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Display Alternatives for In-Vehicle Warning and Sign Information: Message Style, Location, and Modality

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In-vehicle displays offer a promising alternative to road signs; however, little human factors research exists to guide their design. In this study we examined message style, the physical grouping or location, and visual as opposed to auditory messages to identify how such message characteristics affect driving safety and compliance. Important intervening variables such as driver self-confidence, trust in the system, situation awareness, and workload helped explain the influence of in-vehicle messages on driving behavior. Data collected from 16 older and 16 younger drivers using a driving simulator suggest that message style (command vs. notification messages) may be an important design characteristic influencing both compliance and safety. Results of this study suggest that command messages promote greater compliance but may also reduce safety. Although message style has not been widely studied, these tentative results suggest that it merits consideration along with more commonly studied design parameters of display modality and location. Whether or not in-vehicle messages were presented with redundant road signs emerged as another important issue. In-vehicle messages without redundant roadway signs led to lower levels of safety. Intervening variables of situation awareness and workload suggest that the lack of redundant road signs reduced safety because drivers distribute their attention inappropriately as opposed to in-vehicle messages exceeding their information-processing limits. These results suggest that the evaluation of in-vehicle information systems should consider the inappropriate distribution of attention and other possible failure modes in addition to information processing capacity limits.

Advanced Traveler Information Systems (ATIS) are intended to provide travelers with real-time information regarding traffic and roadway conditions, vehicle navigation, roadway hazards, weather conditions, and motorist services. In-Vehicle Signing Information Systems (ISIS) and In-Vehicle Safety Advisory and Warning Systems (IVSAWS) are essential components of ATIS and have the potential to provide drivers with a variety of information via an in-vehicle display. ISIS are intended to convey information that is currently depicted on external roadway signs, such as noncommercial routing, warning, regulatory, and notification information. IVSAWS are

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intended to warn drivers of hazardous or unsafe conditions on the roadway ahead, including accidents, construction zones, and the presence of emergency vehicles. These new sources of information offer many benefits over traditional roadside signs. Specifically, in-vehicle information is not susceptible to reduced visibility associated with weather and nighttime driving. Moreover, in-vehicle messages can present customized information tuned to the specific needs of a driver—something that is not feasible with traditional signs. However, in-vehicle displays have many design alternatives and human factors challenges, and little data exist to guide designers.

In considering ATIS display alternatives, it is important to remember that ATIS information has the potential both to facilitate driver decision making and to distract the driver from controlling the vehicle. Many ATIS design parameters contribute to driver performance. In this study, we examine the effects of message style, of physical grouping or location of displays, and of visual as opposed to auditory messages on driver compliance with warning messages. We also investigate whether particular ATIS message characteristics degrade driving safety. It is also important to consider these design parameters in the context of the driving population and the roadway environment. Here, driver characteristics include age and gender; environmental characteristics include the ATIS and road-sign infrastructure.

MESSAGE STYLE

We define *message style* as the degree to which a message directs a driver to perform a specific action. At one extreme, messages might simply inform drivers of a particular roadway condition (e.g., "Icy Road Ahead"). At the other extreme, messages might command drivers to take specific actions in response to the condition (e.g., "Slow Down"). *Notification* and *command* messages define the endpoints of this dimension. Notification information advises the driver of a particular situation but leaves him or her with complete autonomy in terms of both interpreting the situation and deciding how to respond to it. In contrast, command information suggests a specific course of action to the driver. To give information in the form of commands, the system might be required to integrate various kinds of data automatically. Before issuing a command message, it would need to evaluate existing roadway conditions, real-time traffic data, and vehicle data and then to select the most appropriate action. Command messages can reduce certain information-processing requirements of the driving task (e.g., perception of relevant information, integration of multiple sources of driving information, and complex decision making), but it also has the potential to misdirect drivers should the command fail to consider all the relevant factors—for example, a command to change lanes when the lane is occupied by another car. The distinctions between command and notification can be considered as different levels of automation, in which command messages represent a higher level of automation (Sheridan, 1988).

Although message style has not been investigated empirically in the context of the driving task, studies in other domains have examined similar questions. For example, researchers have investigated the effects of mothers' message styles (directive or suggestive) on children's compliance. Suggestive styles have been found to lead to greater compliance in children (Crockenberg & Litman, 1990; Lytton, 1977; Rocissano, Slade, & Lynch, 1987). The suggestive messages used in these studies correspond to the notification message style in this experiment. Extrapolating this result to the driving context suggests that notification information might induce greater compliance.

Extensive research has been done on the effects of directive and nondirective leadership styles on performance and compliance. Generally, a directive style of leadership has been found to increase compliance (Lippitt, 1940) but to reduce both group performance and satisfaction (Hendrix & McNichols, 1982; Miller & Monge, 1986), especially when measured in the field, as opposed to laboratory studies. Simpler tasks (which are more common in the laboratory) are frequently performed better under directive leadership, whereas more complex tasks are best performed under a more democratic style (Becker & Baloff, 1969; Rudin, 1964). A less directive style also seems to lead to better performance with highly anxious participants (Misumi & Peterson, 1985). Extrapolating these results to our study suggests that the command style would promote greater compliance but that it might also undermine driving safety and the driver's satisfaction with and trust in the system.

The effectiveness of authoritarian leadership seems to be related to the amount of knowledge possessed by the leader. When the autocratic leader knows more than the other members of the team, authoritarian leadership produces the most effective performance. If, however, the authoritarian leader knows less, or is given misinformation, the team will do much worse than if led by a less knowledgeable or misinformed democratic leader (Blyth, 1987; Cammalleri, Hendrick, Pittman, Blout, & Prather, 1973; Fiedler & Garcia, 1987; Shackleton, Bass, & Allison, 1975). This suggests that the notification style is preferable for unreliable systems and for messages that require integration with other information sources.

Given the complexities and uncertainties associated with extrapolating these findings to ATIS design, it is difficult to draw firm conclusions. However, several studies have addressed situations that parallel the driving situation more closely. One study (Van Houten & Van Houten, 1987) examined traffic signs with specifically worded prompts, which were similar to the command message style in our study. They found that the specifically worded prompts resulted in large reductions in the percentage of people traveling over the speed limit. This result contrasts with those of studies that found that generally worded signs have little effect on drivers' speed (Van Houten & Van Houten, 1987). Wickens (1992) reviewed status and command displays, which correspond to the notification and command messages in this study. He concluded that command displays are most appropriate for conditions of high stress and time pressure. In addition, a study (Crocoll & Coury, 1990) of decision aids using status and recommendation information showed little difference in performance when the system was reliable but that performance declined significantly when the decision aid was unreliable. These findings suggest that a command style would promote greater compliance than a notification message style but that the benefits of this might be outweighed if drivers followed the ATIS commands blindly and ignored important roadway information. Thus, we might expect a trade-off for compliance and safety. This study will directly examine the differences in these two messages styles and their effect on driver safety and warning compliance.

DISPLAY LOCATION

Another important dimension of ISIS and IVSAWS message design is the physical grouping or location of displays. At one extreme, ISIS and IVSAWS information might be centralized on a single screen. At the other extreme, ISIS and IVSAWS information might be distributed across several locations using several display modalities (e.g., instrument panel, center-mounted display, and head-up display [HUD]). For auditory displays, a centralized approach might refer to the concurrent use of all speakers in the vehicle, whereas a distributed approach might use individual speakers to localize sound and provide directional cues.

In the context of this study, we will refer to this ATIS message characteristic as the distinction between *centralized* and *distributed* warning information. The literature on attention and time-sharing does not provide unequivocal guidance on the relative merits of a centralized versus a distributed approach. At issue is which approach to the display location makes the most effective use of available attentional resources and supports the most efficient time-sharing between assimilating warning information and the primary task of driving.

In this regard, the centralized display option may be a somewhat simpler and more conservative approach in that it reduces the requirement for drivers to attend to and visually scan more than a single in-vehicle display. Specifically, attentional resources associated with instrument scanning can be focused on a single display rather than distributed over numerous displays. There is some support for this approach in the literature. For example, signal detection performance for simple stimuli decreases as the number of display locations increases (Shaw, 1984). Similarly, Konrad, Kramer, and Watson (1994) compared the effect of multiple displays to a single sequential display using a simple monitoring task. They found that response time and response accuracy were better with the single (centralized) display. In addition, a centralized approach may address the tendency of people to engage in less-than-optimal scanning strategies when multiple displays must be monitored (Moray, 1981).

On the other hand, display location can act as an alternate code to identify the urgency or type of displayed information. Thus, the location of the information can serve as a cue that may reduce processing time and aid driver interpretation, decision making, and response. For example, information requiring an immediate response from the driver can be presented on a HUD (which generally minimizes eye and head movement requirements), and less urgent information can be presented on one or more head-down CRTs. Although poor time-sharing will take place if the spatial separation across displays is too great (Wickens, 1992), the consistent mapping of message content and display location may support automatic processing (Schneider & Shiffrin, 1977), resulting in efficient processing of distributed displays.

In summary, it is not clear whether the centralized or distributed approach will be more effective. The centralized approach may be more effective with relatively simple stimuli and responses. The distributed approach may be more effective when a large number of messages can be divided into a small number of meaningful categories. This study examines whether message location can be used to help drivers identify and respond to messages associated with lane change and speed change maneuvers.

SENSORY MODALITY

For many travel-related information displays (e.g., speed-limit signs and traffic signals), designers have little choice regarding the sensory modality used to convey the information. However, with ATIS information, designers have the option of using either auditory or visual displays to present ISIS and IVSAWS information. The auditory channel can have an advantage over the visual channel due to its attention-getting qualities (Sanders & McCormick, 1993). In addition, because driving already places high visual demands on drivers, auditory messages are an attractive option. The use of auditory messages might allow better time-sharing of limited processing resources, that is, time-sharing between two sensory resources may be superior to sharing within a single resource (Wickens, 1992). However, the visual channel is the more traditional mode for the presentation of driving information. It is also associated with relatively higher information rates than the auditory channel and is less likely to startle the driver (Sorkin, 1987). Potential interaction with message style is another important consideration in selecting message modality. The effect of command messages may be enhanced when delivered in an auditory format as compared to a visual format. Specifically, Noy (1990) and Perez and Mast (1992) have argued that a verbal instruction is more likely to result in unquestioning compliance, particularly when in the form of commands.

