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Situation awareness and workload in driving while using adaptive cruise control and a cell phone

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Abstract

Little work has empirically examined the cognitive construct of situation awareness (SA) in driving tasks involving the use of advanced in-vehicle automated technologies and personal communication devices. This research investigated the effects of an adaptive cruise control (ACC) system, and cell phone use in driving, on a direct and objective measure of SA, and assessed the competition of multiple driving and communication tasks for limited mental resources in terms of driving performance. Eighteen participants drove a virtual car in a driving simulation and performed a following task involving changes in speed and lateral position. Half of the participants were required to respond to cell phone calls and all completed trials with and without use of the ACC system. Task performance was measured in terms of lane deviations and speed control in tracking a lead vehicle, as well as headway distance in the following task. SA was measured using a simulation freeze technique and SA queries on the driving situation. Subjective workload was measured using a uni-dimensional mental workload rating. Results indicated use of the ACC system to improve driving task SA under typical driving conditions, and to reduce driver mental workload. However, the cell phone conversation caused deleterious effects on driving SA and increased driver mental load. The cell phone conversation (secondary task) competed for limited mental resources of drivers, leading to less attention to, and accurate knowledge of, the driving situation. Results also revealed the ACC system to improve driving performance along multiple dimensions; however, the cell phone did not have an effect. The latter result may be attributed to a short duration of the cell phone conversations during the experiment. This study has implications for the implementation of in-vehicle automation to support driver SA under normal driving conditions and regulations on the use of cell phones while driving.

Relevance to Industry: The results of this study have relevance to the introduction of advanced automation in commercial vehicles for supporting driver SA and regulation of cell phone use in driving. The study brings to light the critical role of attention-demanding distracter tasks, such as cell phone conversation while driving and using in-vehicle automation.

Keywords: In-vehicle automation; Situation awareness; Workload; Adaptive cruise control; Cellular phone

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1. Introduction

The concept of situation awareness (SA) is well developed in the aviation domain. There have been operational definitions developed for commercial aircraft piloting and forms of air traffic control, for example, Endsley and Rodgers (1994) and Endsley (1989). There have also been many empirical studies of SA in this context (e.g., Endsley, 1995a). Although there are some similarities between the domains of flying and driving, the concept of SA has received less attention in the domain of driving. There remains a need for operational definitions of SA in driving. There is also paucity of empirical studies of SA in driving towards identify underlying influential task, environment and individual factors. Driving, like flying, can be thought of as a dynamic control system in which system input variables change over task time. The input variables are primarily environmental variables with some degree of uncertainty. They include roadway conditions, weather conditions, vehicle conditions, and driver conditions. Based on information detected on the state of the environment, drivers select courses of action that may or may not change the state of the system. Driver actions can include slowing down, accelerating, passing a vehicle, turning, etc. In theory, the construct of SA in dynamic systems fits very well to this domain. In general, driving tasks involve five time-phased information processing (IP) functions, including perception, comprehension and projection, as well as a decision on a course of action and implementing the action. The perception, comprehension and projection functions are the basis for driver situation awareness. This IP cycle may or may not result in changing the state of the system after which a new cycle of activities starts again.

Aviation systems often integrate advanced automation and technologies posing high mental demands on human operators (Billings, 1997). Increasingly, advanced automation technologies (e.g., adaptive cruise control (ACC)) and electronic in-vehicle devices (e.g., cell phone, internet systems) are being introduced in private and commercial driving vehicles. For example, the Audi A6, which is scheduled for sale in Europe in May 2005, integrates an ACC system from Robert Bosch GmbH. This company also developed the ACC system for the new BMW 5- and 7-series vehicles (Graham, 2005). Adaptive cruise control systems will likely be implemented in the US in 2005, as well. Ford has publicized that ACC is to be an option on the new 2005 Jaguar S-TYPE (Ford, 2005). Regarding the use of in-vehicle electronic devices, in general, Edwards (2001) has observed that cell phone and wireless communication device use has increased at an exponential rate over the past two decades (Edwards, 2001). Related to the present research, in a study by Goodman et al. (1999), 90% of all cell phone owners reported that they used their cell phone while driving. With more and more cell phone usage during driving, it is highly likely that drivers may use advanced vehicle automation technologies, such as ACC in combination with cell phones in the near future. In general, advanced automation technologies have been expected to improve system and operator safety, efficiency and comfort (Ward, 2000) by providing, for example, control and navigation assistance. However, such technologies may also generate negative effects on driver behavior (Ward, 2000), including increased monitoring workload and attention distraction from driving task performance (e.g., going "heads-down" to concentrate on in-vehicle device interfaces). This is because automation can change the nature of demands and responsibilities on the operator, often in ways that were unintended or unanticipated by designers (Sheridan, 2002). Consequently, the application of in-vehicle automation and/or the use of in-vehicle devices has the potential to lead to accidents. For instance, cell phone usage while driving may distract drivers' attention from the driving environment causing breakdowns in driving SA and performance. Therefore, it is important, at this point in time, to know the exact influences of the introduction of automation and cell phone use when driving on behavior and performance.

1.1. Existing theory on SA in driving

It is important to understand how drivers may achieve SA in driving, or to identify components or elements of SA, and how they may interact with each other. Endsley (1995a) identified three general components or levels of SA, including perception of elements in the environment (Level 1 SA), comprehension of their meaning in relation to task goals (Level 2 SA), and projection of their status in the near future (Level 3 SA). She said that operator achievement of higher levels of SA is dependent upon the extent to which one accurately and completely perceives states of the task environment. For example, in the context of driving, projection of the behavior of other drivers on the roadway is dependent upon accurate perception of indicators of driver intent (e.g., turn signals, brake lights, and lane changing).

