The Impact of Vehicle Automation on the Safety of Vulnerable Road Users (Pedestrians and Bicyclists)

SAFER SIM

SAFETY RESEARCH USING SIMULATION

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Abstract

Previous studies have demonstrated that young drivers fail to both scan for and mitigate latent hazards, mostly due to their cluelessness. This study investigated whether these skills could be improved by providing young drivers with alerts in advance of an upcoming threat using a driving simulator experiment. A warning was presented on head-up displays (HUD) either 2 s, 3 s, or 4 s in advance of a latent threat. The hazard anticipation, hazard mitigation, and attention maintenance performance of 48 young drivers aged 18-25 years was evaluated across eight unique scenarios either in the presence or in the absence of latent threat alerts displayed on a HUD. There were four groups overall: one control group (no alert) and three experimental groups (2 s alert, 3 s alert, and 4 s alert). The analysis of the hazard anticipation data showed that all three experimental groups with HUD warnings (2 s, 3 s, 4 s) significantly increased the likelihood that drivers would glance towards latent pedestrian and vehicle hazards when compared to the control group. The hazard mitigation analysis showed that in situations involving a pedestrian threat, HUD alerts that were provided 3 or 4 s in advance of a potential threat led drivers to travel significantly more slowly than the control group or the 2 s group. No significant effect of a HUD alert on drivers' speed was found when the latent hazard was a vehicle. An analysis of eye behaviors showed that only 7 out of 597 glances at the HUD were longer than the 2 s safety threshold, indicating that the warnings do not seem to distract the driver.

INTRODUCTION

According to the U.S. Department of Transportation (DOT), drivers between 16 and 24 years are more likely to be involved in motor vehicle crashes than drivers in any other age cohort [1]. The prevailing view for much of the previous 50 years was that young drivers were careless, not clueless. That is, the young drivers ignored potential hazards and engaged in more risky behaviors such as speeding [2], not because they were unaware of the risks (clueless), but because they were risk-seeking (careless). However, this view has changed over the past decade and so too the view of just how one could reduce novice driver crashes. Below we describe how this view has changed, what countermeasures are now in place, and, most importantly, how this motivated the countermeasure we evaluated.

The prevailing view changed in the early 2000s when McKnight and McKnight [3] analyzed more than 2000 crashes involving young drivers aged 16 to 19 years. They found that errors in attention and the failure to recognize and respond to potential dangers, rather than thrill-seeking or deliberate risk-taking, accounted for most non-fatal crashes. These safety-critical cognitive skills were later summarized as attention maintenance, hazard anticipation, and hazard mitigation. In particular, hazard anticipation skills are those used to decide where to scan the areas of the roadway where potential (as opposed to actual) hazards may exist [4, 5], hazard mitigation skills are those used to avoid or mitigate visible and potential hazards [6, 7], and attention maintenance skills are those used decide how to divide attention between monitoring the forward roadway and glancing at secondary, in-vehicle tasks [8].

Not only are the above three skills – hazard anticipation, hazard mitigation, and attention maintenance – ones that explain a large majority of novice driver crashes, but it has been well documented over the last ten years or so that in young drivers the above three skills are underdeveloped compared to older and more experienced [9, 8, 4, 10]. The question is then what can be done to improve these skills. Training programs are one possibility. They have been developed for hazard anticipation [11], hazard mitigation [7], and attention maintenance [12]. Most of them have been proven to be effective, as evaluated on simulators [13], in controlled field experiments [14], and through the analysis of crash reports [15, 16]. However, they have one inherent weakness. Their implementation depends on states (or other jurisdictions, depending on the country) requiring that novice drivers receive the training that has proven effective at reducing crashes and at changing the behaviors that lead to crashes. This has been difficult to do, at least in the United States, though perhaps less so in other countries [17].

If young drivers are clueless, then another way to help them anticipate a latent hazard (and perhaps mitigate the hazard without distracting them) would be to provide the young drivers with alerts in advance of the upcoming threat. Many cars are now equipped with collision warning systems that can alert drivers in the event of impending collisions. For instance, studies report that forward roadway collision warning systems reduce rear-end crashes [18, 19]. The warning systems are getting even more sophisticated, telling the driver not only that a threat exists but highlighting the actual threat in the road ahead. For example, two studies have tried to direct drivers' attention to roadside hazards (pedestrians, vehicles, and warning signs) using augmented reality cues (i.e., visually directing the driver's attention to the actual threat) [20, 21]. They found that the cues could decrease drivers' response times (marginally significant) and increase the likelihood that pedestrians and warning signs were detected, but had no effect on the likelihood that vehicles were detected.

The above two studies focused either on elderly drivers [21] or middle-aged drivers [20]. The effect of augmented reality HUD forward collision alerts on young drivers, the cohort shown to have the worst hazard anticipation skills, has not yet been investigated. Moreover, in the above two studies, the hazards that triggered the alerts were always visible from a distance, were never obscured on approach, and always materialized as real threats as the driver passed near the threat. This is important to note because the alerts provided by forward collision warning systems do not activate in those scenarios in which novice drivers differ most from experienced drivers, scenarios where latent or potential hazards exist [4]. The sensors, like drivers, cannot see the threat in such scenarios.

An example of such a scenario may help the reader at this point understand more concretely what we mean by latent hazards and why sensors are not useful upstream of the threat. Suppose that a driver is traveling a two-lane road (one travel lane in each direction) with a parking lane on each side. The driver is approaching a marked mid-block crosswalk. A large vehicle is parked immediately upstream of the crosswalk, obscuring the driver's (and sensor's) view of a pedestrian who may have entered the crosswalk. As the driver approaches the crosswalk, he or she should slow, steer to the left, and scan to the right for any potential pedestrians that might emerge suddenly from in front of the parked vehicle.

Although not currently available, forward collision warning systems in the very near future may be able to recognize latent threats, threats that they cannot see using video analytics. Video analytics can now easily recognize pedestrians from camera-based systems and predict whether they would collide with a vehicle [22]. Video analytics is now being used to recognize more complex traffic configurations, e.g., work zones [23]. It seems only a matter of time until video analytics could progress to the point where it could be used to recognize scenarios in which latent threats might materialize (e.g., to recognize a marked mid-block crosswalk and a truck or other large vehicle obscuring a potential pedestrian). With this as background, we wanted to know whether novice drivers, drivers who we know from previous research do not look for latent threats, would increase their likelihood of looking for a latent threat if given some information about the presence of a latent threat.

We chose to display the information on a HUD because it is well documented that a HUD is less distracting than a head-down display [24, 25, 26]. However, it is not totally distraction-free [27]. Perceiving the information on the HUD still requires drivers to glance away from the roadway directly ahead to the warning itself, and glances greater than 2 s away from the roadway directly ahead have been shown to significantly increase the crash risk [28]. This may not be as much of a problem with HUDs as it is with head-down displays, however, since glances towards a HUD have been found to be relatively short, with an average glance duration of 0.13 s as reported by Pierowicz et al. [29] and about 0.24 seconds as reported by Caird et al. [30].