ATIS AND ROADWAY INFORMATION AVAILABILITY

Related to these display design issues is the issue of the availability of ATIS and roadway information. ATIS information will not be universally available. Particularly during initial implementation, ATIS information may often be inaccurate or nonexistent. When ATIS information is not consistently available, drivers may ignore the ATIS and use road signs to guide their decisions. Drivers may encounter ATIS messages paired with redundant roadway information or either roadway signs or ATIS messages alone. In such situations, the driver must adapt his or her own knowledge of the roadway situation and available signage to the information provided by the ATIS and act accordingly. Drivers' level of trust in the ATIS may guide this adaptation because people are reluctant to rely on equipment that they do not trust (Lee & Moray, 1992). Beyond trust, self-confidence may also play an important role in mediating drivers' sampling strategy (Lee & Moray, 1994). This experiment examines how drivers' trust in the ATIS interacts with their self-confidence to influence compliance with ATIS messages.

The redundancy of ATIS and roadway information is an important consideration for ATIS implementation. One option is to present ATIS messages without redundant roadway messages, such as changeable-message signs. Another option is to augment signs with redundant in-vehicle messages. Redundant information might enhance driver compliance with the warnings, but it might also overload the driver with too much information. This information overload may decrease driving safety. Drivers' perception of the redundancy of ATIS and roadway information, and the associated information processing load, may depend on ATIS message style (notification vs. command), display locations (centralized vs. distributed), and sensory modality (auditory vs. visual).

OBJECTIVES OF THIS STUDY

This study provides an initial screening of important design characteristics for in-vehicle messages, with a focus on message style and its interactions with more commonly studied display options such as message modality and location. Considering different levels of ATIS and roadway infrastructure development, the three parameters of ATIS display design generates four issues of particular importance: (a) the effect of notification versus command message style on compliance and driving performance; (b) the effect of centralized versus distributed display location on compliance and driving performance; (c) the effect of auditory versus visual information on compliance and driving performance; and (d) the interaction of these parameters in the context of potentially unavailable ATIS information and unavailable roadway information, or both. ATIS information must facilitate rapid and accurate response; however, it must not degrade driving safety by interfering with drivers' ability to consider roadway information.

This study uses multiple measures to examine the effect of different ATIS design characteristics on warning compliance and driving safety. In addition, this experiment examines several intervening variables to better understand the cognitive processes that underlie the influence of ATIS designs on safety and compliance. Factors influencing trust and self-confidence are likely to influence compliance with ATIS warnings.

Similarly, situation awareness, workload, and information assimilation measures should reflect the factors underlying how ATIS messages might compromise driving safety. Specifically, measures of workload may reflect the information overload that might accompany the additional information provided by the ATIS. Situation awareness and message acknowledgment may reflect drivers' distribution of attention to the roadway and ATIS.

Figure 1 shows the major variables considered in this study and their interactions. The left side of the figure shows the independent variables that may influence driver response to in-vehicle information systems. The variables at the bottom of the figure reflect system effectiveness and are clustered into two groups: One group is associated with driving safety, and the other group is associated with driver compliance with messages. Linking the independent variables to the measures of effectiveness are intervening variables that show how design parameters affect driver responses.

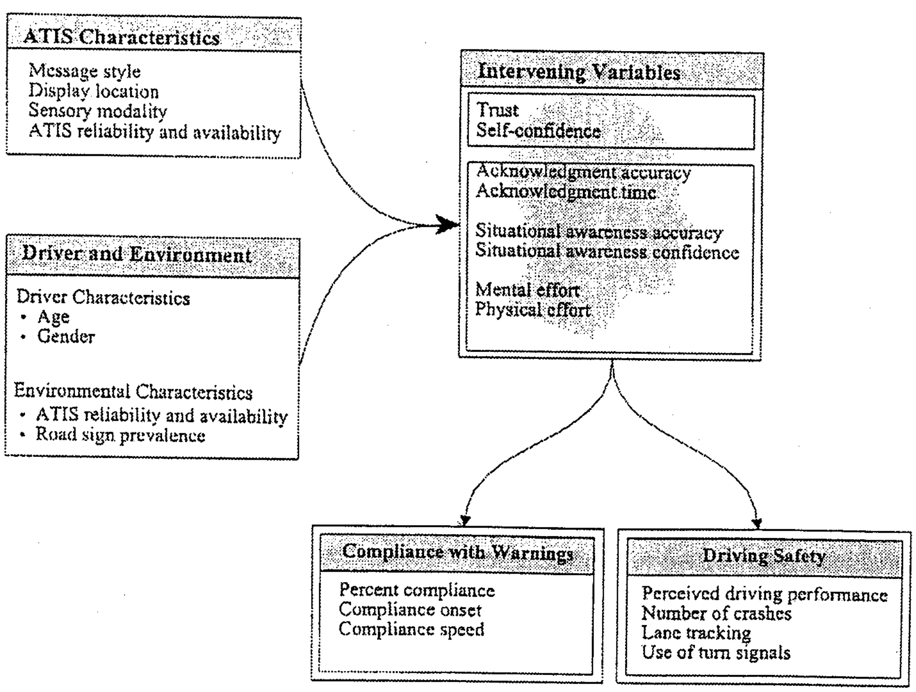

FIGURE 1 Summary of variables investigated in this study and the major categories of analyses.

METHOD

Data were collected using the Battelle automotive simulator, which is a relatively low fidelity automotive simulator equipped with an easily reconfigurable ATIS. The vehicle was equipped so that ATIS messages could be presented visually, through electroluminescent and liquid crystal display (LCD) panels, or auditorially through speakers. The visual scene of the simulation presented drivers with roadway information in a form similar to the changeable-message signs found on many highways.

Participants

Sixteen male and 16 female drivers participated in this experiment for a total of 32 participants. Eight male and 8 female drivers were under the age of 30, with ages ranging from 18 to 29 ($M = 22.4$, $SD = 3.3$). Eight male and 8 female drivers were over the age of 64, with ages ranging from 66 to 83 ($M = 74.4$, $SD = 4.7$). All participants had valid driver's licenses, drove at least twice a week, and had no problems with motion sickness. Younger drivers were recruited from the University of Washington, whereas older drivers were recruited from local church, volunteer, and retirement groups. Each driver was paid $5 per hour, for approximately 3 hr of research time.

Apparatus

The major components of the automotive simulator included (a) the automobile cab, (b) the simulation software, and (c) the simulated ATIS. The cab was constructed using a 1986 Ford Merkur XR4Ti automobile. The dash of the automobile was modified by replacing the standard instrument panel with electroluminescent displays. The steering wheel was modified to include a push-button switch on the lower part of each side of the wheel at approximately 130° and 230°. The rear of the vehicle was open to allow access to the rear speakers. Both doors were operational and had side-view mirrors. The front "windshield" was completely enclosed with a black hood to reduce ambient lighting, and the left side of the windshield housed a 20 in. (50.8 cm) color monitor that displayed the simulated road scene.

A closed-loop, low-fidelity driving simulation software, developed by Systems Technology, Inc. (STI) Software, Version 8.01 (STI, Inc., 1994), was used for the experiment. Running on an IBM-compatible computer, the simulator produced visual scenes and sounds relevant to driving. The fully interactive STI simulator included the following features: five-speed automatic transmission, realistic vehicle dynamics, simulated road noise (engine and drive train), tire squeal to signal loss of control on high-speed turns, and wire-framed rendering of displayed objects. The simulation updated the visual scenes at approximately 10 to 20 Hz, providing relatively smooth apparent motion. The STI software allowed for full driver interaction; the driver was able to steer, change lanes, accelerate, and brake. For this experiment, the vehicle dynamics were adjusted to represent a typical passenger vehicle.

ATIS messages were displayed on either (a) one of two in-vehicle displays or (b) through a speaker system. One display had a viewing area of 4.8 in. (12.2 cm) by 7.0 in. (17.8 cm) and was located in the instrument panel directly in front of the driver. The other display was a 9.4 in. (23.9 cm) diagonal active matrix color LCD display and was centered on the transmission channel of the vehicle. The LCD display was a touch screen so that drivers could answer questions and provide ratings by making selections directly on the display. Situation awareness (SA) questions and subjective ratings of trust, self-confidence, and perceived driving performance were collected using an automated procedure on the LCD touchscreen.

Independent Variables and Experimental Design

This study used a 2 × 2 × 2 × 2 × 2 × 4 mixed factorial design to investigate the independent variables summarized in Table 1. Several variables require a detailed explanation. Display location included centralized and distributed conditions. In the centralized condition, all text messages were displayed on the screen positioned in the instrument panel for the visual condition and through both speakers in the auditory condition. In the distributed condition, related auditory messages were assigned to the right or left speaker in the auditory condition or to one of the two displays in the visual condition. Specifically, all messages involving a change in vehicle speed were presented through the left speaker, and all messages involving a lane change were presented through the right speaker. Similarly, all messages involving vehicle speed were presented through the display in the instrument panel, and all messages involving lane changes were presented through the display positioned over the transmission.