Both Ward (2000) and Matthews et al. (2001) related three general types of driving tasks, including operational, tactical and strategic tasks, to the three levels of SA (perception, comprehension, and projection) defined by Endsley (1995a). At the operational level, drivers are engaged in actions upon vehicle actuators in order to maintain stable vehicle control. This type of task requires Level 1 SA on semi-automatic processes to ensure that the operations are performed appropriately. Level 2 SA may be involved if the automatic processes ‘‘generate error messages’’. At the tactical level, there is a high requirement for Level 1 and 2 SA to facilitate local maneuvering of the vehicle in traffic streams, detecting appropriate environmental cues, and comprehending the driving situation. Tactical tasks also require short span projection of the driving environment, probably less than the extensive projection required for strategic driving tasks (Level 3 SA). At the strategic level, when navigational plans are formulated, there is a high requirement for Level 3 SA. At the time of execution, the strategic plan involves elements of Level 2 SA, in terms of perceptual integration and comprehension. There is also a small contribution from Level 1 SA, since Level 1 SA is the basis for the other two levels of SA (see Matthews et al., 2001).

Matthews et al. (2001) outlined multiple elements of awareness defining SA in driving, including spatial awareness, identity awareness, temporal awareness, goal awareness and system awareness. They said spatial awareness refers to an appreciation of the location of all relevant features of the environment. Identity awareness refers to the knowledge of salient items in the driving environment. Temporal awareness refers to knowledge of the changing spatial ‘‘picture’’ over time. Goal awareness refers to the driver’s intention of navigation to the destination, and the maintenance of speed and direction. System awareness refers to relevant information on the vehicle within the driving environment, which may also be viewed as a system.

Gugerty and Tirre (2000) presented a similar concept of driver situation awareness. They said drivers must maintain navigation knowledge, local scene comprehension (knowledge of nearby traffic for maneuvering), knowledge of spatial orientation, and knowledge of their vehicle’s status to maintain good SA during driving.

With respect to underlying factors in SA, both Gugerty and Tirre (2000) and Matthews et al. (2001) considered in-vehicle system interaction knowledge to be important in a driving environment, for example, when a car traveling at a constant speed under cruise control enters a higher speed limit area, driver awareness of their vehicle speed, the speed limit and knowledge of how to set a higher speed represents good SA. This is in agreement with Endsley’s (1995a) contention that system factors influence operator achievement of SA, including the number and complexity of automation systems. In driving, the development of SA on the roadway may become more challenging as more automation is added to vehicles and driver attention is divided and drawn away from the roadway.

In summary, the various types of driving knowledge identified by prior research as being critical to SA include navigation knowledge, environment and interaction knowledge, spatial orientation knowledge, and vehicle status knowledge. These forms of knowledge can be integrated in a driver IP model to define SA in driving (see Fig. 1). Unfortunately, there is very little empirical research that has assessed this type of theory of SA in driving by using explicit operational definitions of the construct. This research focused on the implication of in-vehicle automation and in-vehicle device interaction on development of operator SA through this type of processing by

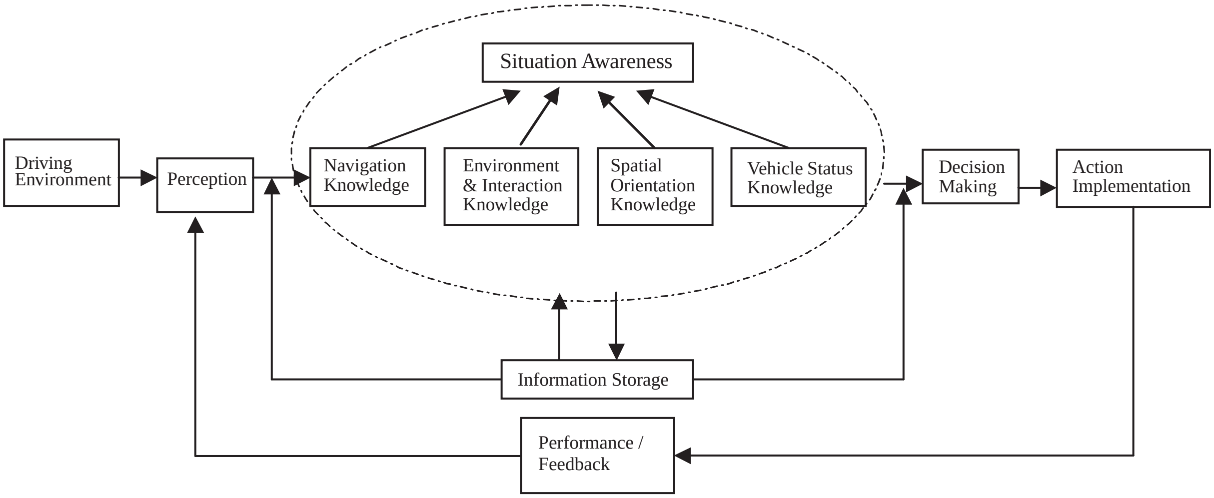

Fig. 1. SA in driver information processing.

using a direct objective measurement of situation awareness.

1.2. Previous studies on in-vehicle automation and driver SA and workload

Intelligent Transportation Systems have been described and introduced into driving tasks, including adaptive cruise control. Adaptive cruise control automates the driving task by adjusting vehicle speed depending upon a defined minimum following distance and by monitoring traffic and instigating braking or acceleration when the detected headway is smaller or larger than the set criteria. Ward (2000) found that ACC appeared to improve driving safety by reducing instances of unsafe headway distance in following tasks. However, there was some evidence of secondary effects of reduced SA, inferred from the observation of poorer attention to lane positioning, failure to yield to traffic, as well as slower response times to unexpected events when using adaptive cruise control. Ward (2000) only used a performance-based measure of SA in his study. In this type of research, an objective measure of SA, with construct validity, is needed to accurately describe the effects of in-vehicle automation on driver situation awareness.

