some real-world situations due to low visibility or drivers' inattention. For example, a careless driver may not pay enough attention on the road (e.g., looking at their cellphone) when a pedestrian starts walking from the road side, and when they refocus on the road, the pedestrian is already in the middle of the road. Another possible scenario is that of low-visibility road conditions (e.g., heavy fog or snow): The driver is not able to see the pedestrian when the latter first enters the road at a far distance, then the pedestrian walking in the middle of the road becomes visible as the car approaches. Because the pedestrian's position was in the center of the driver's visual scene when the signals occurred, the location was not on the same side as the warning signals. Thus, if lateral warning signals captured attention to their location, there would be little benefit for detecting the pedestrian because the pedestrian was still at the center. Nevertheless, the pedestrian was already walking toward the collision direction, and thus the motion was congruent with the side of warning for collision-direction warnings, but it was incongruent for avoidance-direction warnings. Consequently, if SSC plays a role, drivers should react to warning signals more quickly with collision-direction warnings than with avoidance-direction warnings. If attention capture was the major factor to facilitate drivers' reactions, however, there should be little advantage of collision-direction warnings over avoidance-direction warnings in the present experiment.

In addition, we also included a shorter TTC (1.5 s) where drivers would have less time to respond to warnings. This inclusion was intended to evaluate whether the lack of the advantage of the avoidance-direction warnings in Experiment 1 was because drivers in a semiautomated mode of driving had sufficient time to react to a hazard, as compared to manual driving in a previous study (Straughn et al., 2009). If so, we expected that the advantage of the avoidance-direction warnings would emerge for the shorter TTC in the present experiment, which would reveal the role of SRC in driving.

Method

Participants. A total of 47 new participants who were undergraduate students (39 females; age M = 19.79, SD = 2.67) at Old Dominion University took part in the experiment for course credit. Participants were required to have a valid driver's license so that they were familiar enough with driving. This experiment complied with the APA Code of Ethics and was approved by the IRB at Old Dominion University.

Apparatus, stimuli, experimental design, and procedure. The apparatus was similar to those in Experiment 1, although the specific devices used were different. Visual stimuli were presented on a 27-in Dell monitor, which was larger than the 19-in monitor used in Experiment 1. Responses were registered by a Logitech G27 racing wheel, which was of the same size as the wheel used in Experiment 1. Auditory stimuli were presented to participants via Sony MDR-ZX110NC on-ear noise-canceling headphones; this noise-canceling feature was added to ensure room noise was minimized.

Stimuli, experimental design, and procedure were similar to those in Experiment 1, with the following exceptions. The pedestrian appeared in the middle of the road and walked to either side, rather than appearing from either side of the road and walking to the other side. In this case, when a pedestrian appeared in the road center and started walking to the left side, the potential collision was on the left side (Figure 1b). Thus, a left tone would be the collision-direction warning, and a right tone would be the avoidance-direction warning. The TTC varied between 1.5 and 3.5 s with .5 s interval. To accommodate the changes in pedestrian position and the TTC, the fog setting was adjusted to reduce the visibility to approximately 275 ft. The procedure closely followed that of Experiment 1 in all other respects.

Results

Of the 47 total participants that completed the study, two participants' data were compromised due to an error and were discarded. Mean RT and response accuracy were computed with the same criterion as in Experiment 1 (1.8% of all trials were discarded). Three