The information availability variable also requires further explanation. Roadway information was presented as a changeable-message sign in a style that matches most standard warning signs. The notification style for ATIS messages is similar to the style of all roadway signs. During a scenario with the information availability condition "ATIS and roadway information," drivers received four ATIS messages and saw four changeable-message signs, one for each roadway event they encountered. During the "ATIS only" condition, drivers received four ATIS messages and saw only one changeable-message sign. During the "Roadway only" condition, drivers received only one ATIS message and saw four changeable-message signs. During the "Neither" condition, drivers received only one ATIS message and saw only one changeable-message sign. In the "Neither" condition, drivers encountered two events without any warning, received an ATIS message for one event, and saw a changeable-message sign for the remaining event. Thus, in the conditions in which ATIS or roadway information was not available, the failure rate of the respective systems was 75%. The failure rate was set at 75% rather than at 100% to mimic the fact that a completely unreliable ATIS or road-sign system is not realistic. Although a failure rate of 100% would have enhanced the sensitivity of the statistical analyses, it would have reduced the generality and ecological validity of the results. Even in those conditions in which drivers did not receive an ATIS message or see a roadway sign, they still had access to other roadway

TABLE 1
Independent Variables Included in the Experiment

Variable	*Type*	*Levels*
Age	Between	Under 30; 65 and over
Gender	Between	Male; female
Display location	Between	Centralized; distributed
Message style	Within	Command; notification
Message modality	Within	Visual text; auditory
Information availability	Within	Both ATIS and roadway; ATIS only; roadway only; and neither

Note. ATIS = Advanced Traveler Information Systems.

information that informed them of the event. For example, they were able to see crosswalk markings on the roadway and the angle of deflection of an upcoming curve.

Table 2 shows the within-subject variables arrayed in the $2 \times 2 \times 2 \times 2 \times 2 \times 4$ mixed factorial design used in this study. The letters and numbers represent levels of independent variables. The experiment considered three dimensions of ATIS design: (a) display location (centralized vs. distributed), which was a between-subjects variable; (b) message style of ATIS information (command vs. notification), a within-subjects variable; and (c) mode of presentation (auditory vs. visual), again a within-subjects variable. The order of these variables was counterbalanced in a Latin square design. Each row in Table 2 contains a series of 16 scenarios with each scenario representing a separate within-subjects experimental condition. Each scenario contained a sequence of four driving events, lasting approximately 6 min each; each event included an incident, such as an upcoming construction zone, which required a driver decision and action. Each driver experienced 16 scenarios, for a total of 64 events. The design was constructed so that each set of 16 scenarios was experienced by 4 drivers: 1 young male, 1 older male, 1 young female, and 1 older female. The pattern of experimental conditions in Table 2 was replicated so that 16 drivers experienced the scenarios with a centralized display and 16 drivers with a distributed display.

For each scenario, drivers experienced a random selection of four of the events shown in Table 3. Table 3 shows the ATIS warnings for each of six different events. Depending on the experimental condition, drivers received messages, listed in Table 3, either as a command or as a notification message, formatted as an auditory or visual warning, and presented in a centralized or distributed location.

TABLE 2
The Within-Subjects Variables Arranged in a Latin Square Design

Scenarios 1–4	*Scenarios 5–8*	*Scenarios 9–12*	*Scenarios 13–16*
Tc_{1234}	Tn_{1234}	An_{1234}	Ac_{1234}
Tn_{1234}	Tc_{1234}	Ac_{1234}	An_{1234}
An_{1234}	Ac_{1234}	Tn_{1234}	Tc_{1234}
Ac_{1234}	An_{1234}	Tc_{1234}	Tn_{1234}

Note. T = text display modality; A = auditory display modality; c = command message style; n = notification message style.
1 = Advanced Traveler Information Systems (ATIS) and roadway information. 2 = Only ATIS information. 3 = Only roadway information. 4 = Neither roadway nor ATIS information.

TABLE 3
Advanced Traveler Information Systems (ATIS) Messages for Each of Six Different Events

Event	*ATIS Messages*
1. Curve	Reduce speed (command); curve ahead (notification)
2. Crosswalk	Reduce speed (command); pedestrian crossing (notification)
3. Icy roadway	Reduce speed (command); icy roadway (notification)
4. Road construction	Merge left (command); lane closed for construction (notification)
5. Accident in lane	Merge left (command); lane blocked by accident (notification)
6. HOV lane	Merge left (command); HOV lane ahead (notification)

Note. HOV = high occupancy vehicle.

Procedure

Figure 2 shows the experimental protocol. When the participants first arrived, they were given instructions and asked to sign an informed consent form if they agreed to participate. To ensure that the drivers had understood the instructions, they were given a short test. The experimenter reviewed any questions that were answered incorrectly. After receiving the instructions, the participants drove a practice scenario in which they were told to drive normally and obey speed limits. Drivers were asked to acknowledge each ATIS and roadway warning by pressing one of two steering-wheel buttons. Drivers used the button on one side of the steering wheel to acknowledge ATIS messages and the button on the other side to acknowledge roadway signs. Drivers who failed to respond accurately to more than 25% of the events repeated the training scenario. If after two repetitions they were not able to respond accurately, they were paid and escorted from the laboratory.

The training scenario was followed by four 30-min blocks of four 6-min scenarios and a short break. This generated data for sixteen 6-min scenarios. Each 6-min scenario contained four main driving events. These events included disabled vehicles, pedestrian zones, high-occupancy vehicle lanes, accidents, and construction zones. Drivers experienced a random selection of four of these events during each 6-min scenario. At a random point in each scenario, the simulator was temporarily stopped and the drivers answered four SA queries. Each query consisted of a question about the driving situation, and the drivers responded with a forced choice of two alternative answers. After responding to the queries, the drivers continued to drive. The SA queries were placed so that they occurred within 30 sec of an event. Depending on the level of information availability, ATIS and roadway information were presented to alert drivers to each of the four roadway events. While driving, participants encountered other typical roadway features, such as traffic lights, pedestrians, and billboards. Drivers also faced typical driving hazards, such as passing and oncoming traffic. As they drove in the right lane of a four-lane rural road, faster cars approached and passed in the left lane. The passing cars forced drivers to stay within their lane and to check their mirror before changing lanes. A detailed description of all the scenarios and SA queries has been compiled (Lee et al., 1998). At the end of each scenario, drivers rated their trust in the ATIS, self-confidence in detecting roadside hazards, subjective driving performance, mental effort, and physical effort.

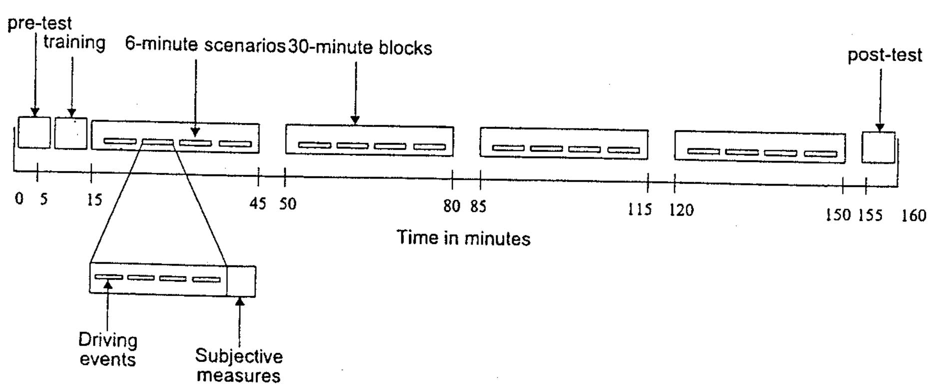

FIGURE 2 The protocol and timeline of the experiment.

Dependent Variables

Two categories of dependent measures were collected. One directly measured driving safety and driver compliance with warnings. The other consisted of intervening variables that may illuminate the cognitive processes that influence the measures of compliance and driving safety. The intervening variables measured drivers' attitudes, SA, and message acknowledgment.

Measures of warning compliance were developed for this study to provide a common unit of measure for drivers' speed and lane change behavior in response to warning messages. For this study, *warning compliance* has been defined as the degree to which drivers correctly respond to messages. For example, a driver who moved to the left lane after a message instructing her to merge left would have demonstrated a greater degree of compliance than a driver who failed to comply with the message and stayed in the right lane. Similarly, a driver who slowed from 45 mph to 25 mph (72.4 kph to 40.2 kph) in a pedestrian zone would have had a greater degree of compliance than one who remained at 45 mph (72.4 kph). Complete compliance with the warning was defined as 100% compliance. Complete compliance was possible for all events and was defined in the same way for all participants. For those events in which drivers were instructed to change lanes, complete compliance was defined as making a complete lane change (i.e., moving from the center of the right lane to the center of the left lane). For those events that required drivers to reduce their speed, complete compliance was defined as a speed reduction to 25 mph (40.2 kph). It was possible to be more than 100% compliant, for example, if a driver swerved to the far side of the left lane to avoid an accident in the right lane or slowed to below the instructed speed. It was also possible to have negative compliance, as when a driver increased speed in response to a message requiring a speed reduction.

Compliance is a complex and dynamic variable that changes as the driver responds to roadway hazards. To capture its dynamic nature, compliance was measured in three ways. The first measure was the *time to 10% of maximum compliance*. This measure reflected reaction time and drivers' delays in responding to the messages. The second measure reflected how quickly compliance increased and was labeled *rise time*. Rise time was the time it took drivers' compliance to change from 10% of maximum compliance to 90% of maximum compliance. Rise time indicated the speed of response. Faster was generally better because a faster response could mean faster and more complete compliance. However, an abrupt, last minute response would have a fast rise time, but it would be less safe than a slower response. The third measure of compliance was *integrated compliance*. This measure was calculated by numerically integrating the level of compliance from the onset of the message to the end of the event and then normalizing by the length of the event. Each of these measures of compliance is shown on Figure 3, which presents the compliance of a hypothetical driver from the point in which the message was delivered to the end of the event. The *end of the event* was defined as the time when the hazardous situation was no longer present, such as when a driver had traversed the curve.

Five measures indirectly assessed driving safety. These included perceived driving performance, the number of crashes per hour, lane position (root mean square [RMS] deviation from center of the lane), speed control (RMS deviation of speed), and the use of turn signals. With the exception of perceived driving performance, each of these measures was based on data from 5 sec before the time that the drivers received an ATIS message or roadway information until 5 sec after the event had ended. Drivers rated their perceived driving performance using a scale that was presented on a touchscreen display at the end of each 6-min trial.

