The Effect of Directional Auditory Cues on Driver Performance in a Simulated Truck Cab Environment

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(ABSTRACT)

A human factors experiment was conducted to investigate the potential benefits of using directional auditory cues in intelligent transportation system technologies in commercial vehicles. Twelve licensed commercial vehicle operators drove a commercial truck-driving simulator and were prompted to select highway numbers on a side-task display. Prompts were presented visually or aurally. Auditory prompts were presented either diotically (both ears simultaneously) or directionally (to either the left or right ear). The search task varied in map density and timing of the prompts in relation to speed limit changes. All experimental conditions were compared to a control condition containing no secondary task. Both driving performance (lane deviation, steering wheel angle, road heading angle error, accidents, and adherence to the speed limit) and secondary task performance (accuracy and response time) measures were collected. Results showed that drivers were able to respond more quickly and accurately to the search task when directional auditory cues were used. Results also showed that driving performance degrades when display density increases and that the use of directional auditory prompts lessens this deterioration of performance for high-density conditions.

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INTRODUCTION

Recent advances in vehicle information systems have led to the introduction of numerous highly technical systems designed to provide commercial vehicle drivers with information intended to increase safety, improve comfort, and reduce operating costs. It is important that these systems be designed in ways that will not adversely affect driving performance. A human factors experiment was conducted to systematically test the utility of auditory prompts for an in-vehicle navigation display search task. The experiment was performed on a fixed-base driving simulator configured to emulate the physical configuration and performance characteristics of a Class 8 commercial tractor-trailer. The simulator was located in the Auditory Systems Laboratory at Virginia Polytechnic Institute and State University. The goal of this human factors experiment was to help optimize the integration of advanced systems.

Americans' dependence on vehicular transportation has created a burden on the nation's roadway infrastructure, reflected both in the congestion of the daily commute to work, and the increased usage of the interstate highway system. In 1989, United States traffic levels climbed to over two trillion vehicle-miles. These levels are expected to increase by four percent per year leading to an estimated four trillion vehicles-miles in the year 2020 (Banks, 1991). With the growing number of private vehicles and an increased dependence on commercial trucks to transport consumer goods, it will be impossible to build enough new roads to meet the projected demand. The United States Department of Transportation is therefore investigating alternative solutions aimed at alleviating the substantial traffic problem (Committee on Public Works and Transportation, United States House of Representatives, 1989; Highway Users Federation, 1993).

Extensive research is currently being conducted to increase the efficiency of private and commercial vehicles. One of the fastest growing areas of research in human factors is concerned with the design and development of Intelligent Transportation Systems (ITS). The mission of ITS is to improve the safety and traffic flow efficiency of both commercial and private vehicles. The ITS mission is currently being accomplished in great part by the National Highway Traffic Safety Administration (NHTSA) and the

Federal Highway Administration (FHWA) funding of the Intelligent Vehicle Initiative (IVI), a government funded research bill that focuses research on systems that will be in production within the next five years (Intelligent Vehicle Initiative Human Factors Workshop, 1997).

The primary means of attaining these goals is through the use of advanced technologies such as road and vehicle sensors, high-speed dynamic communications systems, and electronic displays. ITS technologies are being researched and developed to assist commercial motor vehicle (CMV) operators with problems resulting from overcrowded roadways, information overload within the cab, navigation in unfamiliar locations, vehicle state (i.e., brake condition, tire air pressure), scheduling demands, and adverse weather conditions (Banks, 1991; Bishel, 1987; Chen and Ervin, 1989; Herman, 1990; Manuta, 1992; Schmidt, Wright, and Zwerner, 1990).

Human factors issues are present in all phases of ITS development. However, the most prevalent realm is that of in-vehicle systems requiring interaction with the driver. Driving is already a visually intensive manual control task, so incorporation of ITS information needs to avoid overloading the already heavily-loaded visual channel. It is critical that new driver interfaces be designed to meet the needs, capabilities, and limitations of the driver and the demands of the driving environment. Incorporating auditory cues into the these systems represents a relatively underutilized area of research.