While it is important to present information about latent threats to the driver, particularly to novice drivers, the timing of the warnings is equally critical. Poorly timed warnings may undermine the driver's safety [31]. An early alert may be ignored or interpreted as a false alarm by drivers, while late alerts may disrupt a concurrent vehicle maneuver [32]. Abe and Richardson [33] showed that an early forward collision warning (about 0.8 s after the braking of the lead vehicle) was effective in reducing the brake onset time when the headway to the lead vehicle was both short (imminent) and long (not imminent), while a late warning (about 1.4

seconds after the braking of the lead vehicle) was ineffective when the collision was not imminent and actually delayed the brake onset time when the collision was imminent. Similar results have been reported by Werneke and Vollrath [34]; they compared the effectiveness of an early warning (approximately 70 m before the hazard) and two types of late warnings (approximately 18.5 m before the hazard) designed to assist drivers in detecting and reacting to hazardous vehicles at intersections. In total there were three types of warnings in their study, an early warning projected on a standard HUD, a late warning projected on a standard HUD, and a late warning projected on an augmented-reality HUD. Subject drivers in their study were either in the control group without any warning, or in one of the three warning groups. It was found that among the three warning conditions only the early warning signal significantly reduced the collision risk compared to the control group, and was rated by drivers as "useful."

In a recent driving-simulator-based experiment, Yan et al. [35] compared the performance of seven sets of warning delivery times, ranging from 2.5 s to 5.5 s (with 0.5 s increases), in helping drivers respond to red-light-running events at intersections. The results, when compared with the reference control group (no warning), indicated that earlier warning timings (from 4.5 s to 5.0 s) significantly reduced the brake reaction times of drivers, while late warning times (from 2.5 s to 3.0 s) did not. The 3.5 s warning time was also associated with faster reaction times. The analysis of the eye data further showed that while the warning time onset did not affect the time to first fixation on the red-light-running vehicle, the 4.5 s warning led to shorter and more frequent glances towards the hazardous vehicle [36]. Given that more frequent and shorter fixations are related to a faster information processing time [37], it was concluded that the 4.5 s warning onset is the most effective time to initiate the warning. Not only is performance affected by the warning time, mistimed alerts could diminish drivers' trust of the systems [38].

The objectives of the current research are threefold: (1) examine the effect of HUD alerts on young drivers' latent hazard anticipation and hazard mitigation behaviors; (2) determine which warning time onset provides the most benefits, in a context where young drivers are fully attentive and paying attention to the forward roadway; and (3) identify the distracting effects of the HUD. Based on the literature, it is hypothesized that among the three warning time thresholds studied in this experiment, young drivers are expected to anticipate the hazard and mitigate it best when provided with the 4 s alert in advance of a latent threat.

METHOD

In the current between-group design, 48 participants (24 female and 24 male) aged 18-25 years, with an average age of 20.5 years (SD = 2.3) and an average driving experience of 3.3 years (SD = 2.2), were evaluated on a driving simulator. All participants were recruited from the University of Massachusetts Amherst and the surrounding neighborhood and were remunerated for their participation. The study had complete Institutional Review Board approval.

The participants' hazard anticipation, hazard mitigation, and attention maintenance behaviors were evaluated on a driving simulator. An eye tracker was used throughout to gather eye behaviors; vehicle behaviors were automatically recorded by the driving simulator. The control group received no warning information about the potential latent threat. The three experimental groups received the warning information about the potential latent threat either 2 s, 3 s, or 4 s before the latent hazard. As discussed above, there are many ways one could present the information. In the current case, we decided to present the information visually on the windshield as seen in the right panel (Figure 0.1). The warning was completely visible to the driver after being triggered and until the subject passed the hazard location, regardless of what the driver could see out the front window. The actual detail in the HUD is presented on the left panel (Figure 0.1). Note that this is not a virtual reality augmented HUD. There is not a visible pedestrian over which one can apply a highlight or other warning information. Rather, the HUD represents abstractly the threat that could arise. In this example, there is a crossing for hikers. The hikers are potentially hidden by the shrubs upstream of the crosswalk. The HUD displays a picture of a pedestrian about to enter the crosswalk as a warning only of what could happen.

Figure 0.1-The HUD warning alert (left panel) and the placement of the alert on the windshield as the driver navigates a scenario with a latent threat (right panel). (Note that the yellow box did not appear on the HUD. It is there only to highlight where the warning in the left panel appeared on the windshield.)

The visual warning is a simple representation of the roadway condition and only presents the road and the potential hazard. It does not include other features on the road to prevent visual clutter and enhance perception. The background of the visual image is in black, and the hazard is presented in bright colors with high image contrast. The hazard flashes in red at 2 Hz. The center screen in front of the driver is a 120 cm X 120 cm screen. Considering the bottom left corner of the center screen being the origin, the relative coordinates of the bottom left corner of the warning are (72.0 cm, 30.0 cm) and the coordinates of its top right corner are (96.0 cm, 51.6 cm). The driver's seat is placed in front of the center of the screen, which is about 60 cm from the left edge of the screen. The eye height of the driver varies across different subjects.

We also needed to decide on what warning times to use. Based on the above review of the literature, three warning times, 2 s, 3 s, and 4 s ahead of the hazard, were compared to determine the timing thresholds for these warnings that would most improve the young drivers' hazard anticipation and hazard mitigation skills and be least likely to distract them.

1.1 Apparatus

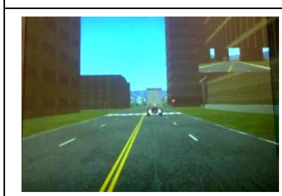
A driving simulator and an eye tracker were used in the current experiment. The driving simulator is a Realtime Technologies Inc. (RTI) full-cab, fixed-base Saturn sedan with three screens (equipped with overhead projectors) that subtend 150 degrees of horizontal field of view and 30 degrees vertical field of view. The simulator is equipped with a surround sound system that generates appropriate environment and Doppler effects in addition to the availability of complete vehicle controls for the navigation of the virtual environment.

An Applied Science Laboratories (ASL) Mobile Eye, head-mounted, monocular eye-tracking system was used to track and record drivers' eye movements during the experiment. The eye tracker has two cameras, one facing toward the scene and an infrared optic camera facing toward the participant's eye, each recording videos at the frequency of 30 frames per second. The eye tracker has an accuracy of 0.5 degrees of visual angle.

1.2 Scenarios, Drives, Visual Display of Latent Threat on HUD

A total of eight scenarios were used in the experiment. The eight scenarios are displayed in Table 0.1. In the first four scenarios displayed in Table 0.1, a pedestrian is the latent threat. In the last four scenarios, a vehicle is the latent threat. The four pedestrian threat scenarios included, in order, a truck parked in front of a crosswalk, a truck parked at the shoulder of the road with emergency lights on, a work zone, and a midblock crosswalk. The four vehicle latent threat scenarios included, in order, a roundabout, a stop-controlled intersection, a queue of parked vehicles, and a hidden driveway. The scenarios and latent hazards have been described in full and previously validated in other studies [39].