Intervening variables included drivers' attitudes that were measured by subjective ratings at the end of each scenario. Drivers rated their trust in the ability of the ATIS to notify them of road-

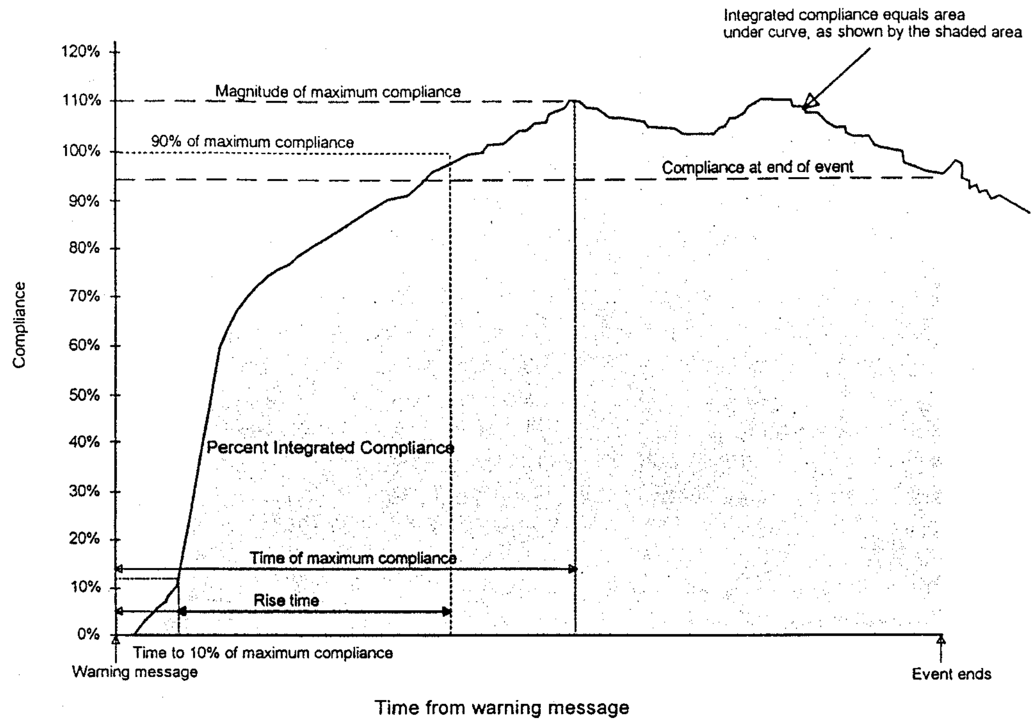

FIGURE 3 Measures of compliance over the duration of an event.

way hazards and their self-confidence in their ability to accurately identify roadway hazards. They also rated their mental and physical effort. The rating scales were presented on a touch-screen display at the end of each 6-min trial.

Drivers' SA was measured once during each scenario using the SA Global Assessment Technique (SAGAT; Endsley, 1995). *SA* has been defined by Endsley (1995) as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 36). SAGAT has been studied extensively and has proven to be a valid and effective measure of SA (Endsley & Kiris, 1995). Using this technique, the simulation was "frozen" while the drivers answered 4 questions. Questions included "What is your current speed?"; "What product was the last billboard advertising?"; and "In the next 30 seconds, which action will you perform?" For each question, drivers were given two choices from which to choose. The SA score was calculated as the percentage of correct responses. Correct answers were identified according to the events and roadside scenery in the scenario. For some questions, such as those regarding speed, the correct answer was calculated based on variables measured during the scenario. The 4 questions for each probe were randomly drawn from a pool of 14 questions. Although SA probes undermine the realism of the driving experience, they provide valuable data that would be impossible to generate otherwise. To minimize their intrusion on the experiment, SA probes were positioned so that they did not occur as a driver approached a hazard but were otherwise randomly distributed through the scenario.

Drivers were asked to acknowledge each ATIS and roadway warning by pressing one of two steering-wheel buttons. Drivers used the button on one side of the steering wheel to acknowledge ATIS messages and the button on the other side to acknowledge roadway signs. The acknowledgment latency and accuracy were measured to estimate the focus of the drivers' attention. If drivers' focus was on the ATIS, then acknowledgment latency should have favored the ATIS acknowledgment. The acknowledgment side was counterbalanced to guard against any right–left bias. To avoid learning effects, acknowledgment side was introduced as a between-subjects variable.

RESULTS

The results will be described in four sections: (a) warning compliance; (b) driving safety; (c) trust in the ATIS and self-confidence; and (d) SA, workload, and message acknowledgment. The first two sections address how ATIS design characteristics influenced compliance with warning messages and driving safety, and the final two sections investigated the intervening variables and cognitive processes that governed compliance and safety. Except where noted, the analyses included age, gender, information availability, message style, message mode, and message location as independent variables. Also, except where noted, the analyses involving information availability included all events and messages associated with that condition. For example, the information availability condition "Neither" included one event that provided drivers with roadside information and one event that provided drivers with an in-vehicle message. We include all events in the analysis because we are interested in examining how drivers' behavior adapts to representative systems more than how drivers' respond to individual messages. Analyzing the complete set of responses to each condition of information availability provides a more robust and generalizable estimate of how drivers are likely to respond to the various scenarios and design configurations. All analyses were performed with the BioMedical Data Processing (BMDP) Statistical Software, Version 7.0 (BMDP, 1990). Where appropriate, the results have been interpreted using the Greenhouse–Geisser adjustment (Stevens, 1996) to the degrees of freedom to compensate for violations to the sphericity assumption in the repeated measures analysis of variance (ANOVA). Standard errors (*SE*) were used as the error bars on the graphs. Each half of the error bar is 1 *SE*, making the total length of each bar 2 *SE*s.

Warning Compliance

The multiple measures of compliance used here provide a detailed description of how drivers respond to warnings of roadway hazards. Each of the three measures of compliance had different statistical properties. Rise time ranged between 0 sec and 35.1 sec and had a grand mean of 9.7, with a standard deviation of 4.6. Time to 10% compliance was slightly less variable. It ranged from 0 sec to 18.4 sec and had a grand mean of 4.7, with a standard deviation of 2.1. Integrated compliance ranged between −11.45% and 109%, meaning that for a few events several drivers actually increased their speed in response to a warning message. The grand mean of integrated compliance was 49.9, with a standard deviation of 21.1. As the results of the statistical analyses will show, the three measures of compliance were not strongly related and responded differently to the independent variables. The correlation between rise time and time to 10% compliance was only .067. Similarly, the correlation between integrated compliance and time to 10% compliance and between integrated compliance and rise time was only .068 and .185, respectively. The three measures of compliance provide a complementary description of the dynamic response of drivers to warning information.

Table 4 shows the three measures of compliance for each of the four conditions of information availability. The effect of information availability was not significant for time to 10% compliance, $F(2.6, 42.2) = 0.90, p > .05$. However, information availability did affect rise time and integrated compliance, $F(2.8, 46.2) = 3.69, p < .05$, and $F(2.8, 45.1) = 46.24, p < .0001$, respectively. Integrated compliance was greater when ATIS messages were present compared than when they were not. Because rise time reflects the time to progress from 10% to 90% of maximum compliance, lower values correspond to a faster increase in compliance. Table 4 shows that drivers who were presented with both roadway signs and in-vehicle messages increased their compliance more slowly than those who received neither roadway nor in-vehicle messages. Considered in the context of integrated compliance, the longer rise time suggests that drivers who received both roadway and ATIS information acted on this information gradually over time but that their maximum compliance was greater. Of the three measures of compliance, integrated compliance was most affected by information availability, showing a difference of 51.3% between the extreme conditions, compared to only 15.5% difference for rise time.

Drivers received one of two styles of ATIS messages, either notification or command; roadway-sign style was not manipulated. Analysis of the compliance measures in Table 4 showed that only the integrated compliance measure differentiated between message styles. The cases in which drivers received an ATIS message were selected from all four conditions of information availability. In these cases, message style had a strong influence on integrated compliance, with the command-style messages generating a compliance of 64.8% compared to 53.2% for notification-style messages, $F(1, 16) = 19.51, p < .001$. No other message characteristics or their interactions had a statistically significant influence on compliance.

The results show that ATIS messages increased compliance and that command messages were particularly influential. No other message characteristics affected compliance. These results also show that integrated compliance was most strongly influenced by the independent variables of this study and that it was not strongly coupled to other measures of compliance.

Driving Safety

A range of safety-related measures were examined. These measures included (a) perceived driving performance, (b) mean number of crashes in each hour of driving, (c) percentage of times the turn signal was used correctly, (d) RMS of lane position, and (e) RMS of speed. In combination, these messages help reveal how in-vehicle messages might affect driving safety.

TABLE 4
Measures of Compliance for the Four Levels of Information Availability

Measure of Compliance	*Road and ATIS*	*ATIS*	*Road*	*Neither*
Time to 10% compliance (*ns*) (in seconds)	4.6 (2.1)	4.8 (2.5)	4.9 (2.3)	4.5 (1.9)
Rise time* (in seconds)	10.4 (5.2)	9.6 (4.6)	9.8 (3.5)	9.0 (5.0)
Integrated compliance** (percentage)	57.1 (19.5)	59.0 (19.9)	44.3 (18.3)	39.0 (20.0)

Note. ATIS = Advanced Traveler Information Systems; *ns* = not statistically significant. Standard deviations in parentheses.

*$p < .05$. **$p < .001$.

