Looming Auditory Collision Warnings for Driving

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**Objective:** A driving simulator was used to compare the effectiveness of increasing intensity (looming) auditory warning signals with other types of auditory warnings.

**Background:** Auditory warnings have been shown to speed driver reaction time in rear-end collision situations; however, it is not clear which type of signal is the most effective. Although verbal and symbolic (e.g., a car horn) warnings have faster response times than abstract warnings, they often lead to more response errors.

**Method:** Participants (N = 20) experienced four nonlooming auditory warnings (constant intensity, pulsed, ramped, and car horn), three looming auditory warnings (“veridical,” “early,” and “late”), and a no-warning condition. In 80% of the trials, warnings were activated when a critical response was required, and in 20% of the trials, the warnings were false alarms. For the early (late) looming warnings, the rate of change of intensity signaled a time to collision (TTC) that was shorter (longer) than the actual TTC.

**Results:** Veridical looming and car horn warnings had significantly faster brake reaction times (BRT) compared with the other nonlooming warnings (by 80 to 160 ms). However, the number of braking responses in false alarm conditions was significantly greater for the car horn. BRT increased significantly and systematically as the TTC signaled by the looming warning was changed from early to veridical to late.

**Conclusion:** Looming auditory warnings produce the best combination of response speed and accuracy.

**Application:** The results indicate that looming auditory warnings can be used to effectively warn a driver about an impending collision.

**Keywords:** auditory displays, driver behavior, reaction time, highway and vehicle design, audition, detection

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**INTRODUCTION**

**Collision Warnings in Driving**

Considerable effort has been put into the development of forward collision warnings for driving (e.g., Hirst & Graham, 1997; McGehee, LeBlanc, Kiefer, & Salinger, 2002; Scott & Gray, 2008) in response to accident analyses showing that rear-end collisions are the most common type of accident involving another vehicle (National Highway Traffic Safety Administration, 2009) and that the majority of these accidents are attributable to driver inattention (Knippling et al., 1993; McGehee et al., 2002). If a collision warning signal can reorient the driver’s attention to the lead vehicle, it is likely to substantially reduce the chance that a rear-end collision will occur.

What type of warning signal should be used? For a warning to be effective, it needs to be detectable, be reliable, and lead to an appropriate behavioral response (Patterson, 1989). If a driver does not first detect that a warning has been activated (e.g., if an auditory signal is masked by background noise), he or she cannot use it. If the reliability of a warning is too low (i.e., the false alarm rate is high), it can become annoying and lead to mistrust, and the system may be deactivated by the driver (e.g., Bliss & Acton, 2003). Finally, even highly detectable and reliable warnings may lead to an inappropriate motor action from the driver. For example, a very loud auditory signal can lead to a startle reaction (Edworthy, 1994). For abstract signals, such as beeps and light flashes, it may also be the case that it takes some time for the driver to determine what event the warning is signaling. This may particularly be the case if there are other warnings present in the vehicle (e.g., a lane departure or backup warning). Fast responses in these situations may require extensive training (Edworthy, 1994).

Collision warning systems have been investigated that use visual signals, such as visual icons presented on the dashboard (e.g., J. D. Lee, McGehee, Brown, & Reyes, 2002); auditory...
signals, such as tones or speech (e.g., Graham, 1999); tactile signals, such as vibrations delivered through the driver’s seat or seatbelt (e.g., Ho, Reed, & Spence, 2007); and multimodal signals (e.g., Ho & Spence, 2008; Lee et al., 2002). Despite these efforts, there is still considerable debate about which type of warning signal is the most effective (Engstrom & Victor, 2009). In the present study, I considered only auditory warnings. In particular, I developed and investigated a new type of auditory collision warning using a looming signal.