Table 0.1 Latent threat simulator evaluation scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Pedestrian Visual Warnings				
	Scenario 5	Scenario 6	Scenario 7	Scenario 8

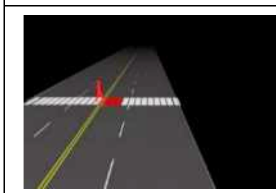
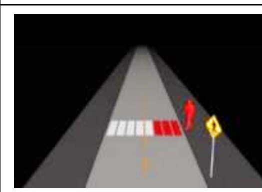
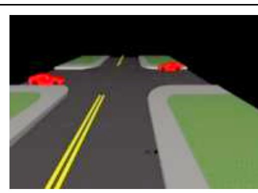
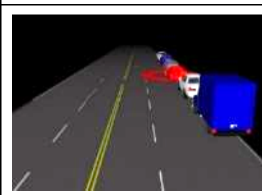
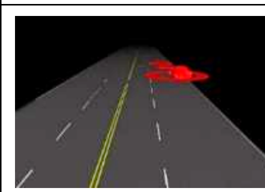
Vehicle Visual Warnings				

It is useful to describe one scenario in Table 0.1 in some depth. Consider the first scenario (Scenario 1). This is a simple variation of the marked mid-block crosswalk scenario described earlier. In this case, there are two travel lanes in each direction. The driver is in the right travel lane. A truck is stopped in the left travel lane, obscuring the driver's view of a pedestrian entering from the left.

The pedestrian and vehicle scenarios were presented in separate drives. Drives are defined as continuous stretches of roadway. Brief breaks were introduced between drives. There were two pedestrian-only drives with two pedestrian scenarios in each drive. In addition, there were two vehicle-only drives with two vehicle scenarios in each drive.

As described briefly above, a separate HUD display was created for each of the scenarios in each of the drives (see Table 0.2 for the HUD warnings corresponding to the simulator scenarios in Table 0.1). The HUD displays were presented during the simulated driving task (see Figure 0.1) with the potential hazard highlighted and repeatedly flickering (red color), and an indication of the direction of the hazards' movement provided in some cases (3 scenarios). The right panel of Figure 0.1 shows a perspective view of one virtual scenario on the center channel of the driving simulator, with the corresponding warning displayed in advance of a potential pedestrian threat (the bottom right corner). The left panel of Figure 0.1 displays an expanded view of what was presented on the HUD display.

Table 0.2 Head-up displays of latent threat. (Pedestrian warnings in top panel, vehicle warnings in bottom panel.)

Pedestrian Visual Warnings	Scenario 1	Scenario 2	Scenario 3	Scenario 4
				
Vehicle Visual Warnings	Scenario 5	Scenario 6	Scenario 7	Scenario 8
				

1.3 Experimental Design & Procedure

A between-subjects design was employed in this study, where each subject completed each of the four drives (each with two latent threats, either both pedestrian or both vehicle) once. There were four groups in total, and participants were pseudo-randomly assigned to one of the groups, either one of the three experimental groups with warnings 2 s, 3 s, and 4 s before the latent threat or a control group with no warning. The sequence of drives presented to the subjects within and across groups was completely counterbalanced using a Latin square method.

Participants provided written informed consent to participate in the experiment. The participants then completed a single questionnaire related to their driving history and demographic information. Following this, participants were outfitted with an eye tracker and their eyes were calibrated. Supplementary instructions were provided to participants at the onset of each drive. Participants who were in either of the warning groups were instructed that visual warnings would be presented to them on the center screen at situations with a potential risk of collision. A practice drive was provided to all subjects to familiarize them with the controls of the simulator and the simulated environment. Finally, the participants were asked to navigate the four simulator evaluation drives either with or without warnings. A brief break followed each drive. Participants were asked to maintain a speed limit of 35 miles per hour throughout all scenarios in the experiment. The complete experiment averaged 35 minutes in total duration.

1.4 Dependent Variables

The first dependent variable in the current study is used as a measure of the drivers' hazard anticipation ability. The dependent variable is scored 1 if the driver appropriately glances at the pre-determined target zone while in the launch zone (and 0 otherwise). As defined in previous studies [41], the target zone is the area of the roadway that the driver should scan to anticipate a potential hazard. The launch zone is the area of the roadway where the driver should begin glancing at the target zone to be able to successfully anticipate and mitigate the threat [41].

The second set of dependent variables is used as a measure the driver's hazard mitigation skills. The velocity was captured from 10 seconds before the hazard to 5 seconds after the hazard as well as 100 feet before the hazard to 50 feet after the hazard. It was recorded continuously from the simulator output. The mean velocity of the vehicle was computed both for the interval defined by time and the interval defined by velocity.

The third set of dependent variables is used as a measure of the distracting potential of the HUD warning. These dependent variables included the number of glances at the warning, the percentage of time during the approach spent looking at the HUD, the glance duration, and the glance onset latency (interval between the onset of the warning and the first glance on the warning). The eye position data were captured from the eye tracker videos. Glances at the HUD that took less than 0.1 seconds were eliminated from the data.

RESULTS

Information from each of the dependent variables in this study was aggregated across a participant, and the aggregate data for the participant was used as the basic data point in the statistical models.

The data for Scenario 8 was excluded from the analysis since the designed hazard appeared to become visible to the drivers who were adopting a slower travel speed too early upstream of the road to have any effect on their behavior in the launch zone.

1.5 Glances at the Latent Hazard

The data were binary coded and therefore binomially distributed when aggregated across a participant. To compare the proportion of latent hazards anticipated across the various HUD onset times, a logistic regression model within the framework of Generalized Estimation Equations (GEE) was used throughout for all analyses. Participants were included as a random effect in the model. There was one between-subjects factor – (a) warning time: either no warning or one of the three warning times (2 s, 3 s, or 4 s) – and one within-subject factor – (b) scenario (as described in the Method section). A backwards elimination procedure was used to trim the model.

1.5.1 Proportion of Pedestrian Latent Hazard Anticipation

Drivers with HUD alerts of latent pedestrian threats presented to them 2 s before a hazard anticipated a smaller proportion of the pedestrian threats (89%) compared to drivers with HUD alerts presented to them 3 s (92%) and 4 s (91%) before a hazard. Drivers in the control group only anticipated 75% of the pedestrian threats. The logistic regression model indicated significant main effects for both group [Wald $\chi_2^2=8.20$; $p<0.005$] and scenario [Wald $\chi_2^2=8.87$; $p<0.003$], and their two-way interaction [Wald $\chi_2^2=17.26$; $p<0.0002$]. Scenarios 2 (82%) and 4 (77%) have low average detection rate across all the groups compared to Scenarios 1 (95%) and 3 (91%). The lowest detection rate is for the control group in Scenario 4 (50%) (See Table 1 for reference on scenario numbers). The proportion of hazard anticipation for pedestrian hazards are presented in Figure 0.1.