Perceived driving performance was a subjective measure collected at the end of each scenario, with a minimum of 0 and a maximum of 100. The average number of crashes per hour was calculated by dividing the number of crashes in each scenario by the scenario duration. Turn-signal use was calculated as a percentage and was based on whether or not drivers used the turn signal as they changed lanes. The RMS measures of lane position and speed were calculated for the period immediately after the message was presented until the point at which drivers acknowledged the message. Because this time period was typically less than 3 sec, the RMS data may not provide stable or accurate estimates of how much the message may have distracted drivers. To enhance the sensitivity of the RMS measures, the analysis used the RMS data for the 5-sec period just prior to the message presentation as a covariate.

Table 5 shows that information availability significantly affected three out of five measures of driving safety. Perceived driving performance was lowest and the number of crashes per hour was greatest when ATIS information was available without redundant road signs. RMS speed showed a different pattern, with the largest deviations in speed occurring when the driver was presented with the ATIS and redundant roadway information. A similar pattern was seen for the RMS lane position, but it failed to reach statistical significance. Turn-signal use did not show a statistically significant difference for information availability.

Table 6 includes data from all the situations in which drivers received an ATIS message, and so it combines data from all four conditions of information availability. Using the RMS data from the period just prior to the message onset as a covariate enhances the sensitivity of the RMS data and reduces the degrees of freedom from 16 to 15. Although the trend of all variables suggests that command messages undermined driving safety, only perceived driving performance and RMS speed reached statistical significance. None of the other safety-related variables showed a significant effect for message style. Similarly, there were no statistically significant main effects or interactions for message style, location, or mode.

Table 7 summarizes the effect of age on the five measures of driving performance. With the exception of perceived driving performance, all measures show lower levels of driving performance for older drivers. Interestingly, although all objective measures of driving safety indicate older drivers perform more poorly than younger drivers, older and younger drivers rate their own performance equally.

TABLE 5
The Effect of Information Availability on Driving Safety

Measure	*ATIS and Roadway*	*ATIS*	*Road*	*Neither*	*Significance Test*
Perceived driving performance	77.0 (17.8)	68.6 (23.0)	78.2 (17.5)	73.7 (22.1)	$F(2.19, 35.1) = 7.37, p < .001$
Crashes per hour	4.9 (10.7)	13.0 (17.9)	4.9 (10.9)	6.2 (14.8)	$F(2.71, 43.38) = 15.73, p < .0001$
RMS lane position (ft)	0.52 (0.38)	0.39 (0.30)	0.51 (0.42)	0.46 (0.30)	$F(3, 47) = 2.48, p > .05$
RMS speed (mph)	0.58 (0.57)	0.42 (0.46)	0.46 (0.38)	0.55 (0.58)	$F(3, 47) = 5.33, p < .005$
Turn-signal use	85.8 (31.4)	90.8 (26.5)	87.4 (28.6)	86.3 (31.3)	$F(2.39, 38.17) = 2.46, p > .05$

Note. Standard deviations in parentheses. ATIS = Advanced Traveler Information Systems; RMS = root mean square.

TABLE 6
The Effect of Message Style on Driving Safety

Measure	*Command*	*Notification*	*Significance Test*
Perceived driving performance	72.2 (18.8)	76.6 (21.9)	$F(1, 16) = 5.70, p < .05$
Crashes per hour	8.0 (15.1)	6.5 (13.5)	$F(1, 16) = 2.35, p > .05$
RMS lane position	0.49 (0.38)	0.44 (0.33)	$F(1, 15) = 4.22, p > .05$
RMS speed	0.54 (0.54)	0.46 (0.47)	$F(1, 15) = 5.33, p < .05$
Turn-signal use	84.3 (29.6)	86.1 (29.4)	$F(1, 16) = 1.04, p > .05$

Note. Standard deviations in parentheses. RMS = root mean square.

TABLE 7
The Effect of Age on Driving Safety

Measure	*Younger*	*Older*	*Significance Test*
Perceived driving performance	74.0 (19.8)	74.2 (19.7)	$F(1, 16) = 0.05, p > .05$
Crashes per hour	4.4 (10.3)	10.1 (16.9)	$F(1, 16) = 8.14, p < .05$
RMS lane position	0.40 (0.28)	0.54 (0.41)	$F(1, 15) = 18.18, p < .001$
RMS velocity	0.38 (0.37)	0.62 (0.59)	$F(1, 15) = 7.78, p < .05$
Turn-signal use	95.1 (21.3)	75.3 (36.9)	$F(1, 16) = 5.86, p < .05$

Note. Standard deviations in parentheses. RMS = root mean square.

Similar to compliance, driving safety was affected by the availability of ATIS messages. The availability of ATIS messages increased compliance, but when it was presented without redundant roadway signs it decreased safety. A similar pattern was seen for message style. Command messages induced greater compliance but also undermined safety. As with compliance, the message characteristics of mode and location had little influence.

Trust in the ATIS and Self-Confidence

Past research has shown trust and self-confidence to be important intervening variables that mediate reliance on automation in general (Lee & Moray, 1994), and ATIS devices in particular (Kantowitz, Hanowski, & Kantowitz, 1997). In this experiment, understanding variations in trust and self-confidence could illuminate the processes that governed compliance with ATIS messages.

Figure 4 shows that trust and self-confidence were affected by information availability, $F(2.6, 40.92) = 36.0, p < .001$, for trust, and $F(2.1, 32.8) = 6.6, p < .005$, for self-confidence. Trust was lower when ATIS information was unavailable and self-confidence was lower when roadway information was not available. This result shows that drivers differentiated between trust of the

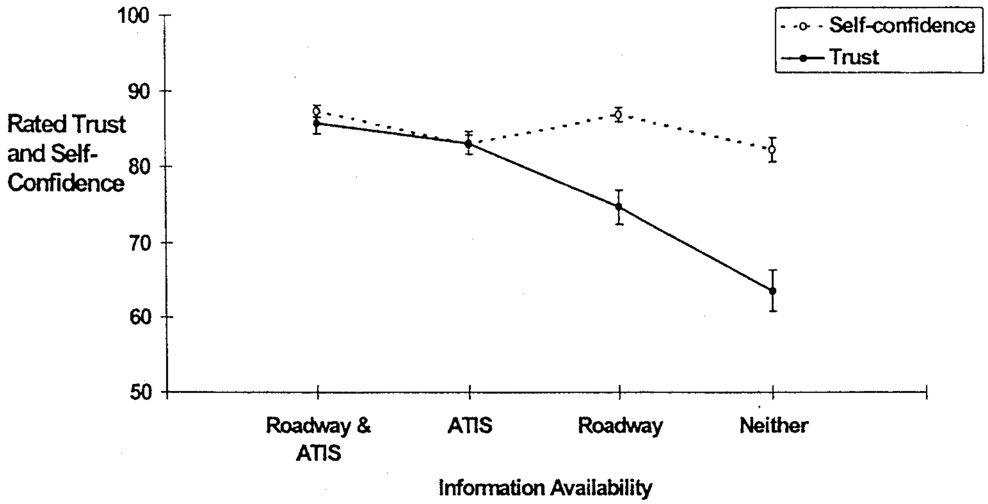

FIGURE 4 The effect of information availability on trust and self-confidence. ATIS = Advanced Traveler Information Systems.

ATIS and self-confidence in their abilities to extract information from the roadway. Interestingly, trust was much more sensitive to information availability than was self-confidence.

A strong interaction between information availability and driver age shows that younger drivers were more sensitive to the reliability of the ATIS, $F(2.6, 40.9) = 7.1$, $p < .005$. When both ATIS and roadway information were available, the mean level of trust was nearly equivalent for older and young drivers, 85.8 and 85.6, respectively. When only ATIS information was available, older drivers remained at the same level ($M = 85.8$), but young drivers' trust dropped to a mean of 80.6. In the situation in which only roadway information was available, or for those in which neither roadway nor ATIS information was available, the mean level of trust for older drivers in the ATIS was 83.6 and 72.7, respectively. In contrast, the mean level of younger drivers' trust in the ATIS dropped to 66.0 and 54.6, respectively. Older drivers' trust in the ATIS was less sensitive to changes in the reliability of the ATIS, compared to younger drivers.

Figure 5 shows a two-way interaction between information availability and message style in which drivers' trust in the ATIS was lower when drivers were forced to rely on command messages and when no roadway information was available, $F(1.97, 31.82) = 5.55$, $p < .005$. However, trust in both message styles declined to approximately the same level when in-vehicle information was not available. Message mode also interacted with information availability to affect trust, $F(1.99, 31.82) = 5.55$, $p < .01$. Figure 6 shows that when ATIS messages were unavailable, drivers' trust in auditory messages declined more than trust in the text messages.

Overall self-confidence was unaffected by message style, $F(1, 16) = 1.17$, $p > .05$. However, the interaction between message style and information availability showed that, similar to trust in the ATIS, self-confidence was lower when drivers were forced to rely on command messages, $F(2.4, 39.0) = 3.42$, $p < .05$. Figure 7 shows that command messages diminished self-confidence when drivers had ATIS information without redundant road signs. Self-confidence for both message styles was approximately equal in those situations in which drivers were not forced to rely on ATIS information.