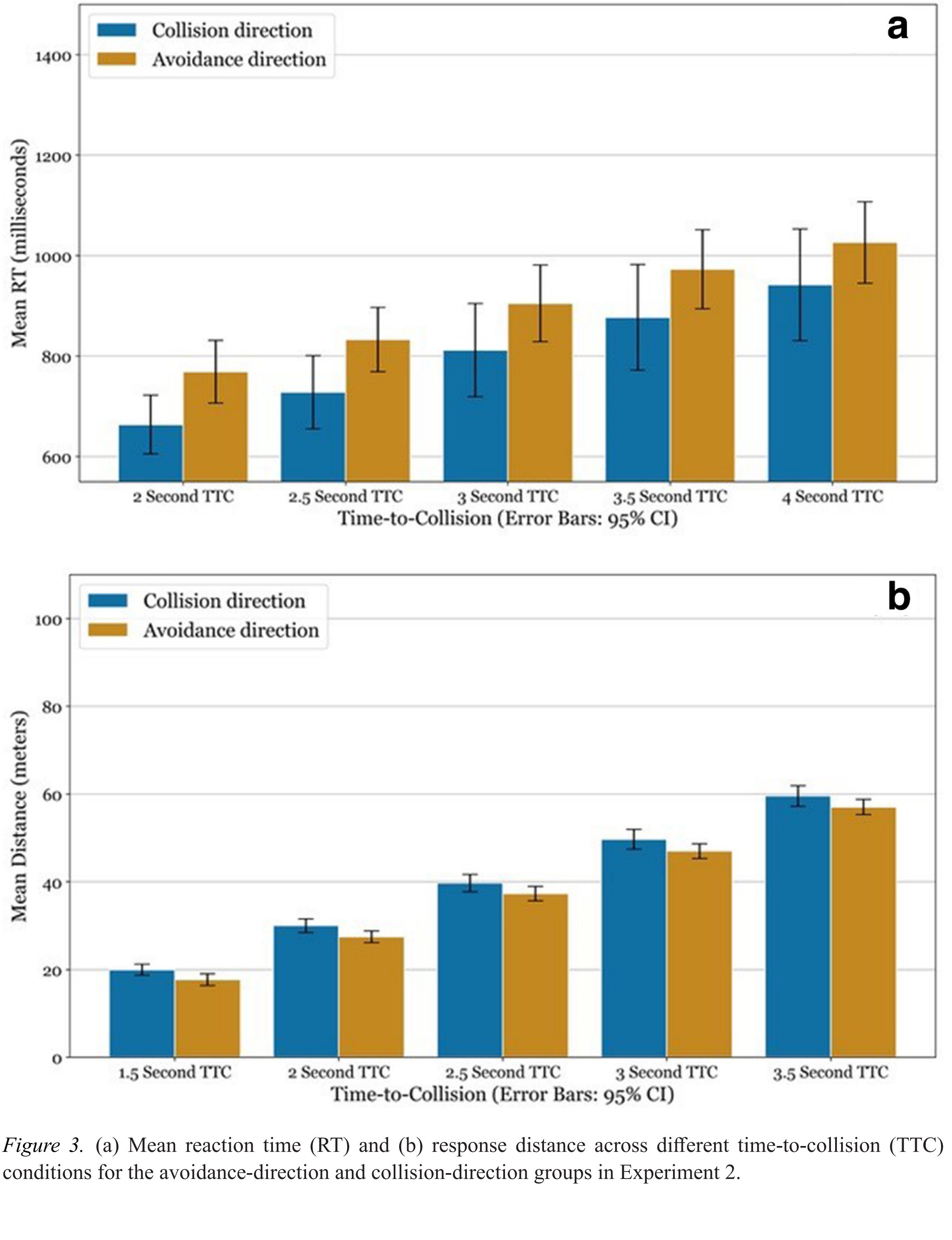

Figure 3. (a) Mean reaction time (RT) and (b) response distance across different time-to-collision (TTC) conditions for the avoidance-direction and collision-direction groups in Experiment 2.

separate 2 (warning direction: collision vs. avoidance; between-subjects) × 5 (TTC: 1.5, 2.0, 2.5, 3.0, and 3.5 s; within-subjects) mixed ANOVAs were conducted on RT, accuracy, and distance to pedestrian, respectively, similarly to Experiment 1.

For the RT (Figure 3a), responses appeared to be faster for the collision direction (M = 804 ms) than for the avoidance direction (M = 901 ms), but the main effect of warning direction was not significant, $F(1, 42) = 3.33$, $p = .075$, $\eta_p^2 = .07$. The main effect of the TTC was still significant, $F(1.66, 69.62) = 152.93$, $p < .001$, $\eta_p^2 = .79$. As in Experiment 1, the RT increased as the TTC increased (Ms = 716, 780, 858, 925, and 984 ms, from 1.5 to 3.5 s TTC, respectively). Pairwise comparisons showed that the RT differed across all TTC levels, ps <.001. There was no significant interaction between the TTC and warning direction, $F < 1$.