Other empirical studies have revealed the influence of in-vehicle automation on performance, workload and attention allocation (e.g., Parker et al., 2003; Rudin-Brown et al., 2003). In general, results indicate that ACC achieves the goal of reducing the frequency of "tailgating" and the severity of rear-end collisions, and there is significantly lower driving workload when ACC is set to a long headway distance (e.g., 2.4 s), as compared to driving without ACC (Parker et al., 2003). However, the driver may direct his/her attention away from the driving task when using ACC, creating an unsafe situation. The study by Rudin-Brown et al. (2003) showed a significant improvement in secondary-task performance under an ACC long-headway condition (2.4 s headway), compared to driving without ACC. Consequently, drivers demonstrated significantly fewer safe braking events under ACC short (39.6%) and long (45.8%) conditions, as compared to driving without ACC (63.5%). These results demonstrate that the use of ACC may improve driver performance on everything but driving. The use of ACC may also lead to unexpected increases in accidents from driver distraction (and failures in Level 1 SA), when performing more in-vehicle secondary tasks.

1.3. Impact of using in-vehicle devices on driver SA and workload

Jerome et al. (2002) offered that one of the central concerns for current day driving is the effect of in-vehicle devices on driver performance and safety. In-vehicle devices are considered to be any device a driver can manipulate while driving, whose functions are not directly related to the driving task (e.g., a cell phone or radio). With more and more cell phone usage during driving, it is critical to know if cell phone conversations in cars increase driver workload, and decrease SA, and ultimately decrease task performance. A cell phone conversation when driving may cause the same disruption for a driver (and his/her achieving SA) as having a conversation with a passenger. Both of these activities compete for limited driver mental resources. However, the cell phone conversation may be worse in terms of impacting SA and performance since the caller cannot visualize the driving situation to assist the driver, and the driver may need to use one hand to hold the phone (hand-held phone).

A study by Chen and Lin (2003) compared driving situations with and without a secondary conversation over a hands-free cell phone using a driving simulator. Results indicated that the use of a mobile phone while driving can have adverse implications for driving safety. They showed that drivers adopted several approaches to reduce additional cognitive workload caused by the phone conversation. Subjects compensated for a need for increased reaction time by increasing the headway distance to lead car and decreasing driving speed during the dual-task scenario (driving and talking). Chen and Lin observed an increase in missed brake responses, which seemed to be caused by a loss of attention to the driving environment in the dual-task situation and could have led to accidents. Furthermore, the dual-task driving tests indicated a loss of attention in subject processing of information presented on road signs.

Another study by Gugerty et al. (2003) assessed differences between remote (cell phone) and in-person (passenger) communication during driving. Results indicated that the pace of the in-person and remote verbal interactions differed. Drivers talking with remote partners generated longer pauses, suggesting that remote verbal interactions may be more difficult and drivers may modulate their conversation in order to maintain adequate driving performance. Situation awareness was also assessed in this study using: (1) location-recall probes, to which participants responded with the locations of cars in traffic; (2) performance probes, in which participants attempted to avoid nearby hazardous vehicles; and (3) scene-interpretation probes, in which participants identified cars that were driving dangerously. Gugerty et al. found that SA was significantly degraded when performing the driving task while talking with a partner, as compared to only driving a car. However, the amount of degradation in SA during in-person and remote interaction did not differ significantly.

Several studies (Hancock et al., 1999, 2002) have indicated that there is a slower response to traffic light changes in the presence of an in-vehicle distractor (cell phone), and have affirmed deleterious effects of competing tasks at crucial points in a driving maneuver using basic automatic-transmission cars. This research suggests a possible decrement of SA (Level 1 SA, perception, Level 2 SA, comprehension, and Level 3 SA, projection) as a result of cell phone usage during driving. That is, conversations may have compromised subject comprehension of perceived driving environment stimuli relative to the goal of maintaining vehicle safety, specifically sudden stopping situations.

In general, it appears that in-vehicle devices presenting distracter tasks to drivers (cell phone conversation when driving) may compete for limited driver mental resources, possibly leading to SA decrements and decreases in human performance. Unfortunately, aside from the Gugerty et al. study, there is paucity of research on SA in driving, when using a cell phone to communicate, involving direct objective measurement of the construct. Furthermore, there has been no study of the interaction effects of using in-vehicle devices, such as cell phones (presenting secondary tasks) along with ACC systems on driver SA and performance.

In summary, our knowledge of SA in various contemporary driving circumstances is incomplete, and there have been few empirical studies of this issue. Although some studies have inferred driver SA based on simulation performance (e.g., Ward, 2000) or used context-dependent measures of driver SA (e.g., Gugerty et al., 2003), the results of such measures may not accurately reflect changes in the construct of SA (perception, comprehension, and projection during driving). Beyond this, there has been no study of the SA effect of the combination of advance-automated technology, like ACC, and cell phone use in driving. This is important because of the dramatic increases in cell phone usage and the advent of ACC in contemporary automobiles. This problem is also relevant to other new forms of automated vehicle systems, including lane-keeping or automated steering technologies. Driver SA and performance may be hindered by increased IP loads resulting from additional tasks of collecting information about the states of such systems and cell phone conversations.

The purpose of the current study was to: (1) investigate the effects of ACC and cell phone use in driving on a direct and objective measure of SA and perceived driver workload; and (2) to assess the competition of multiple driving and communication tasks for limited mental resources in terms of driving performance. In general, the study was expected to advance knowledge on how to implement in-vehicle automation to facilitate and support driver SA, when automation is critical to driving performance. It was also expected to provide insight into how people should balance driving and secondary tasks to ensure good SA and performance.