Drivers' trust and self-confidence responded to information availability in an orderly manner, with trust declining when the ATIS did not present warnings reliably and self-confidence declin-

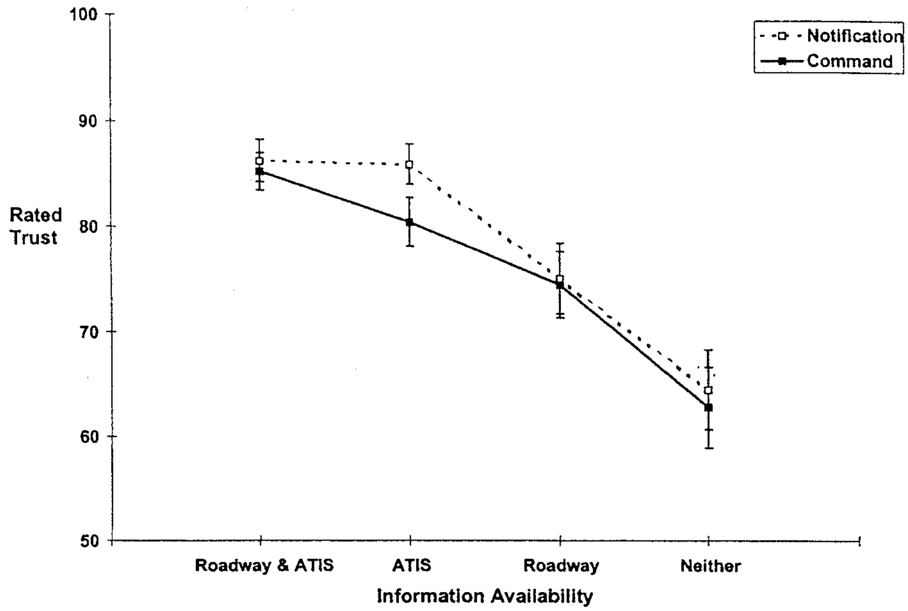

FIGURE 5 The effect of information availability and message style on trust in the Advanced Traveler Information Systems (ATIS).

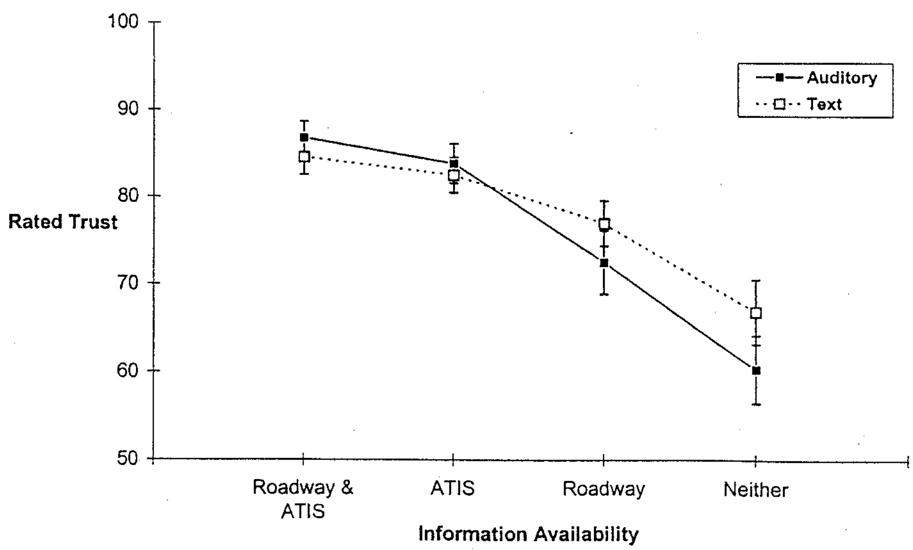

FIGURE 6 The effect of information availability and message mode on trust in the Advanced Traveler Information Systems (ATIS).

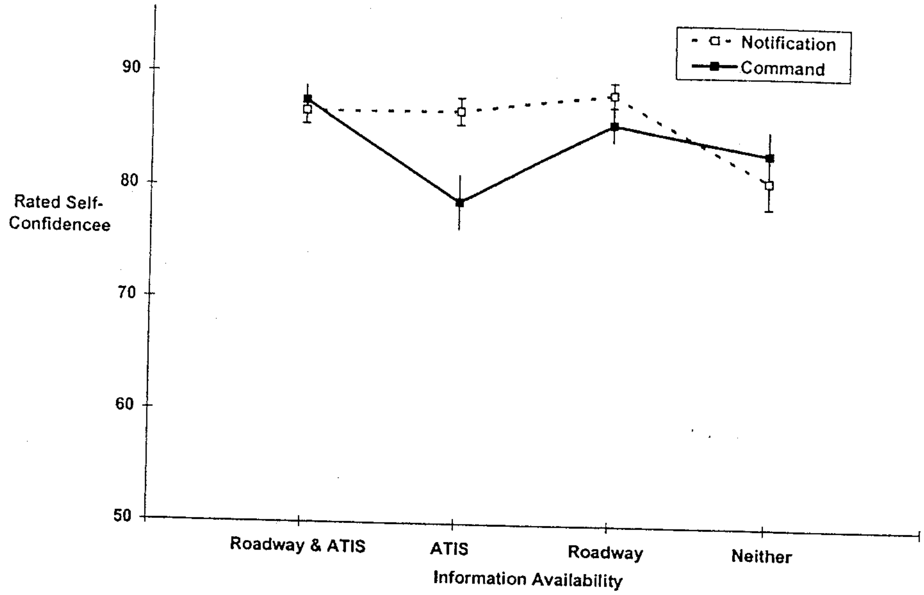

FIGURE 7 The effect of information availability and message style on self-confidence. ATIS = Advanced Traveler Information Systems.

ing when road signs were not available. The lower level of trust and self-confidence when command-style ATIS messages were presented without redundant road signs parallels the effect of command-style messages on driving safety.

SA, Workload, and Message Acknowledgment

SA, workload, and message acknowledgment are important intervening variables that may illuminate the influence of ATIS messages on driving safety. The analysis of message acknowledgment examined only those cases in which drivers received both ATIS and roadway information, and thus, information availability was replaced by acknowledgment type (acknowledgment of ATIS messages vs. road signs) in the ANOVA. Message acknowledgment can be considered as a secondary task that also identifies how quickly drivers process in-vehicle and roadway information.

Figure 8 shows that information availability had a strong effect on SA, with the lowest levels of SA occurring when in-vehicle messages were presented without redundant roadway information, $F(2.59, 41.50) = 27.41$, $p < .0001$. These results paralleled the trends observed for the measures of driving safety. In addition, Figure 8 shows a two-way interaction between age and information availability in which the effect of information availability on SA was greater for young drivers, $F(2.59, 41.5) = 4.64$, $p < .01$. SA for younger drivers was greater than that of older drivers in all cases, except when in-vehicle information was presented without redundant roadway signs. In this situation, younger drivers' SA dropped below that of older drivers. Message characteristics and their interactions did not have a statistically significant effect on SA.

Drivers' ratings of mental and physical effort showed no main effects for message characteristics and only two interactions. Physical demand showed a marginally significant interaction between message modality and style, $F(1, 16) = 4.77$, $p < .05$. This interaction reflected a higher mean rating of physical effort for auditory notification messages (37.21) compared to text-based notification messages (34.23), whereas the mean rating for text-based command messages

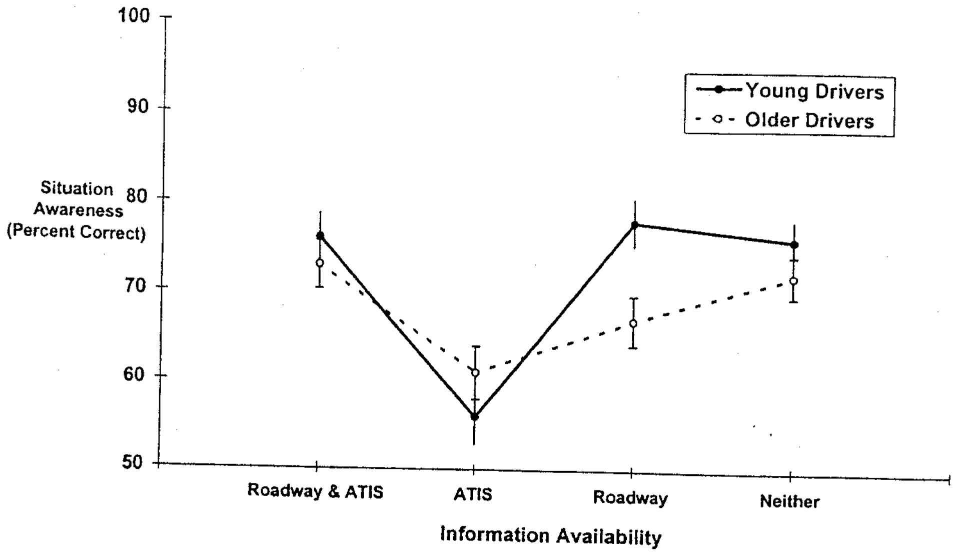

FIGURE 8 The effect of information availability and driver age on situation awareness. ATIS = Advanced Traveler Information Systems.

(35.06) and auditory command messages (35.02) were almost identical. Although the ratings of mental and physical effort were not sensitive to message characteristics, they were sensitive to differences in driver age. Older drivers had a mean rating of mental effort of 64.5, compared to a mean rating of 35.2 for younger drivers, $F(1, 16) = 20.21, p < .0001$. Like mental effort, physical effort also showed a strong effect due to age, with older drivers having a mean rating of 55.3 compared to a mean rating of 15.5 for younger drivers, $F(1, 16) = 41.68, p < .0001$. Age interacted with message style, where young drivers showed lower mean levels of mental effort with notification messages (33.3) compared to command messages (37.1). Older drivers showed the opposite pattern, with more effort for notification messages ($M = 66.1$) and less effort for command messages ($M = 62.8$), $F(1, 16) = 9.29, p < .01$.

Message acknowledgment latency showed no statistical differences for any message or driver characteristic. The percentage of messages to which drivers correctly responded did show several interesting effects. There was a main effect for age. Younger drivers correctly acknowledged messages more often than older drivers, 95.5% compared to 80.5%, respectively, $F(1, 16) = 24.46, p < .001$. There was also a main effect for message modality. Drivers responded to text-based messages more often than they did to auditory messages, 92.0% compared 85.4%, respectively, $F(1, 16) = 6.38, p < .05$. Message acknowledgment accuracy also depended on whether drivers were acknowledging a road sign or an in-vehicle message, but only in an interaction with age and ATIS message mode, $F(1, 16) = 7.09, p < .05$. In Figure 9, the data labeled "Roadway Auditory" refer to the percentage of correct acknowledgments of road signs when drivers were presented with an auditory ATIS message. Figure 9 shows that young drivers almost always responded to in-vehicle messages and that they failed to respond to road signs most frequently when they were presented with an auditory in-vehicle message. Older drivers showed a different pattern, failing to respond to in-vehicle auditory messages most frequently. Acknowledgment accuracy also depended on whether it was a road sign or an in-vehicle message through an interaction between ATIS mode and style, $F(1, 16) = 5.96, p < .05$. Figure 10 shows that drivers were more likely to respond to text-based command messages than auditory command messages.