**Auditory Collision Warning Research**

Graham (1999) compared four types of auditory warnings: (a) a ramped tone, (b) a voice saying “ahead,” (c) a car horn, and (d) skidding tires. Participants performed a head-down tracking task while seated in front of a monitor that displayed videos of rear-end approaches. There were also a small number of false alarm conditions. The participant’s task was to press a brake pedal to avoid a collision. Mean brake reaction times (BRT) were significantly faster for the horn and skidding-tires sounds than for any of the other warnings; however, the percentage of false alarm brake presses was also significantly higher. These findings suggest that warnings that convey some of the natural information that occurs during a driving collision event may be more effective than abstract warnings; however, there may be a trade-off between response speed and response appropriateness.

Ho and Spence (2005) compared the effectiveness of speech and car horn warnings. Participants viewed videos of driving scenes presented on a frontal monitor and via a simulated rearview mirror and were asked to hit the brake pedal if they detected a collision with a lead vehicle or hit the accelerator pedal if they detected that the following vehicle was approaching. Car horn reaction times (BRT) were significantly faster for the horn and skidding-tires sounds than for any of the other warnings; however, the percentage of false alarm brake presses was also significantly higher. These findings suggest that warnings that convey some of the natural information that occurs during a driving collision event may be more effective than abstract warnings; however, there may be a trade-off between response speed and response appropriateness.

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To summarize, previous research has shown that auditory warnings can potentially speed reaction times to an impending collision; however, it is not clear which type of warnings are the most effective. For the most part, symbolic warnings, such as verbal cues, skidding tire sounds, and car horns, have resulted in faster response times than abstract warnings; however, this result also seems to be accompanied by an increase in the percentage of inappropriate responses. It is also the case that the majority of abstract warnings used in previous research have not been designed to convey urgency (see Edworthy, 1994). We next discuss a possible alternative to these types of auditory warning.

**Auditory Looming**

When a sound-emitting object approaches an observer, there will be an associated increase in sound intensity (I). Shaw, McGowan, and Turvey (1991) demonstrated that it is theoretically...
possible to detect the time to collision \((TTC)\) of the object solely on the basis of this rising (looming) intensity. Specifically,

\[
TTC \approx \tau = 2 \frac{I}{dl/dt} \quad (1)
\]

This auditory \(\tau\) is a direct analog of visual \(\tau\) (i.e., the rate of change of size of an approaching object’s retinal image; Hoyle, 1957; Lee, 1976).

Empirically, it has been shown that observers can make reasonably accurate estimates of \(TTC\) on the basis of Equation 1 alone, but there are some biases. Schiff and Oldak (1990) recorded sounds of vehicles approaching at different speeds. Observers were presented with a portion of the recording and were required to extrapolate and judge when the object would have reached them. \(TTC\) was substantially underestimated, with estimated \(TTC\) ranging between 40% and 77% of the actual \(TTC\). Interestingly, blind participants could estimate \(TTC\) on the basis of auditory information alone significantly more accurately than sighted individuals and could estimate \(TTC\) as accurately as sighted participants using visual information. These findings suggest that sighted observers may be able to learn to use auditory \(\tau\) more accurately if given more practice with conditions in which it is the only source of information.

Neuhoff (2001) used speakers that were physically moving toward or away from a stationary observer. Participants were required to judge the starting and stopping location of the sound. Observers could use the acoustic information to estimate the start and stop points, but there was a large bias in their estimates, as approaching sounds were perceived to stop and start closer to the observer than were receding sounds.

Collision warnings based on auditory looming (i.e., intensity increases as the distance been the driver’s vehicle and the lead vehicle decreases) have several potential benefits for driving safety. First, unlike the abstract auditory warnings tested in previous research, a looming signal conveys urgency. Second, because observers tend to underestimate \(TTC\) for auditory looming, there would be a built-in safety bias. Third, the acoustic properties of a looming warning can easily be altered to shorten the \(TTC\) signaled by the warning (e.g., to make a driver respond faster when the road is icy). Finally, because an auditory looming warning signal is novel to a driver, brake response may be more sensitive to the reliability of the warning signal (i.e., drivers may learn not to hit the brake as soon as the signal is detected) than for an “overlearned” signal, such as a car horn.