To date, the majority of the ITS research has focused on systems for passenger cars. More recently, integration of ITS technology into Commercial Vehicle Operations (CVO) has started to receive more research attention (Bowers-Carnahan, 1991; Chen and Ervin, 1989; Perez and Mast, 1992). Major goals of ITS in CVO include increasing safety, decreasing vehicle operating and maintenance costs, reducing delivery time, and improving the communication link between driver and dispatcher (McCallum and Lee, 1993). The Federal Highway Administration has proposed that the efficiency of trucks and other vehicle fleets can be increased through the addition of vehicle identification, communications, and safety advisory systems (Manuta, 1992). Other envisioned ITS system features include per axle weight monitoring, dynamic decision aids, and vehicle state monitoring (Maggio, Maze, and McCall, 1992). Due to safety and economic advantages, the integration of ITS technology into the commercial truck cab has already begun to take place, as evidenced by the production of navigation systems (Alpine & Zexel), collision warning (Eaton VORAD), and fleet-management systems (Highway Master & Qualcomm). To ensure a safe roadway environment for both the truck driver and the vehicles with which he or she shares the road, it is extremely important to understand how the implementation of additional displays and controls will affect driver performance.

To maximize acceptance and safety of ITS technologies in CVO, designers must take into account the abilities and limitations of the drivers (Morlok, Bedrosian, Zarki, and Hallowell, 1989). A major focus of human factors engineering in ITS is to develop systems which do not result in excessive driver workload. Driving is predominately a visually-intensive manual control tracking task, requiring drivers to use their visual resources to successfully navigate and perform the driving task (Verwey, 1991). A second channel for presenting information to the driver that offers great potential is the auditory sensory modality. In building upon recent research, the hypothesis of this experiment was that the presentation of prompting messages in a directional auditory format will allow drivers to respond more quickly and in a safer driving manner to a search and select task than if the prompting messages are presented visually or with non-directional sound. To test this hypothesis, the experiment used a realistic driving scenario in a simulated commercial truck cab environment and prompted drivers (both visually and audibly) to select specific highway icons that appeared on a side map display.

BACKGROUND

The successful design, development, and integration of ITS components into commercial trucks is an extensive process. Experts from many different disciplines will be involved in the incorporation of all the various aspects of ITS into on-road systems. Human factors engineers will be involved in the development of systems which may require additional attentional demand and affect the vehicle navigation and control process. An important human factors goal related to the CVO domain is the optimization of the next generation of commercial vehicle driver interfaces. This can be accomplished by systematically applying relevant information concerning driver capabilities, limitations, behaviors, and motivations during all parts of the design cycle (Sanders and McCormick, 1993).

Attention Issues

Driver workload. One main reason human factors engineers are involved in the design of ITS components is the myriad of safety issues related to introducing additional displays and controls into the vehicle control process. Although driving can be a very demanding task, it can also be quite monotonous, to the extent that operators are known to fall asleep at the wheel. Commercial truck drivers encounter both conditions. They are at times under-loaded by the routine conditions of driving eight to ten hours per day on long stretches of interstate highways. On the other hand, truck drivers also have to attend to additional conditions such as air brake pressure, trailer sway, tire pressure, trailer brakes, load shifts, and braking limitations, all of which increase the driver's workload. Most workload requirements can generally be related to the size of the vehicle; smaller delivery trucks have workload requirements similar to normal passenger cars, while full-size commercial trucks have significantly greater workload demands, especially in regard to the vehicle control task. Although the size of the vehicle is clearly a large factor in the amount of driver workload, it is also important to understand the unique aspects of driving a smaller truck. Drivers of small commercial vehicles, such as delivery trucks, normally navigate through many different types of city streets (as opposed to driving mainly interstate routes) throughout the course of an average day. Although delivery truck drivers may know a specific area better than long haul drivers, they also have the greatest potential need for a navigation system due to their numerous stops each day. Because of the already high workload on commercial drivers, it is important to review aspects of human information processing to gain insight on how adding ITS technologies will affect driving performance.

Human information processing. Coren and Ward (1989) define information processing as "the processes by which stimuli are registered in the receptors, identified, and stored in memory." Any two individuals placed in the same situation would rarely interpret the events in exactly the same way. Examples of differences in interpretation can be seen in many aspects of daily life, from how two students would interpret a lecture, to how two witnesses would describe the same event. A simplified model of human information processing consists of inputs from the environment, sensory memory, short-term memory (working memory), and long-term memory (Gordon, 1994).

Inputs from the environment register in the body's sensory receptors. All physical senses (tactile, olfactory, visual, auditory, and taste) have the ability to capture our attention at any time. Tactile sensations, such as changes in pressures or vibrations can alert a driver to a change in road surface conditions. Auditory cues, such as alarms or the horn of an approaching vehicle often attract a driver’s attention. However, despite these examples, driving relies most heavily on the sense of sight to navigate safely through an environment. The obvious concern about adding more displays into the truck cab is that they will draw attention away from the primary task of driving, while simultaneously increasing the operator's visual workload, and consequently increasing the likelihood of accidents. Wickens (1992) provides a more in-depth description of how humans process information, Figure 1.