Fig. 2. Experiment equipment setup.

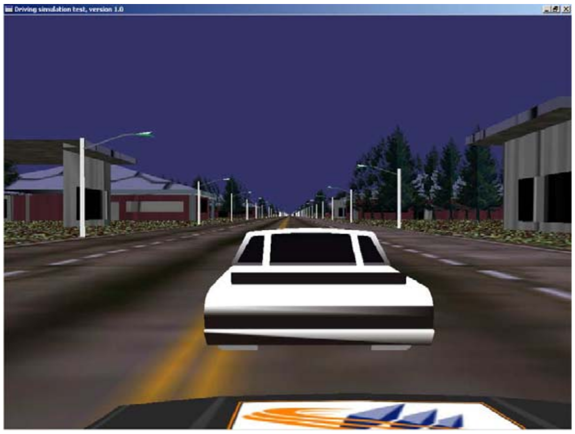

Fig. 3. Close-up of driving simulation display.

2. Method

2.1. Task

The task used in this study was a medium fidelity, 3-dimensional simulation of a freeway-driving environment. It was presented using a virtual reality (VR) system, including a stereo display. User control inputs occurred through realistic automobile control interfaces, including a physical steering wheel, and physical gas and brake pedals (see Fig. 2). The simulation required participants to drive a virtual car and perform a following task, which involved changes in speed and lateral position. The simulation environment included a four-lane highway presented from an egocentric viewpoint inside the driver's sports vehicle. The roadway was marked with conventional lines. There were also many types of signs along the sides of the highway, including: "pedestrian crossing", "slow", "deer crossing", "railroad" and "speed limit". The environment included buildings, grass, rivers and street lights (see Fig. 3). All objects in the virtual environment were modeled to scale and presented with rich, realistic textures.

Participants were asked to drive on the roadway, maintain their vehicle in the right-hand lanes (of the four-lane freeway), keep their vehicle in the middle of a particular lane, and follow the lead vehicle. They were also asked to observe all road signs. Participants were exposed to ACC or no-ACC control modes, of which they were informed in advance. There was no physical interface to the automation, as part of the simulator; it was simply turned "on" or "off". The ACC automated the driving task by maintaining vehicle speed depending upon a defined minimum vehicle following distance and a maximum travel speed. The maximum speed was 80 mph and there was no minimum speed. The defined headway distance was approximately 2.4 s under all driving conditions. The ACC system almost instantaneously adjusted the speed of the user car relative to lead car speed changes (on average 1.4 s). The system was perfectly reliable and always performed well (no errors). Certain participants were also required to talk on a cell phone with a remote party. The cell phone call was considered to be a secondary (distracter) task, in which an experimenter asked participants a number of arithmetic questions (10 problems per call, including a single digit multiplied by a two-digit number or multiplication of two numbers with single digit each).

Participants drove for roughly 25 min during each trial. The freeway was approximately 2 mile in length, including straight-aways and curves, in a giant loop configuration. The average speed of the lead vehicle in all trials was 60 mph.

2.2. Experimental design

The independent variables for the experiment comprised the ACC control modes (active or inactive) and the cell phone use (conversation or no conversation) condition. The ACC condition was manipulated within subjects because of the driving experience of participants; therefore, we expected little or no carry-over effect across conditions. The cell phone conversation condition was manipulated between subjects in order to reduce possible condition carry-over effects, as participants might have become more proficient at responding to the arithmetic questions while driving. Each participant in the cell phone condition groups completed two trials under each ACC setting. In total, all participants completed four 25-min sessions during the experiment.

The dependent variables for the experiment included driver SA. Participant perception (Level 1 SA), comprehension (Level 2 SA) and projection (Level 3 SA) were measured using the Situation Awareness Global Assessment Technique (SAGAT). The SAGAT is a simulation freeze technique in which SA queries are posed to complex system operators (in this case drivers) on the state of the simulation at various points in time (Endsley, 1995b). In the present experiment, the driving simulation was frozen at 7, 14 and 21 min into a trial. During a freeze, the simulation display screens were shutdown and subjects moved to an adjacent workstation at which they found a pencil and SA questionnaire sheet. Each questionnaire presented a sample of nine SA queries from a pool of 27 queries targeting all levels of SA. Each questionnaire included three Level 1, Level 2 and Level 3 SA queries. Participants were required to recall car locations and colors or traffic signs they had passed. They were required to identify any necessary driving behaviors (acceleration, braking and turning) to improve the accuracy of their following position behind the lead car. They also projected times to certain events, such as the time to the next turn or to pass the next sign in view, etc. There was no time limit on participant responding to queries. After participants completed a questionnaire, they returned to the driving simulation workstation and continued the simulation where they left off. The SA response measures for each trial included the average percent correct responses to Level 1, Level 2 and Level 3 queries and a total SA score across all three questionnaires.

We also measured subjective workload after each session by using a mental demand rating scale with anchors of "Low" and "High". Participants marked an "X" on the scale at the position they felt most accurately represented the demand for the trial. The response measure was the distance from the "Low" anchor to the subject's rating divided by the total length of the scale.

Finally, task performance was measured in terms of participant accuracy in lane maintenance and tracking lane changes by the lead car, as well as tracking lead car speed and maintaining safe headway distance (the optimal range was defined as 8–25 m) in the following task. Task performance was recorded automatically by VR computer system at every second. The root mean square errors (RMSE) for the headway distance and following speed, as well as lane tracking and maintenance on the straignt and curve lanes were caculated for each trial.

2.3. Apparatus

The medium fidelity driving simulation was programmed using Visual C++ and the Virtual Environment Software Sandbox was used as a real-time VR engine. Participants wore stereographic goggles to view the VE in 3-D. A Motorola T720 cell phone was used for all cell phone conversations during the experiment. An experimenter called the cell phone during trials from a landline, speakerphone in an adjacent lab room, which could not been seen or heard by participants.

