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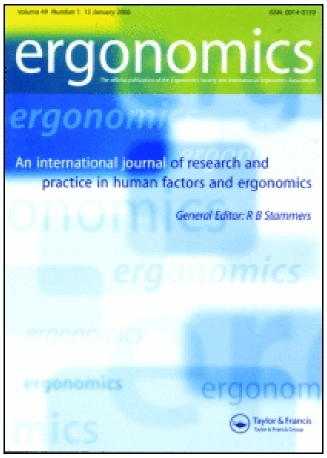

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The influence of distraction and driving context on driver response to imperfect collision warning systems

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Automotive collision warning systems (CWS) can enhance hazard identification and management. However, false alarms (FAs), which occur as a random activation of the system not corresponding to a threat and not interpretable by the driver, and unnecessary alarms (UAs), which occur in situations judged hazardous by the algorithm but not by the driver, may limit CWS effectiveness. A driving simulator was used to investigate the influence of CWS (accurate, UA, FA, none) and distraction on driver performance during non-critical and critical events. FAs and UAs differentially influenced trust and compliance. FAs diminished trust and compliance, whereas the context associated with UAs fostered trust and compliance during subsequent events. This study suggests current warning descriptions based on signal detection theory need to be expanded to represent how different types of alarms affect drivers.

Keywords: Collision warning system; Signal detection theory; False alarms; Trust; Driver behaviour

1. Introduction

In 2005, over six million collisions occurred in the United States, resulting in 43 443 lives lost and approximately two and a half million injuries (National Highway Traffic Safety Administration 2005b). Rear-end collisions constituted approximately 22% of these collisions. Compared to other crash types, rear-end collisions result in relatively few fatalities, yet the financial burden of these crashes in the year 2000 was over $18.3 billion for passenger vehicles alone (National Highway Traffic Safety Administration 2006). The majority of these collisions occur when drivers adopt unsafe following distances or when drivers engage in tasks that divert their attention from the roadway (Knipling *et al.* 1993, Wang *et al.* 1996, Dingus *et al.* 1997, 1998).

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The escalating use of in-vehicle devices while driving, such as navigation systems and mobile phones, poses a significant risk to driving safety (Knipling *et al.* 1993, Dingus *et al.* 1998, Goodman *et al.* 1999, Hampton and Langham 2005). Distraction represents the consequence of events, activities, objects or persons causing delays in perception or reaction to critical information fundamentally related to the driving task (Pettitt *et al.* 2005). Distraction increases the likelihood of collision involvement and undermines driving performance (Wang *et al.* 1996). Mobile phone use can undermine performance by increasing judgement errors and degrading decision-making (Brown *et al.* 1969, Cooper *et al.* 2003). Distraction can cause drivers to exhibit unsafe behaviours, such as greater lane position variability, reduced headway distance and time-to-collision, and may also reduce the driver's capability to respond to hazardous situations, as indicated by delayed reactions (Alm and Nilsson 1995, Lamble *et al.* 1999, Strayer *et al.* 2003).

To avoid a collision, the driver must identify and manage hazardous situations. Management of hazards directly relates to the driver's ability to correctly identify critical situations, situations that will result in a collision if the driver fails to intervene. However, drivers often encounter non-critical situations, situations that fail to evolve into imminent threats and thus do not require the driver to intervene. Collision warning systems (CWS) can help drivers identify these situations and avoid collisions (Ben-Yaacov *et al.* 2002, Abe and Richardson 2004, Maltz and Shinar 2004). This may be especially true when other tasks compete for the driver's attention. Warnings may reduce collision involvement and collision severity of both distracted and non-distracted drivers (Lee *et al.* 2002). Failures of the system to produce warnings that drivers find useful and understandable may diminish the driver's reliance on and compliance with warnings (Bliss and Acton 2003, Wickens *et al.* 2005). Compliance represents the driver's willingness to respond to warnings, whereas reliance represents the driver's willingness to depend on warnings to indicate threats (Meyer 2004). The ability to understand and assess warnings may decline when drivers engage in non-driving-related tasks, resulting in inappropriate reliance and compliance.

Attitudes strongly influence reliance and compliance. Trust mediates reliance between people and between people and automation, such as CWS (Deutsch 1958, 1960, Rempel *et al.* 1985, Gupta *et al.* 2002, Lee and See 2004, Abe and Richardson 2005, 2006, Stanton and Young 2005). Therefore, understanding the interplay between the system and a person may benefit from a consideration of trust. In this study, trust describes the drivers' attitudes regarding whether the CWS will help them identify hazards in situations characterized by uncertainty and vulnerability (Lee and See 2004).

According to Lee and Moray (1992), observations of the system performance, information about how the system operates, and beliefs regarding the purpose of the system collectively influence trust. Specifically, they identified three dimensions that may influence trust in automation: performance, process and purpose (Lee and Moray 1992, Lee and See 2004). Performance or utility defines what the automation does and refers to the ability of the system to aid the driver in collision avoidance. Process or predictability defines how the automation works and refers to how the algorithms and sensors detect and signal hazardous situations. Purpose or intent defines the reason the automation exists and refers to the designers' intent regarding situations that should generate warnings.

These three dimensions suggest that drivers may view the behaviour of a CWS differently than might be expected from the description of warnings based on signal detection theory. Researchers have often used signal detection theory to classify system failures. Although useful in identifying system performance in terms of a system's ability to discriminate between a true signal and noise, it may fail to consider how people perceive different alarms (Green and Swets 1966). Although other taxonomies have been developed to distinguish between different alarm types, no consensus exists (Knipling *et al.* 1993, Xiao and Seagull 1999). To understand how different alarms influence driver attitudes and responses, a classification of warnings should consider warnings from the perspective of the driver, which may diverge from that of the designer (Norman 1998). It is proposed that the three dimensions of trust – utility, predictability, and intent – can form a useful classification of alarms that considers both the users' and the designers' perspectives.

These dimensions suggest a range of alarm types, presented in table 1, which merit examination including accurate, unnecessary, inadvertent and false alarms. Accurate alarms are consistent with the driver's interpretation of the system intent, the driver understands why the alarm occurs and the alarm helps the driver to detect a threat. In contrast, unnecessary alarms (UAs) reflect the designers' intent, but because of the peculiarities of the situation, drivers do not need the alarms, but can understand what caused the alarms to occur. Inadvertent or nuisance alarms occur in situations that designers would not have intended, but may help drivers to understand how the system works. False alarms (FAs) are neither useful nor interpretable, because they occur randomly from the driver's perspective. Table 1 contains examples of other types of alarms defined by the three dimensions that underlie trust.