As in Experiment 1, an ANOVA for the distances to the pedestrian at the time of responding also showed a main effect of the TTC, $F(1.69, 72.59) = 6620.71$, $p < .001$, $\eta_p^2 = .99$, wherein a longer TTC led to greater distances to pedestrians (Ms = 17.6, 27.3, 36.7, 46.4, and 56.3 m for 1.5 to 3.5 s TTC, respectively), indicating that drivers responded earlier with more advanced warnings. Also, consistent with the RT, a main effect of warning direction (Ms = 35.7 m vs. 37.9 m for avoidance- and collision-direction warnings, respectively), $F(1, 43) = 3.21$, $p = .080$, $\eta_p^2 = .07$, and the interaction between the TTC and warning direction was not significant (see Figure 3b), $F(1.69, 72.59) = 0.27$, $p = .724$, $\eta_p^2 = .01$. For response accuracy (Table 1), there were no significant effects, Fs <1.

Discussion

Although there was a numerical advantage for the collision-direction warnings than for the avoidance-direction warnings in both RT and the distance to pedestrians as in Experiment 1, the effect was no longer significant in the present experiment. When the pedestrian appeared on one side of the road and started walking toward the middle in Experiment 1, the collision warning was clearly on the same side as the pedestrian. When the pedestrian appeared at the center position and walked to the left or right in Experiment 2, there was ambiguity as to the side of the pedestrian. Thus, the warning did not benefit the detection of the pedestrian even if attention was captured by the location of the signal. Hence, this outcome was consistent with the suggestion that the advantage of collision-direction warnings in Experiment 1 was due to attention capture, but it was inconsistent with the account based on SSC (De Houwer, 2003; Kornblum et al., 1990) that predicted an advantage of the collision-direction warnings because the tone location was still congruent with the pedestrian's walking direction.

The present experiment included a shorter TTC to examine whether an advantage of the avoidance-direction warning could be obtained (Straughn et al., 2009), but there was no indication of such an effect. Unlike Experiment 1, there was little indication that the collision-direction warnings were more beneficial with a longer TTC either. If any, the difference between the two types of warnings got smaller with a longer TTC (Figure 2b). Therefore, the advantage of the collision-direction warnings appears robust in a semi-automated mode of driving.

GENERAL DISCUSSION

This study examined the effectiveness of lateral auditory warnings in a simulated semi-automated driving scene. In Experiment 1, pedestrians appeared on either side of the road and walked across the road. The collision-direction warnings were more effective than the avoidance-direction warnings, and the advantage of the former was larger with a longer TTC. This advantage of the collision-direction warnings could be explained by attention capture caused by the warnings (Ljungberg et al., 2012; Posner, 1980; Yantis & Jonides, 1990), but were inconsistent with the idea that warnings in the direction of the required action would benefit the driver's reaction because of SRC (Fitts & Deininger, 1954; Proctor & Vu, 2006). These results could be because the benefits of captured attention to the pedestrian by the collision-direction warnings were greater than the potential SRC effect between the locations of the warning tone and the wheel-turn response.

Shorter TTC conditions in Experiment 1 also had faster responses to warning signals, similar to Straughn et al.'s (2009) findings. The faster responses at the shorter TTC were due to the fact that the distance to the pedestrian was also shorter for the shorter TTC, which would require the drivers to make an avoidance action more quickly. When the distance to the pedestrian at the point of response was examined, the drivers did react earlier (i.e., when the pedestrian was farther away) for the longer TTC. Moreover, Experiment 1 showed that the advantage of the collision-direction warnings over the avoidance-direction warnings increased as the TTC increased. These outcomes may also support the role of attention capture in producing the advantage of the collision-direction warnings, as there would be more time to shift attention to the pedestrian with the longer TTC so that the benefit of attention guided toward the pedestrian was more evident.

In Experiment 2, pedestrians appeared in the middle of the road. This condition excluded possible benefits of attention capture by the warnings. Additionally, the advantage of the collision-direction warnings was reduced to a nonsignificant level in this experiment. Although the shorter TTC did result in faster responses to signals as in Experiment 1, there was no sign that the TTC modulated the advantage of the collision-direction warnings. These results again support the role of attention capture in producing the advantage of the collision-direction warnings obtained in Experiment 1, as the advantage disappeared when the warning side did not coincide with the location of the pedestrian even if it was still the direction of a possible collision. The lack of a significant advantage of the collision direction in Experiment 2 also suggested that the SSC (De Houwer, 2003; Kornblum et al., 1990) of the pedestrian motion with the warning side had little influence on reactions to the signals. Therefore, the results of the two experiments indicate that the direction of attention capture, neither SRC nor SSC, should determine the effectiveness of lateral warning directions.