2.4. Participants

Eighteen college students were recruited for the study. Half the participants were randomly assigned to a group required to have cell phone converstions while driving. The order of presentaiton of the four trials (two replicates under each ACC by cell phone conditions) for each participant was randomized. All participants were required to have 20/20, or corrected to normal vision, and at least 1 year of driving experience. Nine males and nine females participated in the actual experiment with an equal number assigned to each cell phone condition. The average age of the participants was 26.6 years, and there was an average of 6.11 years of driving experience. As part of an anthropometric data survey, participants were also asked to rate their prior experience with cruise control systems and cell phones while driving. With respect to the former, the average response (on a scale from 1 = "none" to 5 = "frequent") was moderate (2.3). With respect to cell phone use while driving, on average participants indicated moderate experience (2.9).

2.5. Procedure

Each participant completed the entire experiment in one day according to the following procedures: (1) 20 min of instruction on the medium-fidelity driving simulation; (2) 20 min of training in the simulation driving task under a no-ACC control mode (without cell phone use); (3) 15 min of instruction of the SA questionnaire and subjective workload rating scale to be administrated during experimental trials; and (4) four 25-min. trials, including the three SA questionnaires and the summary workload rating with intervening 5-min breaks between trials. Participants were instructed to concentrate on the driving task and allocate whatever residual attention they may have to other tasks (i.e., cell phone response). If participants were assigned to the cell phone conversation condition, calls were received at 3, 10 and 17 min into each trial, and call lasted slightly less than 2 min. Fig. 4 presents the schedule of events during each experiment trial. The experiment lasted 3.5–4 h for each participant.

2.6. Specific hypotheses

Contrary to Ward's (2000) inferences on SA in driving, we hypothesized that use of the ACC system would improve driver SA under non-hazardous driving conditions (i.e., no unexpected events or hazards). We expected the ACC to reduce task load in terms of the need to monitor for and implement vehicle speed changes and, thereby, free-up cognitive resources for perceiving the driving environment. The use of the ACC system was accordingly hypothesized to decrease driver perceived mental workload as a result of relieving them of the need for continuous speed and headway distance control. Based on Ward's (2000) findings, the ACC system was also hypothesized to provide better task performance than no-ACC driver speed control and headway distance control because of the potential for driver boredom and vigilance decrements over extended periods without ACC control.

The cell phone conversation during driving was expected to compete for limited driver mental resources and to increase driver perceptions of workload and, as Gugerty et al. found, to decrease SA. Based on the results of Chen and Lin (2003) and Hancock et al. (1999, 2002), the cell

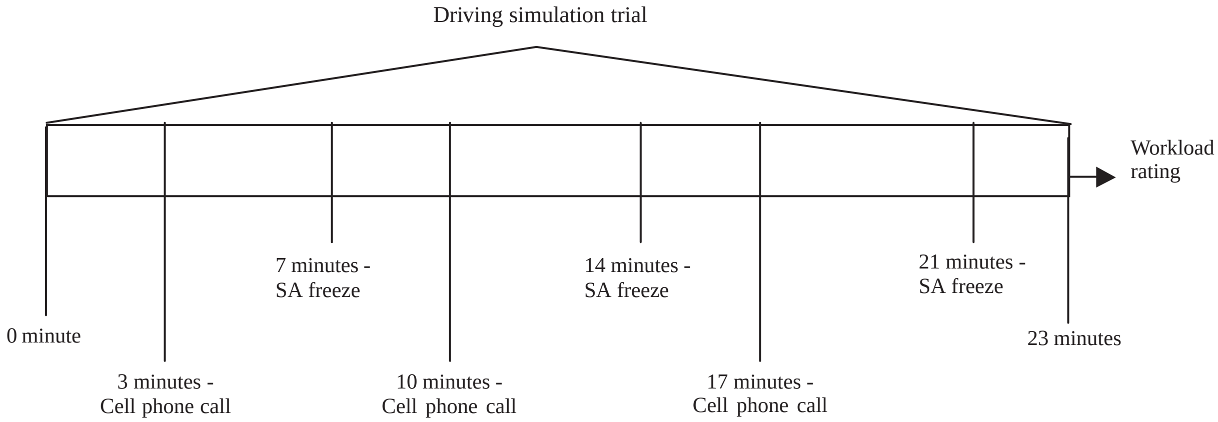

Fig. 4. Schedule for cell phone calls and SA freezes during test trials.

phone use was also expected to degrade driver task performance.

Finally, based on the findings of Rudin-Brown et al. (2003), the combined use of the ACC and the cell phone was expected to create a situation in which the driving workload relief provided by the in-vehicle automation would lead to increased driver concentration on the secondary task (the cell phone conversation). This situation was expected to degrade SA and overall driving performance. One concern that we had with respect to this hypothesis was that prior work examining the effects of in-vehicle highway systems on driver secondary-task performance used simulations in which the secondary task occurred continuously during driving versus intermittently, like real cell phone conversations. We suspected that the intermittent cell phone calls in our trials would be less distracting to drivers than continuous secondary-task performance (e.g., eating while driving) and would constitute a more conservative assessment of the SA effects of the automation and in-vehicle device use.

3. Results and discussion

3.1. Driver SA

Fig. 5 presents the mean Level 1, Level 2, Level 3 and total SA scores for both ACC control mode and cell phone conversation condition. The plot reveals that, on average, drivers exhibited better SA when the ACC control was active and no-cell phone conversation took place.