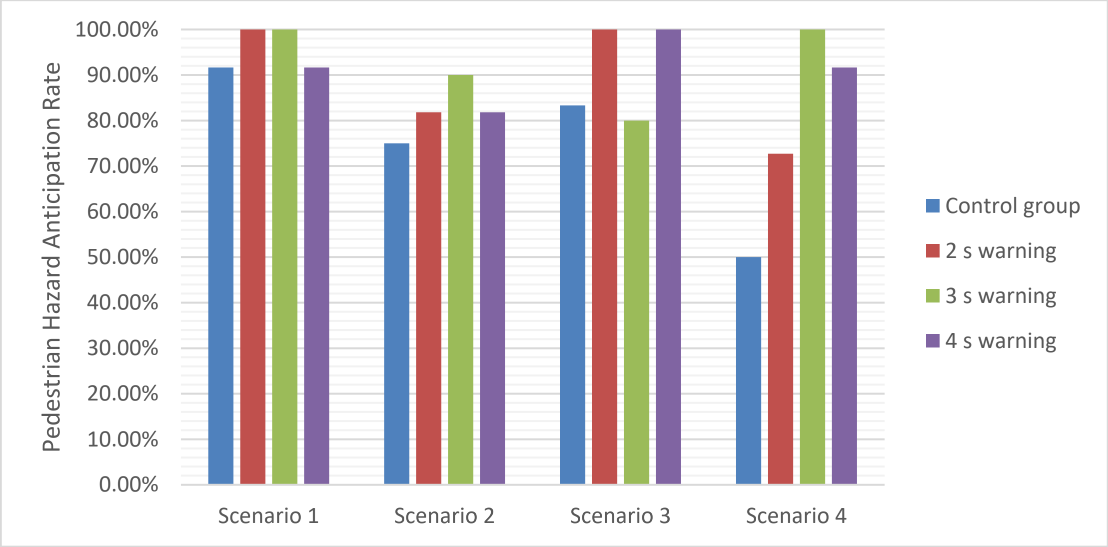


Figure 0.1 Pedestrian hazard anticipation rate in each of the groups by scenario.

Given that the effect of group was significant, a set of t-tests was used to compare the percentage of pedestrian latent hazards anticipated across the four groups: the 4 s (91%), 3 s (92%), 2 s (89%) warning time groups, and the control group (75%). The results showed that drivers in all three warning groups anticipated a significantly greater proportion of the pedestrian latent hazards compared to the control group (2 s vs control: [$t=3.592$, $p<0.0005$], 3 s vs control: [$t=3.834$, $p<0.0002$], and 4 s vs control: [$t=3.583$, $p<0.0006$]). However, the set of pairwise t-test comparisons between the warning groups did not show any statistical difference for the proportion of latent hazards anticipated, implying that the proportion of pedestrian latent hazards anticipated is statistically similar across the 2 s, 3 s, and 4 s thresholds.

1.5.2 Proportion of Vehicle Latent Hazard Anticipation

The proportion of vehicle latent threats anticipated across all the scenarios involving a vehicle hazard was descriptively lower for the 2 s warning group (94%) compared to the 3 s (97%) and 4 s (97%) warning groups. The control group participants anticipated only 69% of the vehicle threats. The logistic regression model indicated a significant main effect only for group [Wald χ_2^2=32.81; p<.0001]. The proportion of hazard anticipation for vehicle hazards are presented in Figure 0.2.

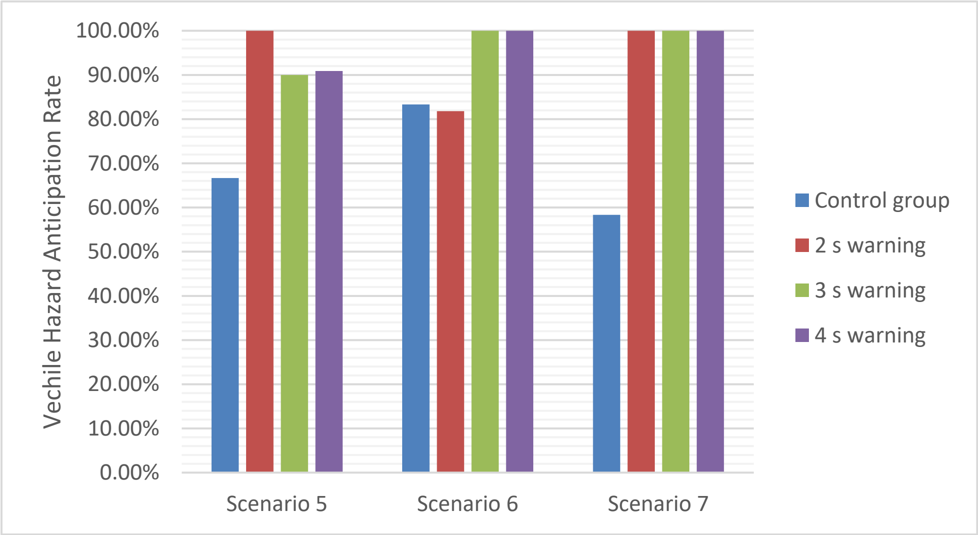


Figure 0.2 Vehicle hazard anticipation rate in each of the groups by scenario.

A set of t-tests was used to compare the percentage of vehicle latent hazards anticipated across the four groups. The results showed that the participants in all three warning groups exhibited statistically higher anticipation rates compared to the control group (2 s vs control: [$t=2.697$, $p<0.01$], 3 s vs control: [$t=3.003$, $p<0.004$], and 4 s vs control: [$t=3.245$, $p<0.002$]). The set of pairwise t-test comparisons between the warning groups did not indicate any statistical difference for hazard anticipation rates, implying that the proportion of vehicle latent threats anticipated was similar across the 2 s, 3 s, and 4 s warning thresholds.

1.5.3 Overall Analysis for Both Pedestrian and Vehicle Latent Hazard Anticipation

Finally, a model including group and scenario was evaluated using a logistic regression within the framework of GEE. Using a backward elimination method, the final model showed a statistically significant main effect only for group [Wald χ_2^2=19.08; p<.0001]. The proportion of latent threats anticipated across all the scenarios was descriptively lower for the 2 s warning group (91%) compared to the 3 s (94%) and 4 s (94%) warning groups. Drivers in the control group only anticipated 73% of all the latent hazards presented to them. The proportion of overall hazard anticipation across groups is presented in Figure 0.3.