**Goals of the Present Study**

The purpose of the present study was to develop and test auditory looming collision warnings in a driving simulator. The first goal was to compare a looming warning with a variety of nonlooming abstract warnings (pulsed, ramped, or constant intensity), a symbolic warning (a car horn), and a no-warning condition. It was predicted that BRTs would be faster for a looming warning than for abstract warning signals. The second goal was to determine whether the looming warnings altered the driver’s perceived \(TTC\) with the lead vehicle. To achieve this end, looming warnings were created that signaled a \(TTC\) that was shorter (or longer) than the actual \(TTC\). If looming warnings change the driver’s perception of \(TTC\), then a “late” looming warning should slow BRT relative to a “veridical” looming warning, and an “early” warning should speed BRT relative to a veridical warning.

**METHOD**

**Driving Simulator**

The DS-600c Advanced Research Simulator by DriveSafety was used. This simulator comprised a 300° wraparound display, a full-width automobile cab (a Ford Focus), and a motion platform. Tactile and proprioceptive feedback cues were provided via dynamic torque feedback from the steering wheel and vibration transducers mounted under the driver’s seat. The motion platform provided coordinated inertial cues for the onset of longitudinal acceleration and deceleration. The data recording rate was 60 Hz.

**Warning Signals**

Seven different warning signals were used: four types of nonlooming warnings and three types of looming warnings. With the exception...
of the car horn warning, all auditory warnings had a frequency of 2000 Hz. All warning signals were presented from a 6.5-cm diameter speaker located inside the vehicle dashboard and aligned with the center of steering wheel. I chose 2000 Hz because it is within the range of frequencies that produce the lowest detection thresholds (Goldstein, 2006). Warnings were triggered by the algorithm developed by Hirst and Graham (1997):

\[ D_w = \frac{dD}{dt} \times TTC_{thres} + SP \times V_f. \]  

(2)

In this equation, \( D_w \) is the distance from the lead vehicle at which the warning is activated, \( dD/dt \) is closure rate (which is determined by the speeds of both vehicles), and \( V_f \) is the following vehicle’s speed. \( SP \) (speed penalty) and \( TTC_{thres} \) (time-to-collision threshold) are values that can be set within the system. The essential goal of this algorithm is to warn the driver earlier when he or she is traveling at a higher approach velocity (thus requiring a greater stopping distance). In the present study, the recommended value of 0.4905 was used for the SP (Hirst & Graham, 1997). Two \( TTC_{thres} \) values were used: 3.0 s (the recommended value) and 7.0 s. The 7.0 s value was used to create false alarm situations, in which the alarm was activated for an event that did not require the driver to respond with a braking maneuver. The \( TTC_{thres} \) value at each instance of warning activation was chosen randomly (without replacement) with 3.0 s having a probability of 0.8 and 7.0 s having a probability of 0.2. This 80% reliability rate has been used in previous studies of collision warnings (e.g., Ho & Spence, 2005).

85 dB. The intensity ramp was identical for all closing velocities. Pulsed warnings had an on-time (i.e., \( I = 75 \) dB) of 300 ms and an off-time (i.e., \( I = 0 \) dB) of 200 ms. These warnings were included because previous research has shown that pulsed auditory signals are perceived to be more urgent than constant-intensity signals (e.g., Patterson, 1989). Finally, the car horn warning was the sound of a real car horn (8000 Hz, 66 dB) downloaded from the Internet (see Ho & Spence, 2005). This sound clip was modified using Audacity software to have a 1.5-s duration.