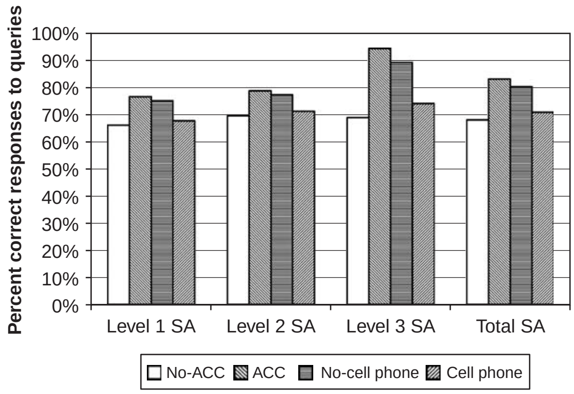

Fig. 5. Mean percent correct responses to SA queries for ACC control and cell phone conversation conditions.

Analysis of Variance (ANOVA) results on driver SA indicated that, in general, the ACC control mode and cell phone conversation conditions were influential in the percentage of correct responses to SA queries during trials. There was no interaction effect of the ACC control mode and cell phone conversation on Level 1 SA. There was a significant effect of ACC control mode on Level 1 SA ($F(1,16) = 18.68$, $p = 0.0005$) with greater perceptual knowledge of the driving environment occurring when the ACC control was active.

There was also no interaction effect of the ACC control mode and cell phone conversation on Level 2 SA. ANOVA results revealed significant effects of the ACC control mode ($F(1,16) = 22.22$, $p = 0.0002$) and cell phone conversation ($F(1,16) = 5.15$, $p = 0.0375$) on Level 2 SA. Drivers demonstrated significantly greater comprehension of the driving environment when using the ACC control. As we hypothesized, the cell phone conversation degraded driver SA and there were significantly higher scores for Level 2 SA when no cell phone conversation took place.

ANOVA results revealed significant level 3 SA effects of the ACC control mode ($F(1,16) = 121.73$, $p < 0.0001$) and cell phone conversation ($F(1,16) = 36.26$, $p < 0.0001$). Drivers demonstrated significantly greater ability to project states of the driving environment when using the ACC control. Similar to the results on Level 2 SA, there were significantly higher scores for Level 3 SA observed when no cell phone conversation took place; that is, the cell phone conversation degraded driver projection of states of the driving environment. There was also a significant interaction effect of the ACC control mode and cell phone conversation condition on Level 3 SA ($F(1,16) = 15.22$, $p = 0.0013$). Fig. 6 presents this interaction effect. Tukey's test revealed significantly higher ($p < 0.05$) projection scores when the ACC was active across both cell phone conditions than when the ACC was inactive and cell phone conversations did not take place. Level 3 SA scores were significantly higher ($p < 0.05$) when the ACC system was active versus inactive and drivers were not engaged in conversation. It also revealed significantly higher ($p < 0.05$) Level 3 SA scores when the ACC was inactive and no cell phone conversation took place, as compared to no ACC with cell phone conversations. The result also revealed significantly higher ($p < 0.05$) Level 3 SA scores when the ACC system was active than inactive, given no cell phone conversation took place.

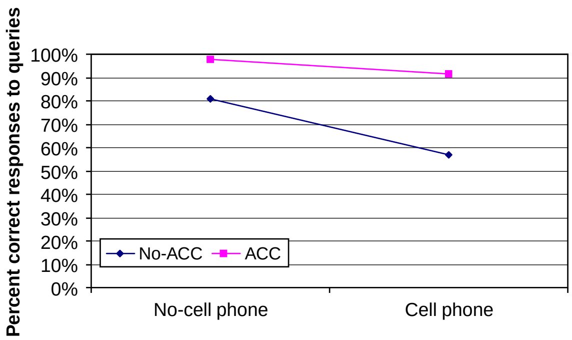

Fig. 6. ACC and cell phone conversation interaction effect on Level 3 SA.

Unlike the results on Level 1 SA, the findings presented here suggest that drivers may not be able to continue to make accurate projections of the driving situation when posed with secondary distracter tasks. Among the various stages of IP encompassed by the construct of SA, the stage of perception may place relatively lower demands on human mental resources, as compared to projection, and consequently drivers may be able to address such demands even when resource competition occurs (i.e., the cell phone call). For system-state projection, humans may not be able to manage information on the driving environment and from a cell phone conversation, and to simultaneously make accurate judgments on the future of the driving situation.

There was no interaction effect of the ACC control mode and cell phone conversation condition on total SA. ANOVA results also revealed overall SA (or the total SA score) to be significantly affected by the ACC control mode ($F(1,16) = 118.38$, $p < 0.0001$) and cell phone conversation condition ($F(1,16) = 20.75$, $p = 0.0003$). There were significantly higher scores for total SA when the ACC control was active. There were also significantly higher scores for total SA when no cell phone conversation took place during the trials.

In summary, these findings support the general notion that introducing the use of automation in vehicles under typical driving conditions allows for improvements in driver SA by reducing driver task load in terms of the need to monitor for, and implement, speed changes. As expected, our results on SA also supported the contention that the cell phone conversation would degrade driver comprehension and projection of states of the driving environment, and overall SA. Although the

ANOVA results did not reveal an effect of the cell phone conversation on Level 1 SA, this may due to the short duration of cell phone conversation time during the experiment (approximately 1.5 min for each call).

3.2. Driving workload

There was no interaction effect of the ACC control mode and cell phone conversation condition on workload. ANOVA results revealed subjective ratings of mental demand in the driving task to be significantly affected by the ACC control mode ($F(1,16) = 68.46$, $p<0.0001$) and cell phone conversation condition ($F(1,16) = 8.54$, $p = 0.01$). Fig. 7 presents the mean percent mental workload for both the ACC control mode and cell phone conversation conditions. The mean percent mental demand was significantly greater when there was no ACC control. There were also significantly greater perceptions of mental workload when cell phone conversations took place.