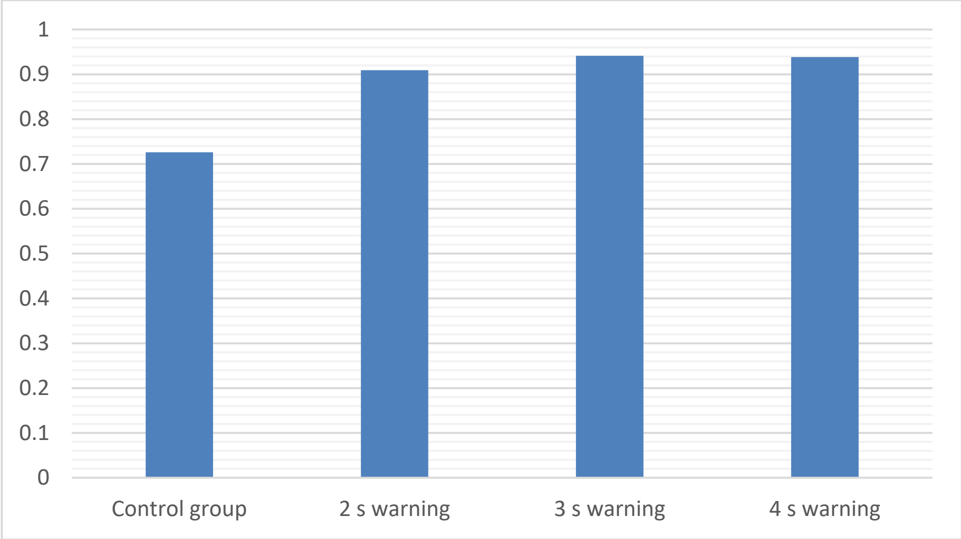


Figure 0.3 Overall hazard anticipation rate in each of the groups.

A set of pairwise t-test comparisons between the three warning groups did not show any statistical difference for hazard detection rate across any of the warning groups. Thus, the 2 s warning has statistically the same effect on latent hazard anticipation as the 3 s and 4 s warning thresholds. The results showed that drivers in all three warning groups anticipated a significantly greater proportion of latent hazards compared to the control group (2 s vs control: [$t=3.044$, $p<0.002$], 3 s vs control: [$t=3.568$, $p<0.0003$], and 4 s vs control: [$t=3.759$, $p<0.0002$]).

1.6 Velocity Profile

The analysis of the effect of HUD warnings on velocity was undertaken only in the area near the location of the latent hazard, the definition of how near the hazard was being defined either in terms of time to collision with the hazard or distance from the hazard. For each of the scenarios, the velocity was measured continuously between 10 s ahead of the hazard and 5 s after the hazard. The estimates of warning time could vary slightly across drivers based on their change in velocity as they approached the hazard. If the driver slowed during the approach to the hazard, then the driver would have been issued an x s alert at a time slightly longer than x s before the hazard. If the driver increased speed during the approach to the hazard, then the driver would have been issued an alert at a time slightly less than x s before the hazard.

Comparisons of the velocity were then made across the four groups of drivers (control group, 2 s, 3 s, and 4 s) during the stated temporal windows. Separate analyses were conducted for each scenario because the velocity profile is expected to vary as a function of the geometry of the scenario. The results of the analysis for one scenario (Scenario 4) are described here. Recall that Scenario 4 is the marked mid-block crosswalk scenario that has been described where the latent pedestrian is on the right, obscured by vegetation.

The velocity of the four groups of drivers in the 15 s temporal window when approaching and passing the hazard is plotted in Figure 5(a). The 0 value of the x-axis represents the time when drivers arrive at the hazard, negative values represent the time upstream of the hazard, and positive values represent the time downstream of the hazard. In general, there is an obvious speed reduction in all three warning groups, while there is not much change in the control group.

The average velocity across the subjects in each warning group was separately compared to the average velocity of the control group as shown in Figure 0.4(b), (c) and (d). The grey area between the thin lines represents the 95% confidence interval of the velocity of each group. When there is no overlap between the grey areas of two groups, it indicates a statistically significant difference in the velocity of the two groups. As shown in Figure 0.4(b), there is no significant velocity difference before or after arriving at the hazard (the 0 point in the plot) between the control and the 2 s warning group. These results suggest that giving the warning 2 s before the hazard is too late. Both the 3 s and 4 s warning groups showed a significant reduction in the velocity compared to those in the control group, Figure 0.4(b) and (c). It should be noted though that although the significant velocity differences started about -3.75 s ahead of the hazard (for the 3 s group), as described earlier, this does not necessarily mean that the difference in the velocities started 0.75 s before the warning (3 s warning) was presented to the driver. Rather, it is due to the reduction in the speed, after receiving the warning, which increased the time-to-collision with the hazard beyond 3 s.

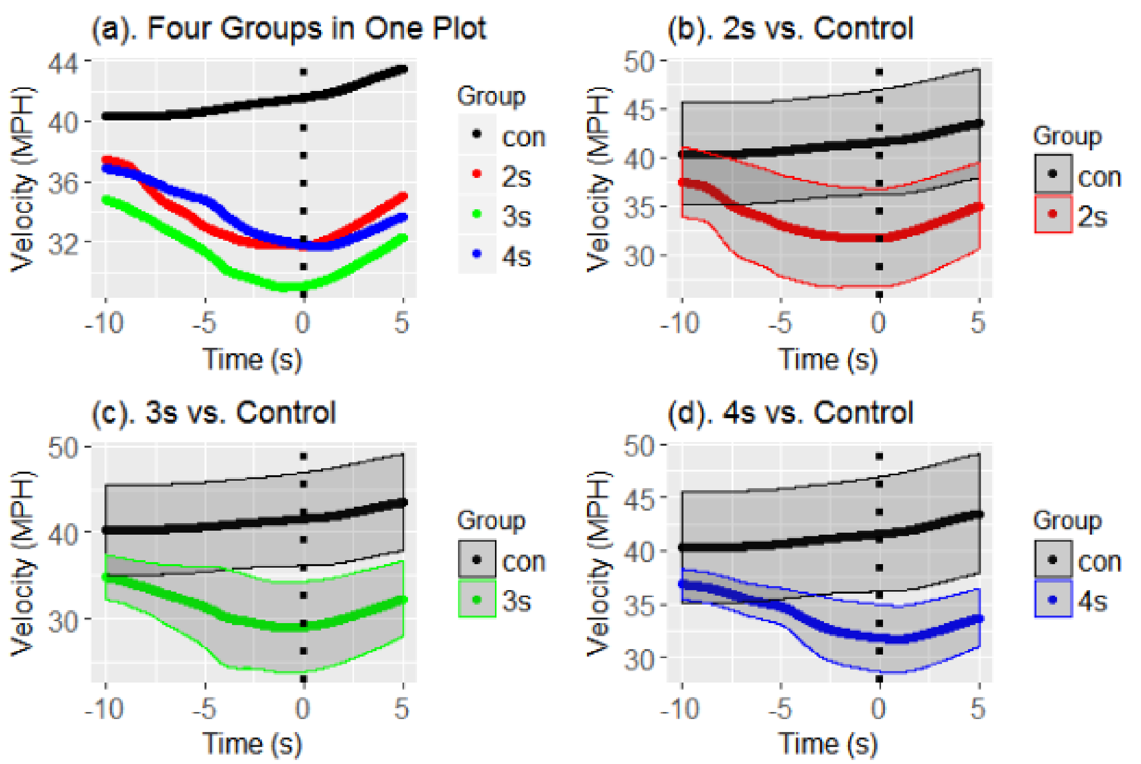


Figure 0.4 Velocity vs. time when approaching and passing the hazard for each the four groups (Scenario 4). (The 0 value represents the time when drivers arrive at the hazard, negative

values represent the time upstream of the hazard and positive values represent the time downstream of the hazard.)