**Looming warnings.** These warnings were either (a) veridical, (b) early, or (c) late. The time-intensity profiles for a veridical warning with three different approach speeds are illustrated in Figure 2A. For the veridical looming warning, intensity was increased according to

\[ I_w \approx a + kD^{-2}, \]

(3)

where the value of \( D \) at each instant was determined by the driver’s speed at the onset of the warning. Values of \( a = 50 \) and \( k = 30,000 \) were chosen to make the intensity of the warning approximately 60 dB at a simulated distance of 100 m (the largest distance at which drivers received a warning in the present study) and to ensure that the intensity level was never greater than 85 dB. This 60 dB value was chosen as the minimum warning intensity to ensure that in all cases, the warning signal was considerably

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**Figure 1.** Time-intensity profiles for examples of the three nonlooming warnings. Note that the velocity of the following vehicle is 29 m/s (65 mph) in these examples. CI = constant intensity.
greater than the combined intensity of the noise of simulated engine, road, and traffic (approximately 50 dB). The sound level of ~10 dB to 15 dB above ambient noise is what is typically recommended for auditory warning signals (Sorkin, 1987).

As illustrated in Figure 2B, for the early looming warning, the driver was presented with a change in intensity that would correspond to an approach with a \( \text{TTC} \) value that was 0.5 s less than the actual value (i.e., that would be indicated by the rate of expansion of the lead vehicle). For the late looming warning, the driver was presented with a change in intensity that would correspond to an approach with a \( \text{TTC} \) value that was 0.5 s greater than the actual value. The early and late conditions created a conflict between visual and auditory cues to \( \text{TTC} \) similar to what has been investigated for visual \( \text{TTC} \) cues (e.g., Gray & Sieffert, 2005; Rushton & Wann, 1999).

**Design and Procedure**

For this study, 20 drivers between the ages of 18 and 42 (\( M = 27.9, \ SD = 10.3 \)) participated. There were 12 females and 8 males. All participants were licensed drivers with between 5 and 21 (\( M = 9.4, \ SD = 3.7 \)) years of driving experience. All drivers completed an informed consent and were compensated for their participation. The drivers were naïve to the aims of the experiment and reported normal hearing.

The drivers followed a red lead car on a rural, two-lane road and were instructed to drive in their own lane and not pass the lead car. Drivers were given two different 5-min practice drives without any warnings to become familiar with the driving simulator. Drivers in the present study received no training with the different warning signals prior to the experimental trials. Drivers were instructed to maintain a 2.0-s time headway (TH) with the lead car (Ho et al., 2007). If the drivers followed too far behind the lead car, the words “Speed Up!” would appear in red text on the driver’s display. There was no analogous “Slow Down!” warning, so drivers were free to maintain any TH below 2.0 s.

The lead car was programmed to unpredictably (to the driver) change speeds at variable intervals. The lead car traveled between 55 mph and 65 mph (with an average speed of 60 mph), with its speed determined by a sum of three sinusoids. The lead car was programmed to make eight unpredictable (to the driver) full stops at \(-6 \text{ m/s}^2\). The behavior of the lead car made it very difficult for the driver to predict when the lead car would speed up, slow down, or stop, creating multiple possible rear-end collision situations. The brake lights of the lead car were disabled so that the present results would be directly comparable to previous studies in this area (Ho et al., 2007; Scott & Gray, 2008). Intermittent opposing roadway traffic was included to more closely simulate real-world rural driving conditions. If the participant contacted the lead vehicle (i.e., crashed), an audio file of a crash...
sound was presented for a duration of 500 ms and the lead vehicle disappeared from the screen.

In all warning conditions, drivers were given the following instructions:

In this condition, you will hear a warning sound indicating that you are about to collide with the vehicle in front. Please use this warning signal in any manner you wish to help avoid a collision. For example, when you hear a warning, you may choose to let off the accelerator, slam on the brake, or do nothing at all.

Each driver completed 16 driving tracks corresponding to two repeats each of the seven warning types plus a no-warning condition. Each track had 10 unpredictable full stops of the lead car and required roughly 6 to 7 min to complete. The location of the stops was randomly varied across tracks. The order of these 16 conditions was randomized for each participant with the constraint that all eight conditions must be presented once before any condition was repeated. Participants received a 5-min rest between conditions to minimize simulator sickness and fatigue.

Data Analysis

For each warning condition, there were 20 lead car braking events: 16 events in which the warning was reliable (i.e., $TTC_{thres} = 3.0$ s) and 4 events in which the warning was unreliable (i.e., $TTC_{thres} = 7.0$ s). Reliable and unreliable warning conditions were analyzed separately.