The findings on workload support our hypotheses that under typical driving conditions the use of the ACC would decrease mental workload and the use of the cell phone would increase driver workload. In this study, the ACC system and cell phone appeared to have comparable influences on mental workload in terms of the magnitude of the response, but were opposite in the direction of influence (see Fig. 7). Our findings support an advantage of the introduction of in-vehicle automation during typical driving conditions, and suggest the importance of limiting cell phone usage. Related to our hypothesis on the interaction effect of the in-vehicle automation and cell phone on the use of cognitive resources, it is possible that the automation did provide workload relief, but that the cell phone conversations exploited this, consequently, washing-out any significant workload effect across conditions.

3.3. Driving performance

In general, performance results indicated that the ACC system was influential in vehicle control, but that the cell phone conversation condition was not. This observation may be attributable to our concern that the cell phone conversations were intermittent and did not pose a continuous secondary load on drivers throughout trials. The specific findings on headway distance, speed control and lane maintenance are presented here.

3.3.1. Headway distance

There was no interaction of the ACC control mode and cell phone conversation condition in terms of headway distance. ANOVA results revealed a significant effect of the ACC control mode on variation in headway distance ($F(1,16) = 42.53$, $p<0.0001$). Fig. 8 presents the RMSE of headway distance (compared to the mean of the optimal range (16.5 m)) for both ACC control mode and cell phone conversation conditions. Drivers appeared to allow significantly greater deviations in headway distance when the ACC control was inactive, possibly suggesting a perceived need for greater caution at the test

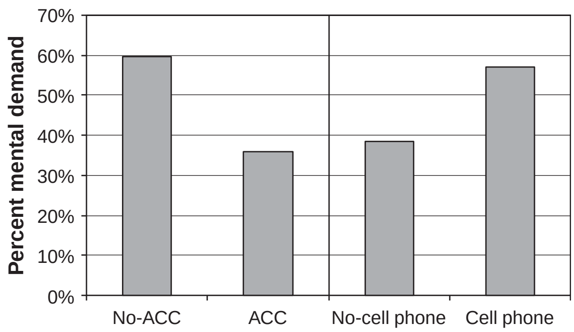

Fig. 7. Mean subjective rating of percent mental demand for ACC control and cell phone conversation conditions.

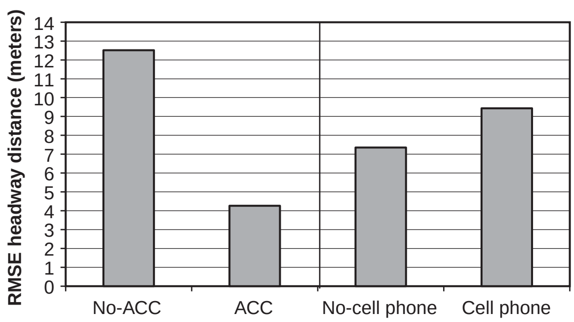

Fig. 8. RMSE of headway distance for ACC control and cell phone conversation conditions.

speeds or limited driver confidence in their ability to quickly react to lead vehicle speed changes.

3.3.2. Following speed

There was no interaction of the ACC control mode and cell phone conversation condition in terms of variations in following speed. ANOVA results revealed a significant effect of the ACC control mode on variations in driver following speed (when tracking the lead vehicle in the simulation) ($F(1,16) = 111.95$, $p < 0.0001$). Fig. 9 presents the RMSE of following speed for both ACC control mode and cell phone conversation conditions. There were significantly greater deviations in following speed with no ACC control.

3.3.3. Lane maintenance on curves

There was no interaction of the ACC control mode and cell phone conversation condition in terms of curved lane maintenance deviations. ANOVA results on driving performance indicated that the ACC control mode had a marginally significant effect ($F(1,16) = 4.36$, $p = 0.0526$) on driver lane maintenance only when negotiating curves as part of the simulated freeway. There was no significant effect of ACC control on lane maintenance on straight-aways. There was a trend for greater lane maintenance deviations on curves when the ACC control was inactive.

In summary, we hypothesized that the ACC system would facilitate better driving performance, including speed and headway distance control, and lane maintenance. Our findings generally support the use of ACC control to improve driving performance under typical driving conditions. Our results did not support the hypothesis, based on Chen and Lin (2003), that cell phone conservations during driving would decrease task performance. However, once again, this may be attributable to the duration of the cell phone conversations during our trials. Although there were three cell phone conversations during a single test, as previously mentioned, they were brief and the total cell phone conversation time for any trial was much shorter than the total driving time (approximately 5 min versus 25 min). Therefore, the cell phone condition did not pose a consistent secondary-task demand on drivers potentially subtracting from performance.

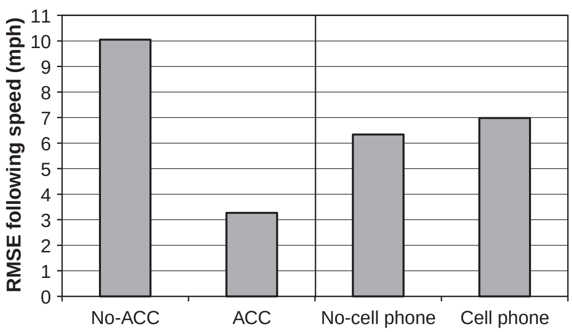

Fig. 9. RMSE of following speed for ACC control and cell phone conversation conditions.

3.4. Correlation analyses

Simple correlation analyses were conducted in order to identify any significant relationships among SA, workload and secondary-task performance (percentage of correct responses to arithmetic problems during cell phone conversations). A Pearson correlation coefficient revealed a significant negative linear association between the total SA score and subjective workload ratings ($r = -0.716$, $p < 0.0001$). There were also highly significant negative linear associations between workload ratings and percent correct responses to queries on each level of SA. These additional findings add strong support to our contention that the in-vehicle automation off-loaded drivers in terms of monitoring motor-control tasks and allowed for greater perception, comprehension and projection of driving environment states.