Similar analyses were carried for each of the other seven scenarios. The same results were found for the other three pedestrian scenarios: Scenario 1 (the truck parked in the left lane), Scenario 2 (the parked truck on the sidewalk), and Scenario 3 (the construction scenario). That is, drivers receiving warnings 2 s ahead of the hazard did not differ in velocity from the drivers receiving no warnings, while drivers receiving warnings 3 s and 4 s ahead of the hazard maintained a significantly slower velocity when approaching the hazard than drivers in the control group. In terms of the other four scenarios, all vehicle scenarios (Scenarios 5 - 8), no significant velocity difference across the four groups was found.

In summary, the 3 s and 4 s warnings were found to improve hazard mitigation only for pedestrian hazards. They were not effective at these time onsets for vehicle hazards. The 2 s onset was not effective either for pedestrians or for vehicles.

1.7 Glances at the HUD

To better understand the glance behaviors related to the HUD warnings, we computed the average number of glances on a warning, the percentage of time during the approach spent looking at the warning, the average glance duration, the average glance onset latency (the time interval between the onset of the warning and the first glance on the warning), and the likelihood that a driver failed to glance at a warning during the provided time. Glances at the warning that were shorter than 100 ms were excluded from analysis since they were not long enough for the driver to perceive, understand, and predict what the HUD warning implied. If the fixation was on the warning before it disappeared, it was treated as an unsuccessful attempt to gain information from the warning.

On average, drivers took 2.39 glances at the warnings across all the groups, the average duration of each glance being 0.596 s. Drivers on average spent 27.9% of the time looking at the warning during the approach. The time interval between the onset of the warning and the first glance toward it was 0.446 s. Fully 89.8% of the warnings were coded as being successfully understood by the drivers. To better understand whether the warning time (i.e., 2 s, 3 s, and 4 s) and the scenario would influence the glancing behaviors, a series of mixed-effect models was carried out.

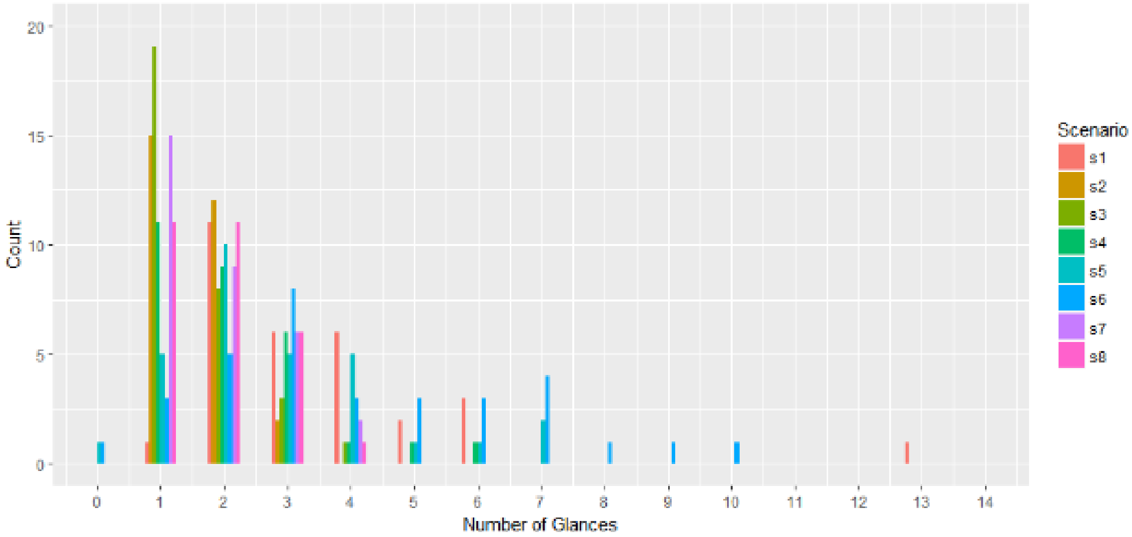


Figure 0.5 Histogram of the number of glances, grouped by scenario.

The number of glances at the HUD followed a Poisson distribution (Figure 0.5), and therefore the mixed-effect Poisson model was used to determine whether there was an effect of group and scenario on the number of glances. It showed that the main effect of both group [F(2, 29) = 9.24, p <0.001] and scenario [F(7, 189)=11.54, p<.001] were significant, while their interaction was not significant [F(14, 189)=0.260, p >0.05]. Post hoc Tukey contrasts showed that there were significantly fewer glances in the 2 s condition compared with the 3 s [z=4.069, p<0.001] and 4 s [z=4.086, p<0.001] conditions (Table 0.1, first column). The difference in the number of glances between the 3 s and 4 s condition was not significant [z=0.034, p >0.05]. We analyzed the above dependent variables scenario by scenario. Drivers glanced most frequently at the HUD in Scenarios 1 and 6, while drivers glanced least frequently at the HUD in Scenarios 2 and 3 (Table 0.2, first column). Perhaps this is because Scenarios 1 and 6 require the driver to stop completely upon approaching the hazard, thus giving the driver plenty of time to make confirmatory glances at the HUD. By contrast, Scenarios 2 and 3 are highway scenarios in which the driver does not need to stop, thus giving the driver relatively less time to recognize the latent hazard.

Table 0.1 Summary data by condition.

Scenario	No. of Glance	Glance Duration	Glance Percentage	Latency	Unsuccessful
2 seconds	1.61	0.56	27.3%	0.34	0.14
3 seconds	2.73	0.63	33.3%	0.42	0.12
4 seconds	2.84	0.59	22.4%	0.60	0.05

Table 0.2 Summary data by scenario.