This study examined three of the alarm types shown in table 1, accurate, UAs and FAs. As a consequence, two of the three dimensions influencing trust were manipulated in this experiment (Lee and Moray 1992). Performance was manipulated through the overall failure rate of the system and process was manipulated by the context associated with the alarm. FAs represent breakdowns at the performance and process levels. The breakdown in the process dimension is due to the random nature of FAs, which impairs the ability of drivers to predict when or why they occur. Consequently, their occurrence does not enhance the driver's understanding of how the system operates. Although UAs also represent breakdowns in performance because they are not needed in the particular situation, they support the process level of trust because they are associated with a context that may allow drivers to understand the reason for the alarm. The purpose of the system was not manipulated in this experiment, but could be by giving different instructions regarding what the system is intended to do. For instance, the purpose of the system may, as in this experiment, be intended to warn drivers of potential threats in their environment, or it might be intended only to warn drivers of imminent collision situations.

Failure to trust warning systems sufficiently diminishes compliance and has been associated with reductions in response frequency, reaction time, appropriate responses and overall task performance (Bliss 2003). A high FA rate is often associated with distrust of the system as well as abrupt unwarranted responses, more overall errors in driving performance and a failure to benefit from the warnings (Wilson 1994, Dingus *et al.* 1997, Ben-Yaacov *et al.* 2002, Bliss and Acton 2003, Maltz and Shinar 2004). In the literature reviewed for this paper, no research had examined the influence of UAs on driver performance or trust in a controlled manner. However, Riley (1996) and Dzindolet *et al.* (2002) suggest that understandable failures, such as UAs, will not diminish trust to the same extent as FAs. Trust may be supported by the process dimension because such failures can help drivers develop accurate expectations of the system.

The purpose of this research was to assess how the driving situation and the history of warnings influence driver response to warnings and to hazardous driving situations.

Table 1. A sample of different types of alarms based on the performance, process and purpose dimensions of trust.

Alarm Type	System characteristics underlying trust: Purpose, Process and Performance	Example	Potential consequences
Accurate	Intended, Predictable, Useful	An alarm associated with a hazardous driving situation that the driver might not otherwise avoid	May help drivers identify and respond to hazards as well as promote trust
Unnecessary	Intended, Predictable, Non-useful	An alarm associated with a situation judged hazardous by the designer, but not by the driver. The driver can understand what triggered the alert	May help drivers understand how the system works, but may also annoy drivers if frequent
Incomprehensible	Intended, Unpredictable, Useful	An alarm associated with a hazardous driving situation that the driver might not otherwise avoid, but is seen as inconsistent by the driver	Depending on the driver's trust in the system the alert may be ignored
Unappreciated	Intended, Unpredictable, Non-useful	An alarm that associated with a situation judged hazardous by the designer, but is not understood or appreciated by the driver	Diminished trust and compliance
Fortuitous	Unintended, Predictable, Useful	An alarm that is inconsistent with the stated purpose of the system, but which helps the driver avoid hazards	May enhance driving performance and trust, but could lead to drivers to use the system differently than the designer intended
Inadvertent/ Nuisance	Unintended, Predictable, Non-useful	An alarm triggered by events that do not pose a threat to the driver and were intended by the designer, such as vehicles in the adjacent lane, roadside objects and clutter on curves*	May help drivers understand how the system works, but may undermine the credibility of the system
Unforeseen	Unintended, Unpredictable, Useful	An alarm triggered in manner that is inconsistent with the designer's intent and is not understandable to the driver, but is useful in avoiding a threat	May enhance driving performance and trust, but could lead to drivers to use the system differently than the designer intended
False	Unintended, Unpredictable, Non-useful	An alarm triggered by sensor noise, system malfunction that neither helps the driver understand the system nor respond to threats	These alarms provide no indication of hazards and may undermine trust

*Zador *et al.* (2000).

This study examines several hypotheses. First, the driving situation will influence how drivers respond to warnings and warnings will influence how drivers respond to the situation. Second, systems prone to different types of failure will influence trust and the drivers' response to subsequent warnings differently. Drivers will trust accurate systems and systems prone to UAs more than systems prone to FAs (Wilson 1994, Dingus *et al.* 1997). Although both the system with FAs and UAs break down at the performance level, because drivers are likely to understand the source of UAs they will trust the system more (Riley 1996, Dzindolet *et al.* 2002, Lee and See 2004). Compared to drivers who receive FAs, drivers will grow to trust the system more and will brake more often, steer less, react faster and have larger speed reductions during both non-critical and critical events compared to drivers who receive FAs (Riley 1996, Dzindolet *et al.* 2002, Bliss 2003, Lee and See 2004). Third, distraction will interact with the types of warning failures such that distracted drivers will be less sensitive to the different types of warning failures.

2. Method

2.1. *Participants*

A total of 64 drivers between the ages of 20 and 35 (mean 23, SD 3.7) years were recruited from the Iowa City and Coralville community through an advertisement placed in several local newspapers. The sample of drivers tested included both students and non-students. Each experimental condition contained an equal number of male and female drivers. Participants were screened for simulator sickness prior to participating in the study. All participants were native English speakers and had an active driver's licence. Participants were compensated $15 per h for their participation. Participants required to perform a distraction task received additional compensation of up to $10 based upon their task performance.

2.2. *Experimental design*

The experiment was a 4 (CWS: 100% accurate alarms, 29% accurate with UAs, 29% accurate with FAs and none) × 2 (distraction: no-distraction and distraction) between-subjects design. Drivers were randomly assigned to a CWS type, with each group consisting of 16 subjects. Half the subjects in each CWS group were required to interact with the distraction task.

The overall system performance for both UAs and FAs represents the success rate of the system in identifying critical situations (percentage of critical events (5) to the overall alarms received (17) = 29%). As a consequence, drivers with an UA system and a FA system received more alarms than drivers with an accurate system. Because the likelihood of a collision is relatively small, the experiment was designed so that drivers would encounter three non-critical medium-onset events for every critical medium-onset event (Parasuraman *et al.* 1997). The frequency of FAs and UAs received by drivers in this experiment was much higher than the rate of alarms recorded in a recent field test, in which one warning occurred per 100 miles and the rate of FAs was 0.45 per 100 miles. Given that the field test was based on 49 000 miles of on-road driving (in which the CWS was engaged) obtained from 66 drivers, these data represent reasonable estimates of real-world FA rates (National Highway Traffic Safety Administration 2005a). A Monte Carlo analysis assessed the probability of generating false and missed alarms in four predominant pre-crash scenarios using four different algorithms. Varying according to the specific pre-crash scenario and algorithm examined, the Monte Carlo analysis results indicated that the rate of FAs ranged from 14.5–74.6% (National Highway Traffic Safety Administration 2002). The failure rate used in this study (71%) corresponds to the upper bound of these FA rates.