For the reliable warnings, the main dependent variable was the driver BRT for each lead car stopping event (WON2B). WON2B was defined as the elapsed time between the onset of the collision warning and brake onset. This variable was chosen to allow for direct comparison with previous driving warning studies (e.g., Scott & Gray, 2008). Note that the time at which the warning is triggered represents a critical threshold (determined by the empirical and modeling work of Hirst & Graham, 1997): If the driver does not begin braking shortly after this critical point in time is crossed, then a collision is likely to occur. Only stopping events for which the driver received a warning were included in the analysis (e.g., I discarded events for which the driver was too far away from the lead car at the time of stopping to receive a warning). The number of collision events discarded per driver ranged between 2 and 5 of the total possible 128 events. There was no significant effect of warning type on the number of valid events. The second dependent variable was the proportion of collisions with the lead vehicle, which was defined as the number of collisions divided by the number of valid stopping events for each driver.

Mean WON2B times (averaged across all of the stopping events for each driver) and the percentage of collisions were first analyzed using one-way ANOVAs with warning type as the factor. Tukey pairwise comparisons ($\alpha = .05$) were then used to compare each warning condition against the others. Cohen’s $d$ was used as an unbiased measure of effect size for all pairwise comparisons.

For unreliable warnings, the dependent variable analyzed was the number of brake activations, where an activation was defined as an instance in which the brake force reached >50% of the maximum force within 1 s of the warning onset. The number of brake activations was analyzed with the use of a one-way ANOVA with warning type as the factor and Tukey pairwise comparisons. Note that the no-warning condition was not used in the analysis for unreliable warnings.

Conditions in which no warning was presented to the driver were included in the analyses because in the present study, I sought not only to compare the relative effectiveness of different auditory warnings but also to determine whether the warnings had any benefit compared with no warning at all. Previous research has shown that collision warnings do not always speed BRT compared with no warnings (e.g., Mohebbi et al., 2009).

RESULTS

Figure 3 plots the mean WON2B times. The one-way ANOVA revealed a significant effect of warning type, $F(7, 133) = 17.3, p < .001$. Pairwise comparisons for the Tukey test are shown in Table 1. The looming early warning had a significantly shorter WON2B time than all other warnings. Effect sizes were large for all of these comparisons (all $d > 1.0$). The looming veridical warning had a significantly shorter
WON2B time than all warnings (all $d > 1.0$) except for the car horn ($d = 0.1$).

Figure 4 plots the mean proportion of collisions. The one-way ANOVA revealed a significant effect of warning type, $F(7, 133) = 2.2, p < .05$. Pairwise comparisons for the Tukey test are shown in Table 2. The only significant differences occurred between the looming vertical and no-warning conditions ($d = 0.8$) and the looming early and no-warning conditions ($d = 0.9$).

![Figure 3: Mean warning onset to brake time (WON2B) for the seven warning conditions and the no-warning condition. Error bars are standard deviations. Note that in the no-warning conditions, WON2B refers to the time elapsed between the time at which the warning would have been presented and the onset of braking. CI = constant intensity.](image)