A Pearson correlation coefficient revealed a significant negative linear association between workload ratings and secondary-task performance ($r = -0.447$, $p = 0.0063$) (i.e., a positive correlation among subjective and objective workload measures). As ratings of mental demand in the driving task increased, secondary-task performance decreased, and vice versa. This finding further demonstrates the mental resource competition among driving tasks and cell phone use. It also supports the use of secondary-task measures of mental workload during simulated driving tasks.

Finally, Pearson correlation coefficients revealed significant negative linear associations between total SA score and variations in headway distance ($r = -0.49882$, $p = 0.002$) and following speed ($r = -0.5498$, $p = 0.0005$). There was also a significant negative linear association between Level 3 SA and variations in headway distance ($r = -0.66129$, $p < 0.0001$) and following speed ($r = -0.70919$, $p < 0.0001$). All these findings indicate positive associations of the construct of SA and driving performance; that is, as SA increased, the RMSE in headway (from the optimum range) and speed decreased. This evidence can be considered validation of our operational definition of SA (objective measure) and further demonstrates the importance of the cognitive construct to driving.

4. Conclusions

We contended that the concept of SA is not well developed in the context of driving (in terms of operational definitions or identities of underlying task and environment factors) and that there is an increasing need to understand the implications of in-vehicle automation and devices on driver situation awareness. Based on existing SA theory, we developed an operational definition of SA in the driving domain and applied it to a medium fidelity simulation to provide further insight into the importance of interaction with in-vehicle systems to human perception, comprehension and projection of states of the driving environment. Specifically, we assessed the effects of ACC and cell phone use on driver SA, workload and driving task performance, and sought to describe the extent to which secondary tasks compete for driver mental resources.

Our results provide support for the application of in-vehicle automation, like ACC, under typical driving conditions for facilitating driver situation awareness. It appears that ACC control relieves drivers of vehicle monitoring and motor control workload, and they may pay more attention to the driving environment (as a primary task). Consequently, drivers may develop more complete and accurate knowledge of driving states (SA). It is possible that this benefit of automation to driving SA (under typical driving conditions) may lead to observed improvements in overall performance. These inferences differ from those of Ward (2000), who observed reduced driver SA through performance data under hazardous driving circumstance (e.g., responses to roadway hazards). However, the positive performance implications of ACC, which we observed, are in agreement with all prior work, including Parker et al. (2003), particularly improvements in variation in headway distance and following speed control.

This study also provided further support for the hypothesis that (hand-held) cell phone usage can be detrimental to driver SA (Gugerty et al., 2003). We provided evidence that cell phone conversations (as a secondary task during driving) compete for the limited mental resources of drivers. Consequently, drivers may not pay enough attention to the driving environment (as a primary task) and they may not develop complete and accurate knowledge of driving vehicle states (SA). This decrease of SA may lead to decrements in driving performance. These inferences are in agreement with the findings of Gugerty et al. (2003) on the driving SA effects of cell phone use. Although Chen and Lin (2003) and Hancock et al. (1999, 2002) demonstrated significant driving performance decrements due to cell phone use (e.g., missed braking responses), we did not observe similar effects with our freeway simulation of a following task under typical conditions. We did expect performance decrements due to the cell phone use, but the short period of the cell phone conversations during our experiment may not have been sufficient to cause problems. Cell phone conversations may result in significant deleterious effects on driving performance with longer, continuous conversations.

In this study, only high-level driver SA appeared to be sensitive to the interaction effect of in-vehicle automation and device use. Similar to Rudin-Brown et al. (2003) results, we found that the benefits of ACC, in terms of workload reduction, were offset by workload increases due to cell phone use, driver distraction from the primary task, and associated degradations in situation awareness. It is possible that the negative impact of the interaction of these technologies may be more pervasive across the levels of SA (perception, comprehension and projection) under more complex, interactive driving conditions posing higher mental workload.

Caution should be exercise in applying any of these results to actual driving systems because of the limitations of the medium fidelity driving simulation used in this study. Drivers may behave differently in operational settings because they are aware of the grave consequences of having an accident. In addition, participants in this study may have experienced less stress and workload in the simulation study because of a lack of a navigational objective. Under actual driving circumstances, people usually have a desired destination in mind and there is usually time pressure to achieve the destination (e.g., driving to a meeting across town).

On the basis of this study, directions of future research include developing broader operational definitions of SA in driving that apply to more than the freeway following tasks examined here, as well as additional empirical work to identify other in-vehicle system factors that may be influential in driver situation awareness. More specifically, there is a need to study the interaction effect of in-vehicle automation and device use on driver SA under hazardous or emergency driving conditions using direct, objective measures of the construct.

Another direction of future work, closely related to the present study, would be to investigate the impact of advanced automation lane keeping systems to determine if the effects on driver SA, workload and performance are comparable to those of the ACC system. Furthermore, it would be worthwhile to examine the compound effect of using multiple forms of in-vehicle automation on driver SA when confronted with secondary tasks, like cell phone use.

The mental resources of drivers will continue to be stretched in the future by the advent of new-sophisticated in-vehicle automation and more elaborate portable, personal communication and data assistance devices used while driving. There is a need to continue to investigate how drivers will achieve and maintain SA in the presence of this technology in support of safe driving performance. Resulting knowledge should be applied to the development of future technologies, or the redesign of existing devices, and reflected in any state and/or federal regulations on in-vehicle device use. In general, future research efforts should be focused on increasing driver SA under normal driving circumstances to better negotiate highway systems and to be prepared for hazardous events.

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