2.3. *Apparatus*

Driving performance data, such as speed, lane position and steering input, were collected at 60 Hz using a medium-fidelity, fixed-base simulator consisting of a fully instrumented 1992 four-door Mercury Sable cab with a 50° field of view. Graphics were generated at a 60 Hz frame rate and a resolution of 1024 × 768 pixels. A 7-inch, 640 × 480 pixel, touch-screen mounted on the dash of the car approximately 32.5° horizontally and 15° vertically from the driver's line of sight, displayed the distraction task. For drivers not required to engage in the distraction task, the touch-screen was turned off.

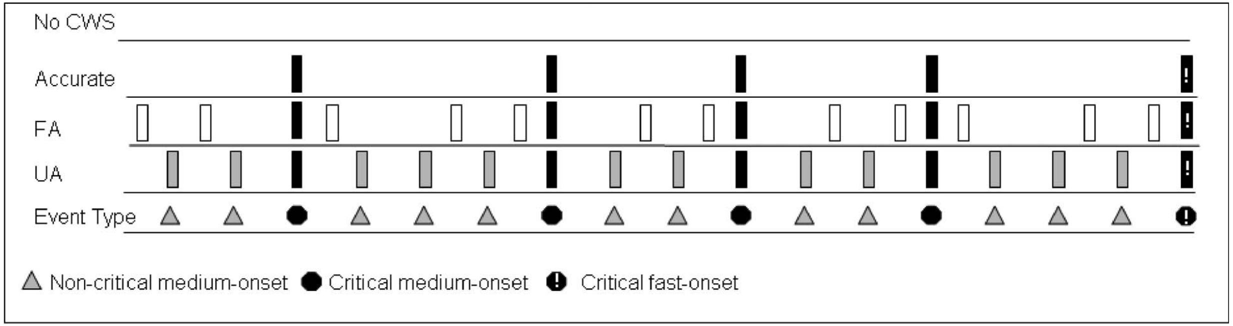
The CWS, used to inform the driver of impending rear-end collisions, consisted of an abstract auditory alarm similar to that used in previous studies (Tan and Lerner 1995, Lee *et al.* 2002). A MIDI device with standard PC speakers presented alarms that lasted 2.1 s. The ambient sound level of the experimental drive was 59 dB(A). In accordance with recommendations indicating that auditory alarms should be 10 to 15 dB(A) above the ambient noise level, the CWS sound level was 71 dB(A) (Graham 1999). Other studies have used similar sound levels when investigating CWS (Bliss and Acton 2003, Lee *et al.* 2004). Alarms paired with events were positioned to occur 2 s prior to the event onset.

2.4. *Driving task: Event severity and collision warning alarms*

According to data obtained from FARS and GES, the highest number of collisions (fatal, injury and property-damage only crashes) occurred when vehicles were traveling between 35 and 40 mph (National Highway Traffic Safety Administration 2003). Therefore, the driving environment consisted of a four-lane industrial/urban setting with a speed limit of 35 mph (56 kph), intermittent oncoming traffic and parked vehicles. Throughout the experiment, all drivers (regardless of the CWS used) encountered 17 events that varied according to criticality and event onset. Criticality reflects the degree of intervention required by the event to avoid a collision. Event onset reflects the time available to the driver to observe and monitor events as they evolve. Of these, 12 were non-critical medium-onset events, four were critical medium-onset events and one was a critical fast-onset event. During both non-critical medium-onset and critical medium-onset events, the driver had time to observe and monitor the event as it evolved; however, non-critical events did not require intervention. The critical fast-onset event represented a situation where the threat evolved quickly and required intervention. The type of system determined in what situations drivers received a warning and figure 1 shows the alarms received by each group in relation to these events.

2.4.1. Non-critical medium-onset events. The 12 non-critical medium-onset events represented routine driving events and did not require the driver to respond to avoid a collision. Although all drivers were exposed to these events, only drivers with an UA system received a warning. Drivers encountered three occurrences of each of the following events: a) parking vehicle: a parking vehicle realigned its position; b) oversized vehicle: a vehicle encroached into the driver's lane, but subsequently moved over into the

(a)



(b)

Collision warning system	Event Number and Criticality																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	N*	N	C	N	N	N	C	N	N	C	N	N	C	N	N	N	F
Accurate			✖				✖			✖			✖				✦
UA	●	●	✖	●	●	●	✖	●	●	✖	●	●	✖	●	●	●	✦
FA	○	○	✖	○	○	○	✖	○	○	✖	○	○	✖	○	○	○	✦
No CWS																	

*N: non critical medium-onset, C: critical medium-onset, F: critical fast-onset

✦ Received alarm for critical fast-onset event

✖ Received alarm for critical medium-onset event

● Received alarm for non-critical medium-onset event

○ Received alarm 100m prior to or following non-critical medium-onset event

Figure 1. a) A graphical representation of the relationship between collision warning system (CWS) alarms with the different types of events; b) a breakdown of the alarms presented by the different CWS with regard to the 17 events; 12 non-critical medium-onset events (N), four critical medium-onset events (C) and one critical fast-onset event (F). The timing of the alarm for drivers with a false alarm (FA) system was offset; the alarm was not directly associated with an event but rather resulted from random noise. UA = unnecessary alarm.

middle of its own lane; c) intruding vehicle: a vehicle intruded into the driver's lane at an intersection and stopped; d) right-turning vehicle: a lead vehicle decelerated at 0.2 g (1.96 m/s^2) to make a right turn. Because of the number of events, they were presented in a fixed random order and were not counterbalanced.

Unlike UAs that were paired with driving events, FAs were not directly linked with events and appeared in a seemingly random manner to the driver. Drivers with the FA system received a warning 100 m prior to or following the onset of each non-critical medium-onset event.

2.4.2. Critical medium-onset event. Four critical medium-onset events were created to mimic the four types of non-critical medium-onset events; however, these events were more severe and required the driver to respond by either braking or steering to avoid a collision. All drivers with a CWS received a warning for these events. Drivers encountered one instance of each event: a) parking vehicle: a parking vehicle realigning its position pulled out and entered the driver's path; b) oversized vehicle: a vehicle encroached into the driver's lane and slowly moved over into the middle of its own lane; however, the vehicle then moved back into the driver's lane cutting the driver off; c) intruding vehicle: after a vehicle intruded into the driver's lane at an intersection and stopped, it re-accelerated, turning into the driver's path; d) right-turning vehicle: a lead vehicle decelerated at 0.4 g (3.92 m/s^2) to make a right turn. The order of these events was counterbalanced.