Unlike the current study, Straughn et al. (2009) found that a collision-direction warning was more effective for early warnings, whereas an avoidance-direction warning was more effective for late warnings. They explained that when the TTC was very short, participants did not have time to shift attention to the potential collision, so it was more effective to respond toward the auditory warning directly. Although the current Experiment 2 evaluated TTC conditions that were even shorter than those used in Straughn et al.'s study, there was still no indication that presenting a warning in the avoidance direction produced any benefit. The discrepancy may be due to the differences in the mode of driving. In the semiautonomous driving scenario of the current study, participants were not responsible for lane keeping and speed, but were required to keep a focus on the road and respond to hazards when needed. Consequently, participants might have enough time to process information even with a short TTC, so that they did not react directly to the warning signals in semiautomated driving.

Among the few studies conducted using lateral auditory warnings for autonomous or semiautonomous driving, Petermeijer et al. (2017) found no significant difference between the collision-direction and avoidance-direction warnings in terms of steer-touch RT (i.e., how quickly the participants touched the steering wheel). The difference in the results of the current study and those of Petermeijer et al. could be due to their measure of the RT for touching the steering wheel, which, unlike our measure using the time of initiating a response, does not involve a directional movement. In addition, only a few of their participants reported noticing the warning was directional, and their drivers were involved in a secondary task. Thus, their null results could also be due to low salience of the warning directionality or participants' lack of attention to the warning. Cohen-Lazry et al. (2019) used tactile alerts on the driver's seat close to participants' thighs and also had participants perform a secondary task. Given that the tactile warnings were on the driver's body and closer to the response effector (i.e., the hands) than to the road hazard, it was more likely that the tactile feedback would direct attention more to the responses rather than the hazard. Thus, their setting tends to enhance the SRC between the tactile warning and the wheel-turning response and reduce the attention captured to the road hazard, leading to faster responses when the warnings were in the direction of the desired responses.

Another potential reason for the advantage of the collision-direction warnings in our results is the location of pedestrians. Pedestrians were presented centrally in Experiment 2, and a relatively central location in Experiment 1. This relatively central pedestrian location could have contributed to the high response accuracy in both experiments. Moreover, as the pedestrian becomes more central on the screen, it is more likely to benefit from the attention captured by the warning on the same side and increase the effect of attention capture. In contrast, the SRC effect relies on the spatial location of the pedestrian, and its effect reduces when the pedestrian becomes more central. As a result, it is possible that the benefit of SRC may increase and that of attention capture will decrease if the pedestrian is presented in a more peripheral position, which might lead to advantages of the avoidance-direction warnings similar to the 2-s TTC condition in Straughn et al.'s (2009) study.

As mentioned in the introduction of this article, it has been shown that command displays can be more effective than status displays in time-critical situations in aviation (Sarter & Schroeder, 2001). In the current study, the avoidance-direction warning is a form of "command" that tells the driver which direction to turn the wheel, yet no advantage of the avoidance-direction warning was found, even at the shortest TTC. In aviation, the scene is usually complex and there may be multiple desired actions, and it takes time for the pilot to analyze the environment and regain situation awareness, and thus it makes sense that the command display, which tells them what to do, is more effective under urgent situations. In the driving scene of the current experiment, the visual scene was simple, and so was the potential action; the hazardous events of pedestrians repeatedly entering the road were also relatively predictable, although the timing was varied. As a result, it works better when the participant has the opportunity to analyze the potential collision risk and then make an action. If the driving scene and drivers' task were more complex (e.g., when drivers perform nondriving related secondary tasks while driving), it is expected that the results may have been more in line with that of Sarter and Schroeder.