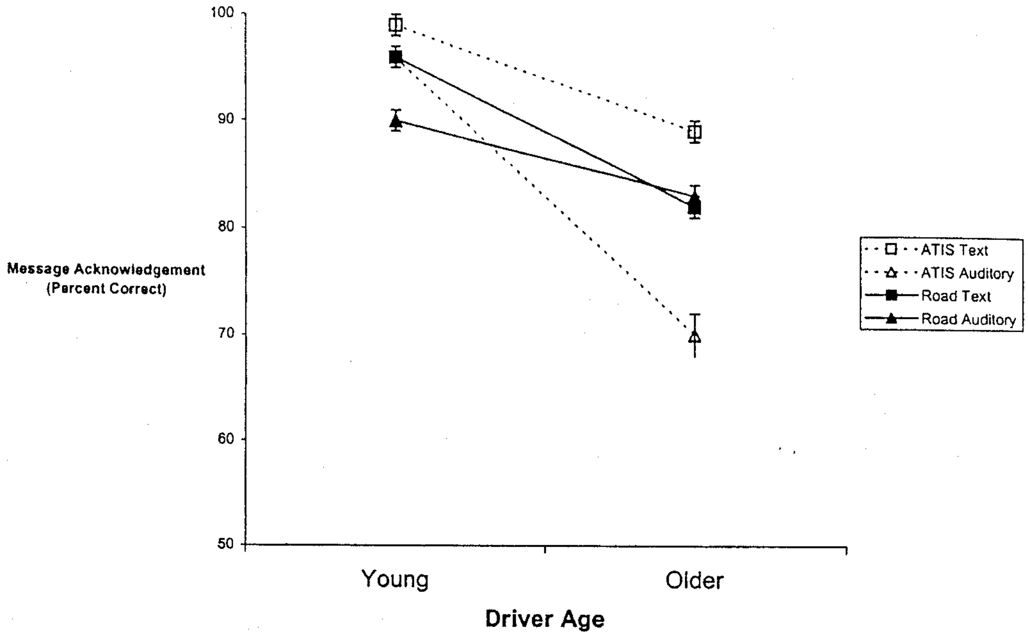

FIGURE 9 The effect of age and message modality on drivers' acknowledgment of in-vehicle messages and road signs.

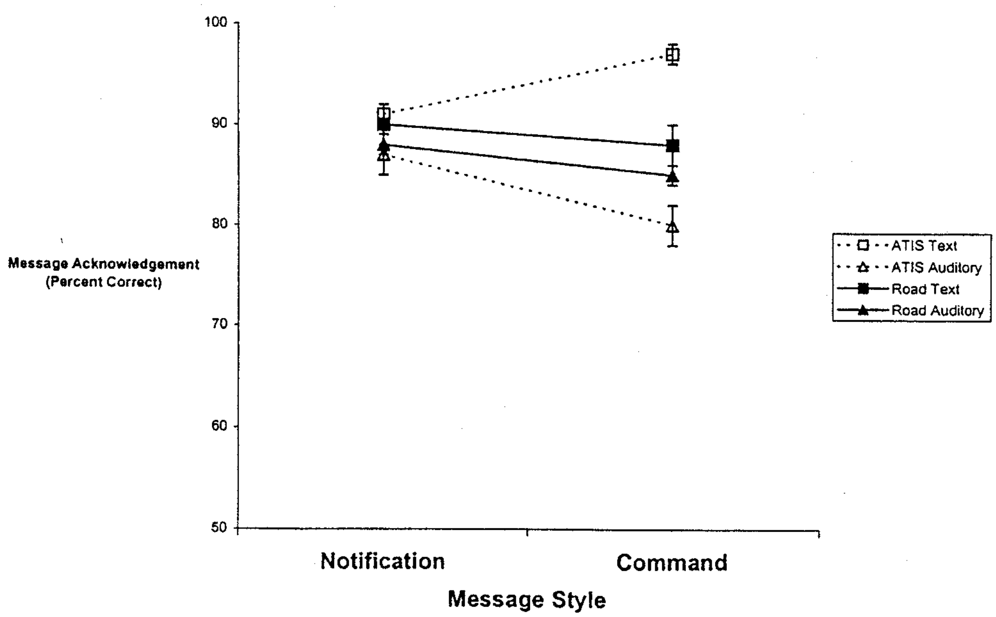

FIGURE 10 The effect of message modality and message style on drivers' acknowledgment of in-vehicle messages and road signs.

The powerful effect of information availability on SA parallels the effect of information availability on safety. ATIS messages presented without redundant road signs led to low levels of SA. Measures of workload were sensitive, as shown by the effect of age, but were not affected by message characteristics. Measures of workload did not respond to information availability in the same way as SA. Workload remained at a relatively low level when driving safety declined as ATIS messages were presented without redundant road signs. Measures of message acknowledgment showed a pattern of results that was different from both SA and workload.

DISCUSSION

A single experiment conducted in a low-fidelity driving simulator cannot provide a definitive description of how the design parameters of an in-vehicle system affect driver behavior and system performance. However, the results of this study suggest important relations that have practical and theoretical implications. Further empirical verification of these findings is needed, but the initial results merit consideration in the design and evaluation of in-vehicle information systems. The results of this study show that message style and its interaction with message modality and location have important effects on warning compliance and driving safety. Examining the influence of these design parameters on important intervening variables provides deeper insight into the cognitive mechanisms that underlie their effects on driver performance. This discussion of results focuses on three important design considerations: (a) the effect of redundant road signs on the interpretation of in-vehicle messages, (b) the effect of message characteristics (style, mode, and location), and (c) the interaction of driver age and gender with these design parameters. The discussion concludes by addressing two important ways that in-vehicle systems may undermine driving performance.

Redundant Roadway Information

In-vehicle displays have many advantages over standard road signs, such as the ability to display dynamically changing messages in a way that is not obscured by fog or rain. These advantages provide some incentive to replace or supplement road signs with in-vehicle messages; however, the consequences for driver safety and compliance are currently unknown. Driver response to in-vehicle messages could be quite different if in-vehicle messages become the primary source of information, compared to the current situation in which road signs are the primary source of information. This experiment takes a first step toward addressing this issue.

The results of this experiment suggest that redundant roadway information makes an important contribution to how people respond to in-vehicle messages. Redundant information does not affect compliance with messages, but it does affect driving safety and several intervening variables that govern safety and reliance on ATIS. Specifically, results show that safety, as measured by the number of crashes per hour and by perceived driving performance, was worst when ATIS information was presented without redundant road signs. The effect of redundant information on SA helps explain these results. Like driving safety, SA was worst when ATIS information was presented without redundant road signs. SA can be thought of as an intervening variable that describes how well drivers direct their attention to performance-relevant information in the environment. As such, a drop in SA may reflect an inappropriate distribution of attention, or information processing demands that exceed the drivers' capacity. Because mental workload remained at a relatively low level as SA dropped, it appears that safety declines because the in-vehicle message led drivers to distribute their attention inappropriately. Thus, it seems that ATIS messages presented without redundant road signs may have led to inappropriate distribution of attention and to lower SA and safety.

Trust and self-confidence also illuminate the effect of redundant roadway information on driver behavior. Overall trust and self-confidence responded to the availability of ATIS and roadway information as expected, with trust declining when the ATIS information was not available and self-confidence declining when roadway information was not available. These results provide further evidence that trust is a useful construct for describing human interaction with technology (Kim & Moon, 1998; Lee & Moray, 1992, 1994; Milewski & Lewis, 1997). Similar to safety, trust and self-confidence were also affected when in-vehicle messages were presented without redundant roadway information. In particular, when drivers received command messages, trust declined if ATIS messages were presented without redundant road signs, but this effect did not occur when drivers received notification messages. A similar pattern occurred for drivers' ratings of self-confidence—self-confidence declined when ATIS command messages were presented without redundant road signs. The combination of lower levels of trust and self-confidence placed drivers in a double-bind situation in which they neither trusted the system to provide good information nor were they confident in their own abilities. No research has examined how such a situation might affect drivers' ability to use technology effectively, but double-bind situations generally undermine humans' adaptive behavior.

These results suggest that in-vehicle messages should be accompanied by redundant road signs, such as changeable-message signs, when possible. This tentative finding requires additional experimental confirmation before strict design requirements can be defined. Because complete replacement of road signs with in-vehicle messages is, at best, many years in the future, this initial finding simply identifies an issue that should be considered as technology advances.

Message Characteristics: Style, Mode, and Location

The message characteristics of mode and location had a surprisingly small effect on driver safety and compliance. Neither of these design characteristics directly affected either driving performance or compliance. Coding message content by display location showed no performance benefit in this study, and other research suggests it may even undermine performance (Wallace & Fisher, 1998). In contrast, message style did have an effect on several important variables. Message style, defined in terms of notification versus command messages, had a significant effect on compliance, with command messages inducing 20% more compliance than notification messages. However, command messages were also associated with lower levels of driving safety. These results require confirmation with further empirical data, but they suggest that message style is an important design parameter that can enhance compliance but undermine safety.

Message modality did not affect driving performance as might have been expected from previous research (Matthews, Sparkes, & Bygrave, 1996; Sorkin, 1987; Wickens, 1992). Visual text messages did not seem to distract drivers or induce higher workload. This result may reflect the relatively modest demands of the primary task of driving and the low visual demands associated with the simple text message. Message modality and style did interact with age to affect message acknowledgment. A lower rate of message acknowledgment for auditory messages by older drivers suggests that age-related hearing loss might impair older drivers' ability to respond to auditory messages. The interaction between message style and message mode showed that text-based command messages produce a more reliable response than auditory messages, consistent with the visual superiority effect discussed by Wickens (1992), in which visual displays are attended to in favor of auditory displays. It is unclear why this effect manifested only with command messages.