2.4.3. Critical fast-onset event. At the end of the experimental drive, participants encountered a critical fast-onset event in which the vehicle in front of the driver suddenly switched lanes and a vehicle quickly entered the road from a parked position, cutting off the subject vehicle. In both the non-critical and critical medium-onset events, the parking vehicle was moving at low speeds and partially in the driver's lane with an offset alignment. In comparison, the parked vehicle in this event was motionless, properly aligned and remained parked until it suddenly pulled out. All drivers with a CWS received a warning.

2.5. *Distraction task*

To examine how distraction influences driver responses and attitudes to different CWS, half of the drivers in this study interacted with a continuous visual–manual distraction task, presented on a touch-screen (Donmez *et al.* 2006). The distraction task is representative of a generic interaction required by many in-vehicle devices, such as MP3 players or navigational devices, in which drivers must select one item from many presented in a list. For this task, drivers had to memorize the three-word target phrase 'discover project missions', look over to the in-vehicle touch-screen, scroll through ten phrases that combined words related to the target phrase and select a phrase that represented a match. A correct match corresponded to a phrase where any of the three words in the selection matched one of the positions as it appeared in the original target phrase. For example, in figure 2, 'discover missions project' represents a match because the position of the word 'discover' corresponds to its position in the target phrase.

After given time to achieve the posted speed limit, the driver was informed by a chime to begin interacting with the distraction task. The driver initiated the task by pressing the 'start' button located on the touch-screen (figure 2a). After a 300 ms delay the task would commence, allowing the driver to scroll through the list by pressing the up or

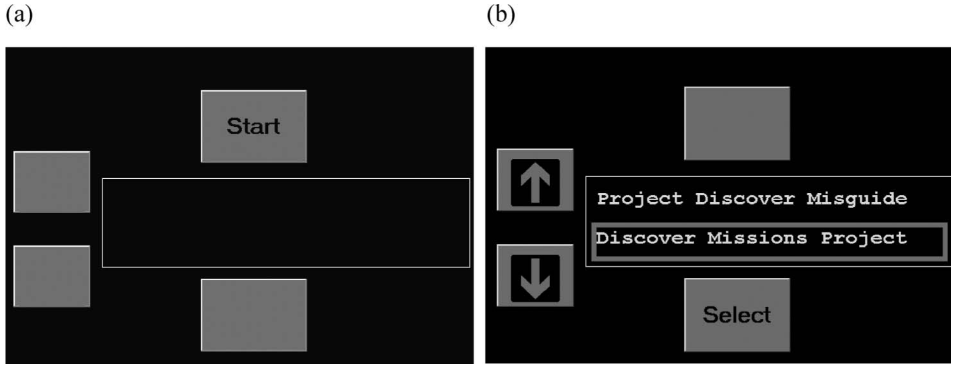


Figure 2. Distraction task display presented on a touch-screen.

down arrow (figure 2b). Upon pressing the select button when a match was identified, participants were given feedback regarding whether they had made a correct selection. Each time participants initiated the search task, the list was presented in a different random order.

Participants were instructed to interact with the task only when comfortable, but pay incentives were used to entice participants to engage in the task and to correctly respond, $0.10 for correct responses and $0.03 for incorrect response. Eye movement data verified that the distraction task caused drivers to look from the road to the in-vehicle touch-screen. Donmez *et al.* (2007) developed and found that this search task represents a significant source of distraction, drawing approximately 25 glances/min and delaying response to lead-vehicle braking events by 0.40 s.

2.6. *Procedure*

Upon arrival, drivers read and signed an informed consent. Drivers who did not have the distraction task drove a 5-min practice drive without the CWS and then a second drive with the CWS. All participants were told that the purpose of the CWS was to detect potential threats within the environment. For drivers required to interact with the distraction task, the CWS was used for the first practice drive. Participants received a practice session with the distraction task, in which they selected the target phrase four or five times. They also practised performing the task while driving. The experimental drive lasted for approximately 27 min. Prior to driving, the researcher instructed the participant to remain in the right lane and maintain the posted speed of 35 mph (56 kph) for the entire drive. The researcher continuously monitored the participant's speed and enforced the speed limit through verbal reminders. The need to verbally remind participants of the speed limit was quite rare. Allowances were made when drivers deviated from the speed limit in response to events.

2.7. *Dependent variables*

To reduce the data for analysis, driving performance measures such as speed as well as lane position, accelerator, brake and steering wheel position were plotted over the entire drive to verify that the responses corresponded to the events of interest. All plots included reference points indicating when the driver received or would have received an alarm.

The final period of interest consisted of three components: 1) 5 s before the warning; 2) the 2.1 s duration of the warning; 3) 5 s after the warning had ended.

Driving performance was assessed by measures of response frequency and the magnitude of the speed reduction. Brake response and steering response frequency were coded as dichotomous variables to indicate whether and how the driver responded. Steering responses were analysed only during critical situations. Decrease in speed is represented by the difference in speed from the time the driver initiated a brake response to the time the driver released the brake. Accelerator reaction time represents the time taken to release the accelerator from the event onset and was analysed only for critical events.

The total number of searches, the average time to complete a search, the average time between button pushes and the average time delay to start the task all assessed distraction task performance. Time between button pushes represents the time it took the driver to make a selection. Delay to start the task represents how long it took drivers to re-initiate the task after they completed a search.

Attitudes regarding trust and self-confidence were solicited using the system trust questionnaire, which is composed of eight statements regarding the opinions about the driver support system, CWS (Lee and Moray 1994, Jian *et al.* 2000, Wiese 2003). An example of a statement is: 'I trust the driver support system'. Drivers rated the degree of agreement with each statement on a scale of 1 to 5: 1 = strong disagreement; 5 = strong agreement. One question, relating to self-confidence rather than trust, was excluded when calculating the mean trust score (Lee and Moray 1994, Jian *et al.* 2000). Participants completed the questionnaire after each drive.

3. Results

Response frequency measures were analyzed using the PROC GLIMMIX procedure in SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) and included CWS and distraction as between-subjects variables, effect size estimates are provided using Pearson's r. However, it was only possible to compute effect size for comparisons among two groups. All other measures were analysed using the PROC MIXED, using an ANOVA model with CWS and distraction as between-subjects variables. The within-subjects variable was the presentation order of events. Subject was represented as a random effect and the compound symmetry covariance structure was used. Effect size estimates were calculated using $\eta_p{}^2 = [SS_{Effect}/(SS_{Effect} + SS_{Error})]$. Pairwise comparisons for both procedures were made using the Tukey-Kramer test and displayed on figures as grey boxes, which encircle those conditions that are not statically significantly different. All non-significant findings, $p > 0.05$, are reported as NS.