**TABLE 1: Pairwise Comparisons From Tukey Test: Warning Onset to Brake Time**

<table>
<thead>
<tr>
<th>Warning</th>
<th>Looming Veridical</th>
<th>Car Horn</th>
<th>Ramped</th>
<th>Pulsed</th>
<th>Looming Late</th>
<th>CI</th>
<th>No Warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Looming early</td>
<td>.1*</td>
<td>.1*</td>
<td>.17*</td>
<td>.19*</td>
<td>.2*</td>
<td>.2*</td>
<td>.32*</td>
</tr>
<tr>
<td>Looming veridical</td>
<td>.02</td>
<td>.11*</td>
<td>.12*</td>
<td>.13*</td>
<td>.13*</td>
<td>.25*</td>
<td>.25*</td>
</tr>
<tr>
<td>Car horn</td>
<td>.1*</td>
<td>.1*</td>
<td>.11*</td>
<td>.11*</td>
<td>.23*</td>
<td>.23*</td>
<td>.23*</td>
</tr>
<tr>
<td>Ramped</td>
<td>.02</td>
<td>.02</td>
<td>.02</td>
<td>.02</td>
<td>.15*</td>
<td>.15*</td>
<td>.15*</td>
</tr>
<tr>
<td>Pulsed</td>
<td>.01</td>
<td>.01</td>
<td>.13*</td>
<td>.13*</td>
<td>.13*</td>
<td>.13*</td>
<td>.13*</td>
</tr>
<tr>
<td>Looming late</td>
<td>.0</td>
<td>.0</td>
<td>.12*</td>
<td>.12*</td>
<td>.12*</td>
<td>.12*</td>
<td>.12*</td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.12*</td>
</tr>
</tbody>
</table>

*Note. CI = constant intensity. $d_t = 0.102$. $p = .05$.*
Table 3. This analysis revealed that the number of brake activations for unreliable car horn warnings was significantly greater than for each of the other warnings (all \( d > 0.8 \)) except for the constant-intensity warning (\( d = 0.48 \)).

To determine whether order or practice effects influenced the effectiveness of the different warnings, I separated the data for the two repeats for each warning type, as shown in Figure 6. These data were then analyzed using two-way ANOVAs with block number (1, 2) and warning type as factors. This analyses revealed a significant main effect only of warning type, \( F(7, 133) = 20.2, p < .001 \). None of the other effects was statistically significant.

**DISCUSSION**

For a collision warning to be effective, it must rapidly elicit the appropriate behavioral response from the driver. Because the difference between stopping safely and crashing can be a matter of milliseconds, warnings that require extensive
cognitive processing are unlikely to be effective. It is for this reason that many researchers have proposed using symbolic warnings that have some natural mapping between the signal and the collision event. Indeed, it has been shown that warning signals such as sounds of car horns or screeching tires lead to faster BRTs than abstract warning signals composed of tones or pulses (Graham, 1999; Ho & Spence, 2005). However, these symbolic warnings also seem to come with a cost: Drivers make more inappropriate braking responses in false alarm situations. Furthermore, in more realistic driving conditions, it is possible that these types of warnings may be confused with naturally occurring sounds (McKeown & Isherwood, 2007) or may be interfered with by the concurrent linguistic processing involved in talking on a cell phone while driving (Mohebbi et al., 2009).

An alternative approach to using symbolic auditory warnings is to develop more complex abstract signals that inform as well as alert an

**Figure 5.** Mean number of braking activations for unreliable warnings in the seven warning conditions. Error bars are standard deviations. CI = constant intensity.

**TABLE 3:** Pairwise Comparisons From Tukey Test: Number of Brake Activations

<table>
<thead>
<tr>
<th>Warning Type</th>
<th>Looming Late</th>
<th>Looming Early</th>
<th>Pulsed</th>
<th>Ramped</th>
<th>CI</th>
<th>Car Horn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Looming veridical</td>
<td>.05</td>
<td>.10</td>
<td>.30</td>
<td>.40</td>
<td>.50</td>
<td>1.05*</td>
</tr>
<tr>
<td>Looming late</td>
<td>.05</td>
<td>.25</td>
<td>.35</td>
<td>.45</td>
<td></td>
<td>01.0*</td>
</tr>
<tr>
<td>Looming early</td>
<td>.20</td>
<td>.30</td>
<td>.40</td>
<td></td>
<td></td>
<td>0.95*</td>
</tr>
<tr>
<td>Pulsed</td>
<td>.10</td>
<td>.20</td>
<td></td>
<td></td>
<td></td>
<td>0.75*</td>
</tr>
<tr>
<td>Ramped</td>
<td>.10</td>
<td>.10</td>
<td></td>
<td></td>
<td></td>
<td>0.65*</td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.55</td>
</tr>
</tbody>
</table>

Note. CI = constant intensity. $d_1 = 0.58$.  
*p = .05.
operator. For example, Edworthy and colleagues (Edworthy & Stanton, 1995) have demonstrated that it is possible to convey different levels of urgency in an auditory warning by varying basic acoustic parameters, such as pulse frequency and speed. However, because there is no direct relationship between the signal and the required response, this mapping must be learned through practice (Edworthy, 1994). This lack of a natural mapping could be problematic in driving because there are not a lot of opportunities for learning, given that collision events occur rarely.