Message modality interacted with information availability. Trust declined more with an unreliable ATIS that presented auditory messages compared to an unreliable ATIS that presented text messages. This interaction presents designers with another consideration when deciding between display modes. This finding suggests that to preserve trust, text displays should be used for potentially unreliable information, whereas auditory messages may be used for reliable systems. Preserving trust in the system will likely enhance user acceptance. This tentative finding merits additional study because it might be an important design consideration, particularly when current design guidelines do not make strong recommendations for a specific display mode.

The Interaction of Driver Characteristics With Design Parameters

A particular choice of design parameters may be appropriate for one type of driver and not for another. In particular, driver expertise, objectives, and individual styles may all result in different design requirements. Age is one of the most important driver characteristics that should be considered in design. This study found that driver age had a large impact on many measures of driving safety. Interestingly, age did not affect compliance, but it did have a significant effect on all measures of driving safety, except perceived driving performance. The lack of an effect on perceived driving performance suggests that older drivers may not be aware of their impairments or may have different norms in evaluating those impairments. Older drivers reported a much higher mental and physical effort compared to younger drivers. These effects suggest that differences in information processing capacity may have contributed to the lower levels of driving performance seen in the older drivers in this experiment (Brouwer, Waterink, Van Wolffelaar, & Rothengatter, 1991). Interestingly, the effect of driver age on SA did not reach statistical significance.

The interaction of age and information availability showed that in some ways older drivers might have been more prepared to adapt to new technology than younger drivers. When ATIS information is presented without redundant roadway information, the SA of younger drivers declined more than that of older drivers. This suggests that older drivers may be better able to distribute their attention between the roadway and the ATIS, a result that is consistent with other studies of experienced and inexperienced drivers that found that experienced drivers distribute visual attention according to the complexity of the roadway and that inexperienced drivers are less flexible (Crundall & Underwood, 1998). Similarly, experienced drivers divided their visual attention between in-vehicle and roadside information more appropriately, compared to inexperienced drivers (Wikman, Nieminen, & Summala, 1998). These results have important implications for driver training, particularly as in-vehicle technology proliferates.

Age also interacted with message style, suggesting that successful ATIS designs may need to consider demographic characteristics of drivers. Moreover, older drivers showed greater levels of trust in the ATIS and their trust declined less when the reliability of ATIS messages declined. Older drivers also showed lower levels of mental effort when they received command messages and higher effort with notification messages. These preliminary results require careful interpretation and do not provide the basis for design guidelines but suggest that older and younger drivers may respond to in-vehicle technology quite differently. Such interactions show that driver demographics can make an important contribution to how a product is perceived and used. This experiment demonstrated that driver age is an important determinant of driving performance and reaction to in-vehicle technology, but other driver characteristics may be even more important.

Specifically, professional drivers may respond to certain technology quite differently than the drivers who participated in this study.

Potential Failure Modes Associated With Driver Response to In-Vehicle Information Systems

Drivers can fail in many ways. Moray (1981) identified several ways in which failures of attention can undermine system performance. Two examples include cognitive tunnel vision, in which people concentrate on some variables at the exclusion of others, and information overload, in which people are swamped with so much information that it exceeds their processing capacity. Many safety-related concerns associated with in-vehicle technology have focused on exceeding drivers' information processing capacity. The worry is that the proliferation of in-vehicle devices will overwhelm drivers with information and detract from their ability to respond to the demands of lane keeping and speed control (Dingus, Antin, Hulse, & Wierwille, 1989; Mollenhauer, Hulse, Dingus, Jahns, & Carney, 1997; Verwey, 1993). Others have argued that in-vehicle devices may undermine driving performance in a more subtle way (Noy, 1990; Perez & Mast, 1992). Instead of being overwhelmed with information, in-vehicle technology may interfere with the distribution of drivers' attention, a problem similar to that of cognitive tunnel vision described by Moray (1981). Drivers may inadvertently direct their attention away from the roadway to the inside of the vehicle.

The results of this study suggest that ATIS information can undermine driver performance through poor distribution of attention. Specifically, performance is lowest when ATIS information is presented without redundant roadway information. Low levels of SA in this condition, combined with modest levels of workload, suggest that driving safety was not compromised by the ATIS messages exceeding the information processing capacity of the driver. Rather, it seems possible that the ATIS undermines performance by enticing drivers to allot a disproportionate amount of their attention to the in-vehicle messages rather than to the roadway. A recent simulator study (Matthews et al., 1996) of driving performance produced similar results; driving performance appeared to be constrained by executive processing associated with managing goals rather than by general information processing demands. Although the results of this experiment are not conclusive, they suggest that ineffective distribution of attention is a potential failure mode that merits consideration along with information overload.

Several recent studies parallel these findings and show that decision aids can undermine performance by inducing an ineffective distribution of attention. Specifically, a financial decision-making aid used by inexperienced decision makers led to seemingly mechanistic responses to the aid's guidance, with decision makers failing to become actively involved in the task or judgment (Glover, Prawitt, & Spilker, 1997). In such cases, an aid will enhance performance when it provides valid advice but will undermine performance when its advice is not valid. Similarly, cuing targets in a visual detection task can enhance detection of expected targets but can also undermine detection of uncued targets (Yeh, Wickens, & Seagull, 1998). Falsely cued targets can also lead people to incorrectly identify targets (Conejo & Wickens, 1997). Performance can also be impaired when a decision aid provides inaccurate information as a recommendation rather than as a status indicator (Crocoll & Coury, 1990). In our experiment, the ATIS did not present any misleading information, although it is certainly possible for actual systems to do so. For example, navigation systems might mistakenly instruct drivers to turn the wrong way down one-way streets. Extrapolating from these studies suggests that command messages might further undermine safety if they provide drivers with misleading or incorrect information. The results of these studies suggest that future evaluations of in-vehicle technology should consider how command and notification message styles might induce an ineffective distribution of attention and undermine safety.

CONCLUSIONS

Ideally, in-vehicle messages should improve compliance with warnings without compromising driver safety; however, the results of this study on in-route IVSAWS and ISIS messages suggest that several combinations of design parameters may actually undermine safety. The findings may also apply to route-guidance messages, but their applicability should be tested. Furthermore, as they are based on the results of a single experiment, further investigation is needed to confirm them and establish the limits of their application to ATIS design. Without redundant roadway signs, safety may decline when information is presented by in-vehicle message systems. Compliance with in-vehicle messages is greatest with command-style messages, but this message style also seems to reduce safety and undermine trust in the system and self-confidence. The decline in safety seems to be caused by an inappropriate distribution of attention, rather than to an overload of the driver's information processing capacity. Although strong design recommendations cannot be drawn from this study, initial design considerations can be identified. The findings suggest that message style should be considered as a potentially important design parameter along with message modality. In addition, effective distribution of attention should be considered in system evaluation along with information processing capacity. These conclusions must be tempered by the limits of the study and the challenges of generalizing the findings to actual systems.

The automotive simulator used in this study is a relatively low fidelity simulator, which can be considered a "microworld" (Brehmer & Dorner, 1993). As a microworld, the simulator presents the driver with many of the demands and circumstances faced in actual driving scenarios; however, the limited field of view, low resolution of images, and the novelty of the ATIS messages limit generalizability of the results. Specifically, the in-vehicle messages may be salient compared to the relatively sparse roadway environment of the simulator. In an actual car, these messages may be less salient compared to the rich array of information available in the actual roadway. It is possible that these differences could induce a safer and more appropriate use of ATIS information, reducing the tendency of drivers to neglect roadway information when faced with the salient in-vehicle information, such as the command-style message. This possibility was explored in a recent on-road experiment (Kantowitz, Hooey, & Simsek, 1998) examining command messages. The results confirmed our findings, with command messages leading drivers to neglect important roadway information. This replication confirms the importance of message style in ATIS design and suggests that low-fidelity simulators replicate psychologically important aspects of the driving task.

Identifying the engineering and safety relevance of the results of this experiment presents an important challenge. The data show many statistically significant results, but whether these data reach levels of practical significance is an important concern. A related issue is the relation between measures of driver behavior in this experiment and measures of system effectiveness and safety that might concern a designer or highway engineer. This question was posed over 30 years ago (Chapanis, 1967) and a definitive answer has yet to emerge (Dingus, 1995; Parkes & Franzen, 1993; Smiley, 1996). Our study adopted several measures of driving performance as surrogates for safety and drew conclusions from several statistically significant results. Many of the effects observed in this study are quite large in an absolute sense and are likely to have important implications for overall measures of system effectiveness. For example, in-vehicle messages increased compliance by over 30%, compared to road-sign messages alone. Similarly, command messages increased compliance by over 20%, compared to notification messages. At the same time, the absence of redundant road-sign information led to a 160% increase in crashes, a 10% decline in perceived driving performance, and a 20% decline in SA. Trust declined 25% with variations of ATIS information reliability and 5% to 10% due to message style and modality. These differences suggest that these variables could have an important effect on actual driving behavior and safety.

The specific relevance of these effects for highway safety and for effectiveness of deployed systems is difficult to estimate, but a pair of studies offers a point of comparison. The first study (van der Horst & Hoekstra, 1994) used a simulator to investigate road design modifications to reduce speeds on two-lane rural roads. This study found statistically significant speed reductions of 5% to 10% in the simulator. A subsequent field study (van der Horst, 1997) at four locations showed a relatively modest speed reduction—2 kph—but a 20% decrease in accidents, compared to an 8% increase in accidents at control locations over a 2-year period. Thus, relatively modest effect sizes can have important safety consequences, suggesting that the results of this study may have important practical implications for system design.

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