Drivers encountered four types of situations. Depending on the CWS, these situations would include an alarm: no event (triggering FAs); non-critical medium-onset events (triggering UAs); critical medium-onset events (triggering all CWS); and critical fast-onset events (triggering all CWS). To examine how alarms and distraction influenced how drivers responded, driver responses were analysed during the following situations: 1) FA and UA alarms; 2) non-critical medium-onset events; 3) critical medium-onset events; 4) the critical fast-onset event. These situations were analysed separately because they represent qualitatively different situations. Data were collected regarding the number of collisions occurring during critical medium- and fast-onset events. Collisions were rare and relatively uniformly distributed across CWS and distraction conditions and therefore are not discussed.

3.1. *Responses to false and unnecessary alarms*

Unlike UAs that were directly tied to non-critical roadway events, FAs lacked any context and occurred in a seemingly random manner. Consequently, it is not surprising that drivers responded differently to these two alarm types (see table 2). Drivers braked more frequently and reduced their speed more with UAs compared to FAs. Drivers with a system prone to UAs responded to the non-critical medium-onset events that triggered UAs by braking 82% of the time, which resulted in speed reductions of 3.35 m/s. In contrast, drivers with a system prone to FAs responded to the FAs by braking 35% of the time, with corresponding reductions in speed of only 0.23 m/s. These results show that drivers did not brake in response to every warning and their response was strongly influenced by the driving context, but not by distraction.

3.2. *Responses to non-critical medium-onset events*

The context associated with UAs, defined by the non-critical events, led drivers to brake more frequently and to a greater degree compared to FAs; however, that same context may also influence drivers to brake even without an alarm. Table 2 and figure 3 show this to be the case. In addition, UAs led drivers to adopt a greater braking response during non-critical medium-onset events. As figure 3 shows, drivers who received UAs braked more frequently than drivers with an accurate system, a system prone to FAs, and drivers without a CWS. Figure 4 shows that drivers with an UA system also reduced their speed more than drivers with a FA system and drivers without a CWS. The distraction task also led drivers to brake to a greater degree when responding to non-critical medium-onset events. Distracted drivers reduced their speed by 3.05 m/s compared to 1.97 m/s for non-distracted drivers. This may reflect a compensatory response to the distraction task, similar to studies showing that distracted drivers adopt larger headway distances (Liu and Lee 2006).

3.3. *Responses to critical medium and fast-onset events*

As evidenced by braking responses to FAs and UAs, drivers tend to comply with alarms even when they do not signal critical events. This section considers the influence of FAs and UAs on drivers' subsequent response to critical events. Table 3 shows that systems prone to high alarm rates, due to FAs and UAs, influence how drivers respond to critical events, but in different ways. FAs tend to diminish responses and UAs tend to enhance responses to subsequent accurate alarms for critical medium-onset events. Table 3 shows that neither CWS nor distraction had a significant influence on any responses during the critical fast-onset event.

Drivers' initial response depended on the type of CWS and whether they were distracted (see figure 5). The substantially delayed initial response of distracted compared to non-distracted drivers without a CWS demonstrates that the secondary task successfully distracted drivers. When not engaged in a distraction task, drivers with a system prone to UAs and those without a system reacted faster compared to drivers with an accurate system or drivers with a system prone to FAs. The presence of a CWS aided distracted drivers in responding quickly to events. Specifically, distracted drivers with an accurate system, a system prone to UAs and a system prone to FAs all responded by releasing the accelerator faster than distracted drivers without a system.

Table 2. Glimmix and ANOVA (F-tests) for responses to false alarms (FAs) and unnecessary alarms (UAs) and for responses to non-critical medium-onset events.

	CWS			Distraction			CWS × Distraction		
Variable	F-value	*p*	Effect size	F-value	*p*	Effect size	F-value	*p*	Effect size
FAs and UAs									
Brake frequency	$F(1,380) = 115.67$	< 0.001	$r = 0.97$	$F(1,380) = 1.69$	NS	$r = 0.007$	$F(1,380) = 2.36$	NS	$r = 0.01$
Speed reduction	$F(1,29) = 64.8$	< 0.001	$\eta_p{}^2 = 0.70$	$F(1,29) = 0.57$	NS	$\eta_p{}^2 = 0.02$	$F(1, 29) = 0.38$	NS	$\eta_p{}^2 = 0.01$
Non-critical medium-onset events									
Brake frequency	$F(3,760) = 9.77$	< 0.001	–	$F(1,760) = 1.57$	NS	$r = 0.06$	$F(3,760) = 0.47$	NS	–
Speed reduction	$F(3,57) = 5.23$	< 0.01	$\eta_p{}^2 = 0.22$	$F(1,57) = 13.04$	< 0.001	$\eta_p{}^2 = 0.19$	$F(3,57) = 1.87$	NS	$\eta_p{}^2 = 0.03$

CWS = collision warning system.

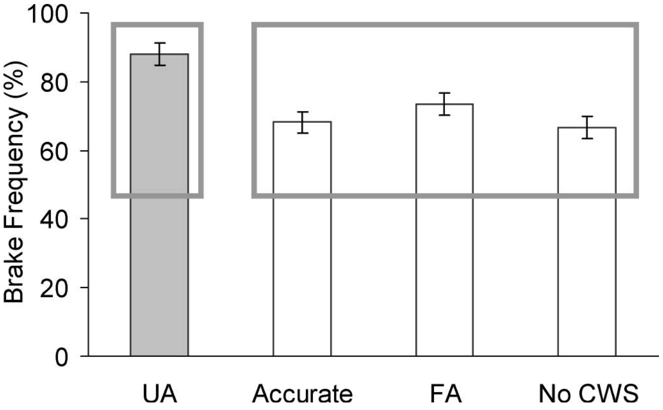


Figure 3. The effect of collision warning system (CWS) on brake response frequency during non-critical medium-onset events. Only drivers with an unnecessary alarm (UA) system (indicated in grey) were warned of these situations. The error bars in this and other figures represent 1 SE. FA = false alarm.