Scenario	No. of Glances	Glance Duration	Glance Percentage	Latency	Unsuccessful
Scenario 1	3.31	0.64	11.4%	0.73	0.00
Scenario 2	1.50	0.66	40.6%	0.34	0.21
Scenario 3	1.50	0.57	26.5%	0.38	0.09
Scenario 4	2.00	0.47	23.1%	0.44	0.07
Scenario 5	2.83	0.67	24.1%	0.29	0.00
Scenario 6	4.15	0.59	33.3%	0.53	0.13
Scenario 7	1.84	0.57	25.7%	0.46	0.06
Scenario 8	1.90	0.60	40.3%	0.40	0.28

In terms of the glance duration, no significant main effect [group: $F(2, 29) = 0.41$, $p = 0.67$; scenario: $F(7, 189) = 0.60$, $p = 0.76$] or interaction effect [$F(14, 189) = 1.07$, $p = 0.39$] was identified (see Table 0.1 and Table 0.2, second column). This suggests that the timing of the warning or the driving environment did not affect the glance duration. Similar analysis was carried out on the variable of glance percentage. Both the main effect of group $F(2, 29) = 6.34$, $p = 0.005$] and the main effect of scenario $F(7, 190) = 10.03$, $p < 0.0001$] were significant, while their interaction effect was not $F(14, 190) = 1.24$, $p = 0.25$] (Table 0.2, third column).

The glance onset latency was not dependent on warning time [$F(2, 23) = 2.24$, $p = 0.12$] or scenario [$F(7, 184) = 1.45$, $p = 0.19$]. The interaction was also not significant [$F(14, 184) = 0.612$, $p = 0.85$]. The average glance onset latency was 0.446 s, showing that the warnings were effective at attracting drivers' attention. However, it was noted that the latency could be very long in some cases (Figure 0.6).

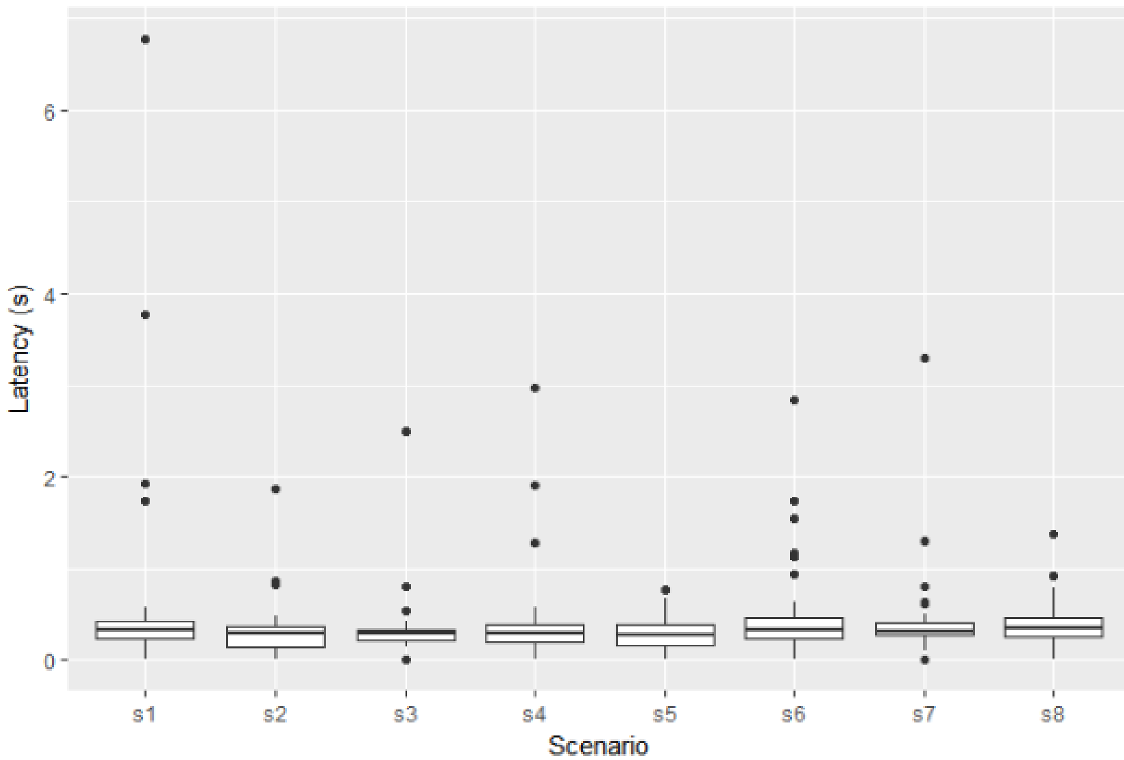


Figure 0.6 Glance onset latency by scenario

A different analysis was undertaken for the likelihood that a driver glanced at and understood the information in the HUD. Specifically, given that we coded understanding as a binary variable (0 as successful perception and 1 as unsuccessful perception), a mixed-effect logistic regression was carried out. The only (marginally) significant result identified was that it was more likely for drivers to perceive the warnings in the 4 s condition than in the 2 s condition ($z=-1.76$, $p=0.08$). As mentioned above, on average, 89.8% of the warnings were successfully perceived by the drivers. The data are provided in Table 0.1 and Table 0.2, fifth column.

Finally, one needs to be especially concerned about the frequency of especially long glances. There is plenty of evidence in the literature showing that off-the-road glances longer than 2 s are a significant contributor to crashes [28]. Of the 597 glances recorded, only 7 of them (about 1.2%) are longer than the 2 s safety threshold, which suggests that the warnings in our experiment are only minimally detrimental, or a source of distraction.

DISCUSSION

Previous studies of latent hazard skills have shown that young drivers fail to scan adequately for latent hazards compared to more experienced middle-aged or older drivers [9]. Earlier studies have also shown that young drivers fail to mitigate hazards as well as more experienced middle-age drivers, even when they anticipated those hazards [7]. Finally, prior research has shown that novice drivers are more easily distracted than experienced middle-aged drivers [8]. Given this, the current study investigated how the display of HUD alerts at different onset latencies influenced the hazard anticipation, hazard mitigation, and attention maintenance behaviors of young drivers across two latent hazard types (pedestrians and vehicles). The hope was that the alerts would improve younger drivers' hazard anticipation and hazard mitigation skills without compromising their attention maintenance skills.

It should be noted that the HUD alerts in this study are presented to the driver 2 s, 3 s, or 4 s before the hazard assuming the vehicle is going with the constant speed. However, if the driver decreased or increased speed after seeing the warning until approaching the hazard, then the driver would have been issued a slightly longer or slightly shorter warning time before the hazard, respectively. In the real-world condition as well the warning systems cannot control the exact timing before a threat that a warning is presented because drivers will vary in how they decide to speed up or slow down as they approach the hazard. First, consider the effect of the HUD alert on hazard anticipation. The results indicate that appropriately timed HUD alerts can improve the latent hazard anticipation ability of young drivers in the presence of potential threats such as vehicles and pedestrians. As hypothesized, drivers who received HUD alerts anticipated a greater proportion of latent pedestrian and vehicle hazards compared to drivers who navigated the same scenarios without any warning message presented to them. Drivers who received the warnings were significantly more likely to glance at the potential hazard compared to the control group. However, when comparing the effectiveness of the timing of the warnings, there were no significant differences between the 2 s, 3 s, and 4 s warnings with respect to hazard anticipation.