Whereas the results of this study have important implications for improving driving-assistance systems for semiautomated driving, some limitations should also be acknowledged. In particular, due to the use of video clips, the drivers in the present experiments might not have felt the threat posed in the current task to be as real as we hoped. We controlled all aspects of the environment except for the appearance of the pedestrian because other elements in the driving environment could be used as a cue by the participant for predicting the pedestrian. This blank landscape, though, reduced the fidelity of the driving scenario. Also, we were not able to measure drivers' post-takeover driving performance in the case that they successfully avoided a crash using the video stimuli. It would be beneficial to examine whether the effectiveness of the warnings extends to after the takeover. Further, to focus on the relation between lateral warnings and lateral responses, we only allowed steering-wheel responses. In the real world, a driver could press the brake pedal in response to crossing pedestrians. Therefore, the current findings should be replicated in a high-fidelity driving simulator as well as in actual driving scenarios with other complex visual and auditory road elements, and allow for all possible driver responses including pedal press.

The purpose of the current study was not to compare warnings of different modalities, but to examine how spatialized warnings function within one modality. Thus, we focused on auditory warnings. However, the communication between the vehicle and the driver can occur in forms of auditory, visual, and haptic warnings. An obvious question is whether the current results can be generalized to warnings in other modalities (Meng & Spence, 2015). Indeed, Straughn et al. (2009) examined both tactile and auditory warnings, although they plotted the data from both together due to similar results for both modalities. Additionally, studies have shown the benefits of using multimodal warnings in comparison to unimodal warnings (Biondi et al., 2017; Ho et al., 2007; Lu et al., 2013; Petermeijer et al., 2017). Thus, it is likely that drivers would benefit from warnings in other modalities and those in multimodalities.

The theory that our results support is the attention capture function of the warning tone (e.g., Ljungberg et al., 2012; Posner, 1980; Yantis & Jonides, 1990). It would be interesting for future investigations to evaluate how other models of human performance, such as the N-SEEV model (Steelman-Allen et al., 2009), could inform the present research. Eye-tracking measures are arguably the most effective way of measuring participants' attention allocation (Hayhoe & Ballard, 2005; Werneke & Vollrath, 2012). Future studies could utilize the eye-tracking method to validate the attention capture function of the warning, as well as whether participants have followed the instruction to focus on the road. In addition, participants' self-reports of potential mind wandering (Casner et al., 2016; Walker & Trick, 2018), as well as their perception about the warning (e.g., urgency, annoyance, and favorability) could also provide useful information to the design of the warning interface (Campbell et al., 2018).

Lastly, participants in the current study were college students. This younger sample has on average less driving experience than the overall driving population, and thus the current results are not readily generalizable to the population as a whole. Future research should examine these results among other age groups for the goal of generalization.

CONCLUSION

The use of directional warnings to signal the locations of hazards can help improve safety. This study examined drivers' responses to auditory warnings that signaled pedestrians who suddenly appear on either side or in the middle of the road, by alerting drivers in either the direction of a potential collision or the direction to avoid a potential collision. The results of the two experiments suggest that the relative location of the pedestrian and the warning influenced the effectiveness of the warnings due to the warning capturing participants' attention. The results also indicate that the effectiveness of the auditory warnings depends on the context (e.g., the location of the pedestrian at the time of warning presentation). Overall, these findings provide practical implications for vehicle designers and manufacturers and support the idea that it would be best to implement auditory warnings to signal the potential collision location.

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KEY POINTS

- Auditory warnings in the collision direction facilitated drivers' taking over control from the semiautonomous vehicle and responding to the potential collision.
- The advantage of the collision-direction warnings over the avoidance-direction warnings became insignificant when the location of the pedestrian did not align with that of the warning.
- The advantage of the collision-direction warnings was due to the attention capture function of the auditory warnings, and it did not depend on the time to collision.
- Overall, lateral collision warnings are recommended to be presented in the collision direction.

ORCID iD

Jing Chen https://orcid.org/0000-0003-0394-0375

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Jing Chen is an assistant professor of human factors psychology at Old Dominion University. She received her PhD in cognitive psychology and MS in industrial engineering at Purdue University in 2015.

Edin Šabić is currently the director of research at Electronic Caregiver. He received his PhD in experimental psychology at New Mexico State University in 2020.

Scott Mishler is a doctoral student of human factors psychology at Old Dominion University. He received his MS in psychology at Old Dominion University in 2019.

Cody Parker is a doctoral student of human factors psychology at Old Dominion University. He received his BA in psychology at University of Central Oklahoma in 2016.

Motonori Yamaguchi is a senior lecturer of psychology at University of Essex. He received his PhD in cognitive psychology at Purdue University in 2010.

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