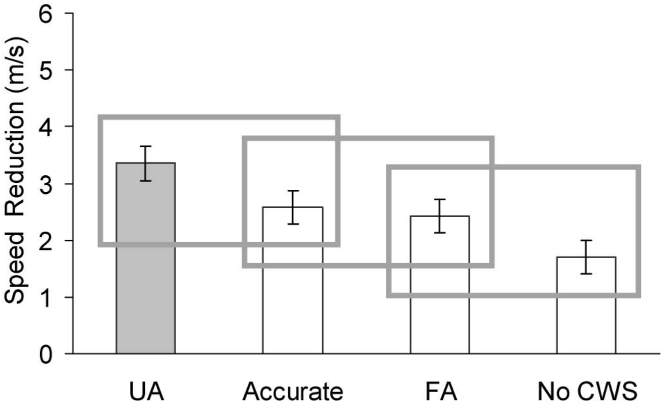


Figure 4. The effect of collision warning system (CWS) on speed reduction during non-critical medium-onset events. Only drivers with an unnecessary alarm (UA) system (indicated in grey) were warned of these situations.

Beyond the initial braking response, the systems prone to FAs and UAs have substantial and consistent effects on the subsequent management of the collision situation. The system prone to UAs led to a greater compliance with the warning and the system prone to FAs diminished compliance. Figure 6 shows that drivers who had received UAs responded by braking more frequently than drivers with an accurate system, drivers with a FA system and drivers without an aid. Drivers with a system prone to UAs and drivers with an accurate system also reduced their speed more compared to drivers without aid and drivers with a system prone to FAs (see figure 7). In contrast, figure 8 shows that drivers who received FAs and drivers without a system responded by steering more frequently than drivers with an accurate system and drivers with a system prone to UAs. These results suggest that drivers who experienced FAs tended not to comply with the warning and as a consequence their responses were delayed, leading to

Table 3. Glimmix and ANOVA (F-tests) for responses to critical medium-onset events and for responses to the critical fast-onset event.

	CWS			Distraction			CWS × Distraction		
Variable	F-value	p	Effect size	F-value	p	Effect size	F-value	p	Effect size
Critical medium-onset events									
Brake frequency	$F(3,248) = 5.00$	0.002	–	$F(1,248) = 56.69$	< 0.0001	$r = 0.96$	$F(3,248) = 1.91$	NS	–
Steering frequency	$F(3,248) = 5.7$	< 0.001	–	$F(1,248) = 0.03$	NS	$r = 0.001$	$F(3,248) = 1.36$	NS	–
Speed reduction	$F(3,57) = 10.11$	< 0.0001	$\eta_p^2 = 0.35$	$F(1,57) = 164.02$	< 0.0001	$\eta_p^2 = 0.75$	$F(3,57) = 1.45$	NS	$\eta_p^2 = 0.07$
Accelerator release time (s)	$F(3,57) = 3.07$	0.04	$\eta_p^2 = 0.15$	$F(1,57) = 6.56$	0.01	$\eta_p^2 = 0.08$	$F(3,57) = 4.39$	< 0.01	$\eta_p^2 = 0.19$
Critical fast-onset events									
Brake frequency	$F(3,56) = 1.53$	NS	–	$F(1,56) = 0.28$	NS	$r = 0.04$	$F(3,56) = 1.44$	NS	–
Steering frequency	$F(3,56) = 0.9$	NS	–	$F(1,56) = 0.98$	NS	$r = 0.13$	$F(3,56) = 0.33$	NS	–
Speed reduction	$F(3,56) = 0.88$	NS	$\eta_p^2 = 0.05$	$F(1,56) = 0.01$	NS	$\eta_p^2 < 0.01$	$F(3,56) = 0.7$	NS	$\eta_p^2 = 0.04$
Accelerator Release Time (s)	$F(3,41) = 0.39$	NS	$\eta_p^2 = 0.04$	$F(1,41) = 0.28$	NS	$\eta_p^2 < 0.01$	$F(3,41) = 0.49$	NS	$\eta_p^2 = 0.04$

CWS = collision warning system.

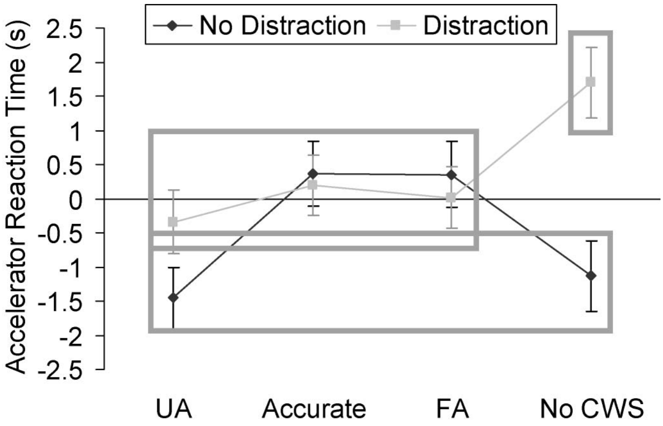


Figure 5. The effect of collision warning system (CWS) on accelerator release time during critical medium-onset events. All but the drivers without CWS (indicated in white) were warned of these situations. Zero corresponds to the time the alarm was or would have been received. UA = unnecessary alarm; FA = false alarm.

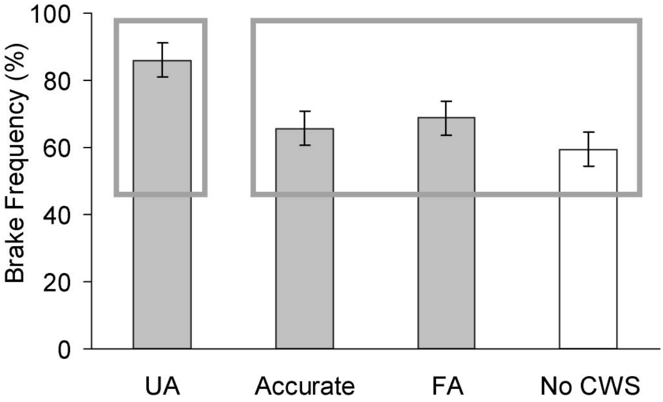


Figure 6. The effect of collision warning system (CWS) on brake response frequency during critical medium-onset events. Only drivers without CWS (indicated in white) remained unwarned of these situations. UA = unnecessary alarm; FA = false alarm.

relatively small speed reductions that forced them to swerve rather than brake to avoid the collision (Lechner and Malaterre 1991, McGehee *et al.* 2000).

3.4. *Performance on the distraction task*

The presence of a CWS did not lead drivers to spend more time interacting with the distraction task, nor did it influence distraction task performance. Specifically, CWS did not significantly influence the number of tasks completed ($F(3,26) = 1.93$, NS, $\eta_p^2 = 0.18$), average completion time ($F(3,26) = 1.86$, NS, $\eta_p^2 = 0.17$), average time between button pushes ($F(3,26) = 1.56$, NS, $\eta_p^2 = 0.15$) or average delay in initiating a task ($F(3,26) = 0.63$, NS, $\eta_p^2 = 0.06$).