The results of the present study suggest that an auditory looming warning is an effective compromise between these two alternatives as an abstract, easily modifiable signal that carries a natural association with real-world collision events. As shown in Figure 3, the veridical looming warning produced significantly speeded BRTs relative to the other abstract warning signals (pulsed, ramped, and constant intensity) and to the no-warning condition. On average, BRTs were 77 to 115 ms faster for the veridical looming warning as compared with the abstract warnings (corresponding to a distance of 1.9 to 2.8 m for a speed of 24.5 m/s [55 mph]) and 217 ms faster for the veridical looming warning compared with no warning (corresponding to a distance of 1.9 to 5.4 m for a speed of 24.5 m/s [55 mph]). Only the car horn warning produced a similar improvement in BRT. However, consistent with previous findings (e.g., Ho & Spence, 2005), the car horn warning produced a significantly greater number of false alarm brake presses than did the veridical looming warning. Finally, unlike the car horn, the veridical warning led to a significant reduction in the number of collisions as compared with the no-warning condition. Therefore, in terms of response speed and accuracy, the looming warning was the most effective of all the warnings tested in the present study.

The significant difference between BRTs for the three different looming warnings found in the present study may also be important for application. As discussed by Gupta, Bisantz, and Singh (2002), not only is it important for driver assistance systems to warn drivers about potential hazards, but these systems must also be sensitive to the roadway conditions. For example, if the collision warning given to the driver is the same for dry and icy road conditions, it is likely the driver will respond similarly in both cases. The results from the present study suggest that it would be possible to create a system where an early looming warning is used when the assistance system detects poor road conditions. A similar manipulation could be used when the assistance system detects the driver is fatigued (Yang et al., 2009).

The findings of the present experiment were limited by the driving simulator paradigm used. It will be important for future research to investigate looming warnings in conditions in which the brake lights are activated and when the driver is engaged in secondary tasks, such as talking on a cell phone. It would also be interesting to investigate whether looming signals would be effective for pedestrian warnings (e.g., Straughn, Gray, & Tan, 2009). Finally, it would be interesting for future research to test a car horn warning for which the intensity value varies as a function of $D_w$.

**CONCLUSION**

Driver inattention is the most common cause of rear-end collision accidents. Previous research suggests that auditory rear-end collision warnings can be effective in directing a driver’s attention to an impending collision, thus reducing
the braking reaction time and decreasing the chance of a rear-end collision. However, it is not clear from this previous research which type of signal is most effective, since there appears to be a trade-off between response speed and response accuracy. The present study developed and tested a novel looming auditory collision warning in a car-following scenario. Looming warnings had the best combination of braking response speed and response false alarm rate of any of the warnings tested. Furthermore, it was shown that it is possible to alter the TTC signaled by the looming warning to artificially speed up or slow down a driver’s reaction. Thus, looming warnings show promise as effective rear-end collision warnings.

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KEY POINTS

- Increasing-intensity (looming) auditory warning signals produce decreases in brake reaction times to an impending collision of a magnitude similar to a symbolic car horn warning but with very low false alarm braking rates.
- Looming warnings are informative to a driver because they take advantage of a natural mapping: As a sound-emitting object approaches an observer, there will be an associated increase in sound intensity, and the rate of change of intensity will be related to the object’s time to collision.
- The acoustic properties of a looming warning can easily be altered to shorten the time to collision signaled by the warning, resulting in a further decrease in brake reaction times.

REFERENCES


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