Second, consider the effect of the HUD alert on hazard mitigation. The velocity profile analysis shows that for pedestrian hazards, the 3 s and 4 s warning groups adopted a significantly slower speed after the warning was presented to them compared to the control group. However, the velocity profile for the 2 s warning group was not significantly different from that of the control group. These results suggest that the 3 s and 4 s warnings are effectively assisting the driver in their hazard mitigation when the potential hazard is a pedestrian. However, the 2 s warning does not provide the driver with sufficient time to mitigate the hazard (i.e., to slow down) when the hazard is a pedestrian. It also indicated that the significant reduction in the velocity is a result of the conscious adaptation to the hazard, rather than being a result of the distracting effect of the warning (since no significant velocity change in the 2 s group was found compared to the control group). However, when the potential hazards are vehicles, the 2 s, 3 s, and 4 s warnings are all ineffective in terms of improving hazard mitigation behavior.

The above results may be due to the fact that drivers are much more cautious when it comes to striking a pedestrian than they are when it comes to striking another vehicle. Alternatively, perhaps the drivers understood the pedestrian HUD alerts better than they did the vehicle HUD

alerts. This could be examined in future studies. Whatever the reason, it is worth pointing out that similar results have been reported by Rusch et al. [21].
One might posit that the reduction in the speed for the pedestrian hazards might be due to the distracting effect of the warning itself. Perhaps the drivers take their foot off the accelerator, not quite sure what is happening. However, the fact that the velocity in the 2 s warning group was not significantly lower than the control group suggests that the decreased velocity in the 3 s and 4 s warning groups might not be due to the distracting effect of the warning but rather due to an increased awareness of the hazard. Moreover, the ineffectiveness of the warnings in reducing the velocity for vehicle hazards runs counter to the hypothesis that the warnings are distracting.

Third, consider the effect of the HUD alert on attention maintenance. The analyses of the glances at the HUD show that the number of successful glances at the HUD alert was higher for the 3 s and 4 s groups than it was for the 2 s group. Also, the total number of glances at the warning was higher for the 3 s and 4 s groups than it was for the 2 s group. Glance duration and latency were not any different across the different warning groups.

The glancing behaviors provide some insights into why the 2 s warning is not as effective as the 3 s or the 4 s warnings in improving hazard anticipation and hazard mitigation behaviors. Absolutely, the drivers given 2 s warnings are less likely to have glanced long enough to have picked up any information. But even when they do pick up some information, they glance less frequently than drivers in the 3 s and 4 s warning conditions. At the same time, the similar number of glances at the warning for the 3 s and 4 s groups might suggest that the longer duration of the warning does not necessarily lead to an increased number of glances or a longer glance duration at the warning. Drivers did not glance at the warning after enough glances had been made to fully comprehend the warning. Based on the data shown in Table 3, three glances on average, each with the average duration of about 0.61 s, may be sufficient for the driver to understand the meaning of the warning.

One might further suggest that the unsuccessful glances may not necessarily be translated as unsuccessful comprehension of the warning, but rather it may just be a cut off from the confirmatory glances. However, since the 4 s warning group had fewer unsuccessful glances than the 2 s warning group, and as many glances as the 3 s group, unsuccessful glances probably would have been taken to comprehend the warning rather than being taken as confirmatory. Still, it should be noted that with the current definition of an unsuccessful glance (in this manuscript, a glance is considered unsuccessful if the warning turns off when the subject is still glancing at it) we cannot completely distinguish between unsuccessful glances toward comprehending the meaning of the warning and cut-offs from unnecessary confirmatory glances (i.e., there may be some confirmatory glances counted towards unsuccessful glances). It is recognized that it might be a confounding factor in assessing the effective timing of the warnings, but this definition was deemed the best that could be provided.

There are still a couple questions that remain to be answered. First, people may argue that the increased glances to the latent hazard were simply due to that driver’s gaze being automatically attracted by the salient warning. In certain scenarios (Scenarios 2, 3, 4, 7, and 8) where the latent hazards emerge from the right side of the driver (the warning is constantly located towards the right of the drivers’ forward field of view), such confounding effect may exist.

However, the location of the warning and the hazard changes based on drivers' distance from the hazard, and there is no overlap. The accuracy of the eye tracker system is enough to distinguish the two areas. Therefore, it is unlikely that drivers would fix on the hazard simply because they were attracted by the warning. Moreover, the fact that the warnings are also effective at improving drivers' anticipation of a hazard emerging from the right (Scenarios 1 and 5) suggests that it is more likely due to drivers' awareness of the presence of the hazard. Still, it is acknowledged that further investigation (e.g., looking at the sequences of the glances or introducing another group – images without hazard information) could be undertaken to completely rule out this potential confound. Another question is whether the warnings cause the drivers to drive more cautiously in general. As observed from the data, there is a trend in all the scenarios for the average velocity in each of the three warning groups to be lower than the control group. Although the difference was not always statistically significant, it was constantly observed during each of the drives. Also, if there is a positive effect from the warning, we still do not know whether it would be a short-term effect and whether, after a while, drivers would get back to their normal driving habits, or whether there may be any permanent benefits from the warnings. Moreover, providing warnings to the drivers, in the long run, might even cause them to drive less cautiously due to an overreliance on the warning system. There is evidence of both positive and negative adaptation to warnings over time [42]. A second question is how drivers would respond were the warnings not completely reliable. All of the warnings used in our study were reliable, so it is not possible to say how a more realistic implementation, one that included warnings that were not completely reliable, would affect drivers' behavior over the near and the far term. A third question is whether mixed-modal or multi-modal messages can further improve hazard anticipation and hazard anticipation skills without at the same time compromising attention maintenance. A fourth question is whether the variability in the actual onset latency of the alerts could have influenced the results. Recall that the onset latency was predicted by using the vehicle velocity 10 s ahead of a latent threat. It is inevitable, in both the laboratory and the real world, that one will not be able to predict precisely just how long a period of time will elapse between when an alert is issued and when a collision with a latent threat could occur. The driver will always be free to adjust his or her velocity, and therefore the prediction will remain a best guess, not a hard and fast fact. Perhaps increasing the precision of the warnings might improve drivers' reliance on the warnings. These questions could be examined in future studies.

While the findings of this research have implications for decreasing the likelihood that drivers will strike a pedestrian or a vehicle that appears as a latent hazard, the results have implications for other crash types as well. Consider rear-end crashes as just one example. By increasing drivers' hazard anticipation and hazard mitigation skills in the presence of latent threats, one is decreasing the likelihood that the driver will suddenly brake and be rear-ended by the following car, say due to the late recognition of a pedestrian at a crosswalk or a failure to notice an obvious change in the cross traffic while navigating an unsignalized intersection or rotary.

In summary, the results of this study illustrate the effectiveness of HUD alerts on drivers' hazard anticipation and hazard mitigation behaviors as well as illustrating the fact that the alerts do not seem to distract the driver. This information is critical for designing Advanced Driver Assistance Systems (ADAS) systems.

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