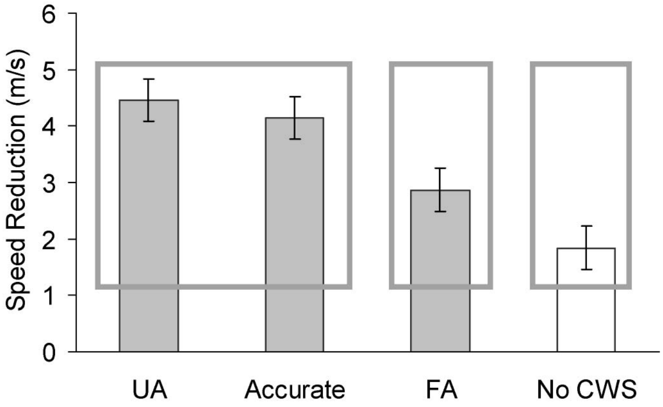


Figure 7. The effect of collision warning system (CWS) on reductions in speed during critical medium-onset events. Only drivers without CWS (indicated in white) remained unwarned of these situations. UA = unnecessary alarm; FA = false alarm.

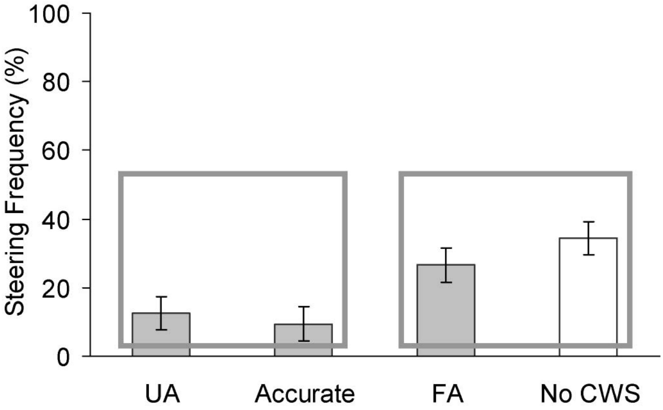


Figure 8. The effect of collision warning system (CWS) on steering response frequency (figure on right) during critical medium-onset events. Only drivers without CWS (indicated in white) remained unwarned of these situations. UA = unnecessary alarm; FA = false alarm.

3.5. *Trust*

Trust reflects the drivers' subjective rating regarding whether or not the CWS will aid them in collision avoidance and has important implications for how drivers rely on the CWS. The type of CWS influenced the degree of trust in the CWS ($F(2,42) = 5.38$, $p = 0.008$, $\eta_p^2 = 0.20$). Drivers with an accurate system (mean 3.3, $t(42) = 2.14$, $p = 0.038$) and drivers with an UA system (mean 3.8, $t(42) = 3.39$, $p = 0.002$) trusted the system more than drivers with a FA system (mean 2.5). Distraction did not influence the level of trust in the CWS ($F(2,42) = 1.11$, NS, $\eta_p^2 = 0.04$) and the interaction between CWS and distraction was not significant ($F(2,42) = 1.03$, NS, $\eta_p^2 = 0.05$).

4. Discussion

This study shows that the driving context and the history of warnings influenced driver response to warnings and to hazardous driving situations. Consistent with the first hypothesis, the results show that context influences compliance with alarms, with drivers complying more with UAs, which occur in a context of a non-critical driving event, compared to FAs, which occur in a seemingly random fashion. This result is consistent with previous research, which shows that drivers' compliance with warnings is conditioned by the severity of the event (Lee *et al.* 2002). This result is consistent with the response of drivers to imperfect collision warnings experienced by drivers on the road – drivers do not blindly comply with warnings (Lee *et al.* 2002, National Highway Traffic Safety Administration 2005a).

The results also show that alarms condition how drivers respond to events. Drivers who received UAs responded more often and to a greater degree to non-critical driving events compared to drivers who did not receive an alarm in these situations. This result provides preliminary evidence that a CWS can influence how drivers evaluate roadway threats, making them more cautious and sensitive to potential threats. Drivers, particularly novice drivers, often fail to appreciate hazardous situations and fail to scan the road appropriately (Fisher *et al.* 2002). Depending on how well drivers appreciate hazards, the triggering conditions of UAs may serve as a useful function of attuning drivers to potential hazards. Whether such warnings serve to enhance drivers' sensitivity to hazards or shift their threshold in responding to events was not addressed by this experiment and merits further investigation. Unfortunately, with extended exposure, drivers may view UAs as unnecessary and consider them an annoyance (National Highway Traffic Safety Administration 2005). The balance of the benefits associated with increased sensitivity to potential hazards and the potential for annoyance may depend on interface. This study used a single-stage auditory alarm; different warning modalities and sound parameters may make it possible for drivers to benefit from UAs without becoming annoyed (Lee *et al.* 2004, Marshall *et al.* 2007).

Consistent with the second hypothesis, this study showed that different types of alerts have substantially different effects on drivers' subsequent response to accurate warnings in situations that require a response. The system prone to UAs led drivers to comply more with alarms in critical situations, whereas the system prone to FAs led drivers to comply less. The difference in compliance paralleled drivers' trust in the system. Consistent with previous research, drivers trusted the accurate system more than the system prone to FAs (Wilson 1994, Itoh *et al.* 1999, Bliss and Acton 2003). More interestingly, drivers trusted the system prone to UAs to a similar degree as the system that produced only true alerts. UAs fostered trust and compliance and FAs diminished trust and compliance.

These results support the general suggestion that the three dimensions of trust (utility, predictability and intent) offer a framework for classifying alarm types in a way that can explain driver response to warnings that the signal detection theory description of simply false alarms does not. The description of warnings according to signal detection theory is not sufficient to account for driver responses to imperfect CWS. The overall failure rate resulted in a breakdown at the performance level for both the FA and UA systems. However, UAs support a process-based understanding of how the system works and helped drivers to trust by enabling the driver to link the driving context (non-critical medium-onset events) to the onset of the alarm. In contrast, FAs fail to provide the driver with information regarding when or why alarms occur, which impairs the ability of the driver to understand how the system works.

The third hypothesis, that distraction would interact with the type of CWS, found mixed support. One might expect distracted drivers to comply more with alarms because they might have less opportunity to observe and verify alarms. Similarly, one might expect distracted drivers to rely on the CWS more because they might be less able to detect events themselves. These effects might then influence drivers' interpretation of FAs and UAs and their subsequent ratings of trust. However, the results support neither of these suppositions. The failure of the distraction conditions to interact with the type of CWS does not stem from a failure of the distraction task to distract drivers. Previous research has demonstrated substantial distraction associated with the task used in this experiment (Donmez *et al.* 2006). Furthermore, the condition in which drivers were not warned of critical situations provides a test of the distraction manipulation and showed a substantial effect of distraction on drivers' initial response.

CWS and distraction did interact to influence drivers' initial response to critical medium-onset events, such that drivers with a system prone to UAs often responded before the alarm onset and faster than the other drivers with a CWS. Interestingly, non-distracted drivers without a CWS responded in a similarly proactive manner. This result suggests that the accurate system may have induced an inappropriately high level of reliance, indicating a potential for drivers to respond only when warned (Singh *et al.* 1993, Parasuraman and Riley 1997). Although the initial response to critical medium-onset events was similar for those with accurate systems and systems prone to FAs, it may be for different reasons. Drivers with the system prone to FAs may have been less compliant with warnings compared to drivers with the accurate system, who may have been overly reliant. This interpretation is supported by the overall response pattern in which drivers who experienced FAs failed to comply with the alarms and braked less, were forced to swerve to avoid a collision, exhibiting a similar pattern as those without a CWS. These results correspond to other research suggesting that FAs may cause drivers to intervene only when they independently verify the source of the alarm (Dingus *et al.* 1997, Bliss and Acton 2003). A more precise assessment of how systems prone to different warning types influence reliance and compliance requires scenarios in which the CWS fails to warn drivers. In these scenarios, the response of overly reliant drivers would be delayed.

5. Limitations

The driving simulator makes it possible to measure driver responses in precisely controlled situations that would be too hazardous to intentionally replicate on the road. As with any simulator study, there are important caveats associated with generalizing these results to on-road behaviour (Harris *et al.* 2005). Although simulators expose drivers to no actual risk, observations over the course of the study suggest that drivers behaved and reacted in a similar manner to what might occur in real-world driving. They did not respond to alarms indiscriminately and they did not disregard driving in favour of the distraction task. The frequency and magnitude of responses observed here may not generalize to on-road situations where greater penalties exist for collision involvement.

The simulator also makes it possible to condense the exposure to many situations into a relatively short period. However, assessing driver responses and attitudes to a large number of threatening situations experienced in a short time does not correspond to the typical driving experience and so drivers may have developed expectations during the experiment that were unrealistic. It is believed that these expectations are not fundamentally different to those that might evolve in actual driving because the proportion of false alarms was representative of actual systems. The events encountered are very similar to situations that would be experienced on the road. The absolute magnitude of the effects is likely to be quite different and will likely depend on response patterns and attitudes that evolve when interacting with these systems over long periods.

Beyond these general challenges, several specific issues should caution the generalization of the results. The occurrence of FAs was not entirely random because the onset of these alerts always occurred 100 m prior to or following a non-critical medium-onset event. Drivers may have associated the onset of these alerts with upcoming or previously experienced events. As a consequence, drivers may have been able to extract some useful information from the onset of the FAs and so diminished the influence of this experimental manipulation. A major limitation of this study concerns its relatively low power; consequently, more research is required to verify these results. This is particularly true of the interaction of distraction and the type of CWS. This experimental design could detect only a large effect and so further research is needed to assess whether a more modest, but potentially important interaction between distraction and CWS exists.

6. Further exploration of a driver-centred interpretation of signal detection theory

A number of important issues remain unaddressed by the present study. Although this experiment examined two different types of alarms that signal detection theory might describe as ‘false alarms’, table 1 outlines other types of alarms that merit investigation. Specifically, the influence of the purpose-dimension of trust remains unexamined. The purpose of a system, as defined by designers, may guide the drivers’ initial expectations, acceptance and interpretation of alarm failures (Walker *et al.* 2006). Manipulations of the purpose dimension may influence how drivers interpret information relative to both the performance and process dimensions of trust. For instance, drivers may be less accepting of UAs when informed that the purpose of the system is to detect only imminent hazards that require driver intervention. Greater emphasis concerning the process dimension, such as giving drivers more information about how automation works and how alerts relate to context, may influence the ability to detect and respond to hazards (Bagheri and Jamieson 2004, Seppelt and Lee, 2007). Research is needed to understand how both system performance and system expectations guide trust and reliance on these systems in real-world driving.

The current study focused on responses to inappropriate alarms, but warning systems may also fail by missing events. Recent research on the concept of easy errors (in relation to both misses and FAs) may help inform CWS design (Madhavan and Weigmann 2003, Madhavan *et al.* 2003, Madhavan *et al.* 2006). The ease of target detection corresponds to how easy it is to confirm or disconfirm the existence of a target. When little information is available about the automation, people believe it will outperform them when making a decision (Dzindolet *et al.* 2003). Consequently, when the user is able to easily deduce that a target is present or absent, they expect the decision aid to agree (Dzindolet *et al.* 2003, Madhavan *et al.* 2006). When the operator easily identifies a target that goes undetected by the system, trust and reliance diminish, even if the overall reliability of the system exceeds that of the operator in difficult target detection (Dzindolet *et al.* 2003, Madhavan *et al.* 2006). However, reliance increases when operators compare their overall performance to that of the automation while remaining unaware of individual decisions made by the automation (Dzindolet *et al.* 2003). In line with the easy-error hypothesis and the dimensions of alarms, future research should assess whether the ease of detection influences how drivers perceive and rely on CWS that miss threats.

Similar to previous investigations of alerting systems, a driver-centred interpretation of signal detection theory suggests that the joint performance of the human and alerting system depends on the characteristics of the human and the warning system (Sorkin and Woods 1985, Sorkin 1988, Sorkin *et al.* 1988). This paper suggests that the specific characteristics of the warnings may interact with the person's state and expectations to affect how the warnings are interpreted. A technology-centred description of the warning system performance using signal detection theory may fail to describe how people will respond to individual warnings and how people might adapt to the warning system over time. As a consequence, a driver-centred perspective suggests new types of design trade-offs that go beyond balancing false alarms and misses. A driver-centred consideration of signal detection suggests that reducing false alarms by making the system more complex and adaptive might increase the relative proportion of false alarms and easy misses and might have the unexpected consequence of undermining trust and compliance.

7. Conclusions

This study demonstrated that the context of an alarm influences drivers' compliance with the alarm and that alarm influence drivers' response to the driving situation. More importantly, two types of alarms that might be classed as false alarms according to signal detection theory had substantially different effects on subsequent true alerts. UAs enhanced trust and compliance and FAs diminished trust and compliance. As a consequence, designers should place greater emphasis on eliminating FAs than on eliminating UAs. More generally, the dimensions underlying the development of trust suggest other types of alarms that might have substantially different effects on the reliance, compliance and acceptance associated with warning systems.

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