One of the key areas in the information processing model is the allocation of attentional resources. Wickens (1992) states "when performing any task, different mental operations must be carried out (responding, rehearsing, perceiving, etc.) and performance of each requires some degree of the operator's limited processing resources." In the event that operators do not have sufficient processing resources available to simultaneously perform all of the required tasks, the operator divides (or time-shares) his or her attentional resources.

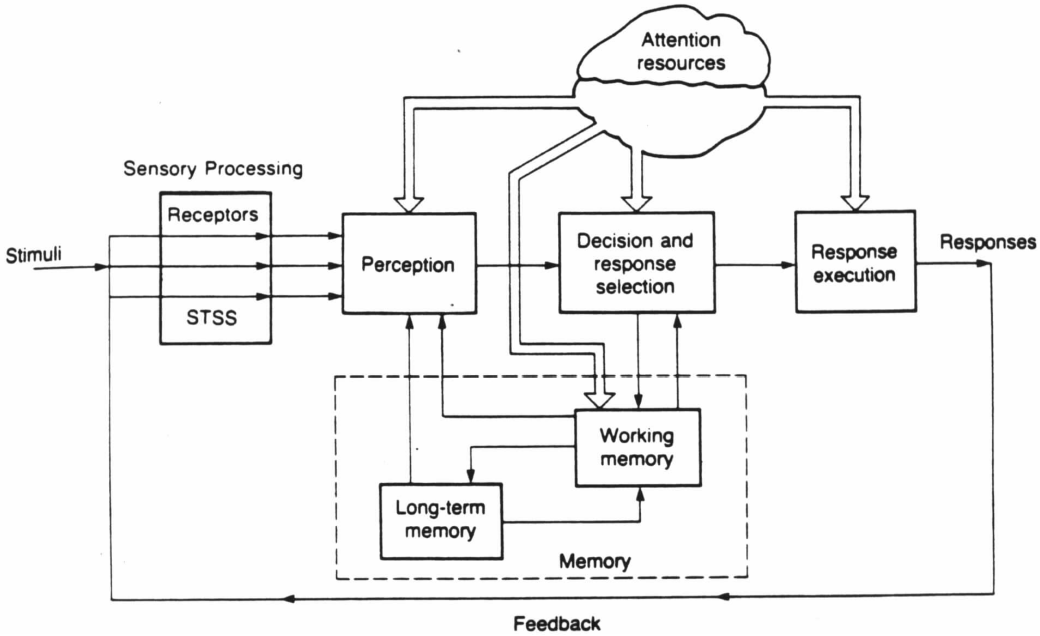


Figure 1. A model of human information processing.

(adapted from Wickens, 1992)

Driving is a complex task that requires an operator to divide his or her visual attention in order to perform activities such as adjusting the car stereo or checking the speedometer. Although time-sharing is sometimes done at the driver's convenience, some of the proposed ITS devices could immediately demand a driver’s attention, which could lead to overloading the driver’s attentional resources, and therefore compromise driving safety. Research on secondary task loading is a good example of what can happen when an operator is overloaded. One problem with introducing secondary tasks (such as interacting with a navigation system) into the commercial truck cab is that they may interfere with and disrupt performance of the primary task (Wickens, 1992). Before introducing new information into the truck cab, system designers and engineers need to determine if processing this new information will compromise normally safe driving practices.

Verwey (1991) tested driver workload in specific driving situations and found that when overloading the visual modality (via a visual secondary task) drivers' performance decreased even though their cognitive abilities as a whole were not overburdened. Verwey also found that "under certain circumstances, probably involving high levels of visual load, drivers may look at visual messages without interpreting them" (emphasis added). This implies that drivers (if overloaded) might view things in the environment which are critical to their driving performance without realizing their potential significance. Thus, it is extremely important that ITS technologies not overload the drivers.

Simultaneous processing of information divided between two or more visual (or two or more auditory) tasks decreases performance very rapidly (Coren and Ward, 1989). Divided attention is eased when the sources of information are directed to different sensory modalities (such as vision and audition). Although it is still difficult to process information from multiple channels, it is important to note that with adequate repetition, some tasks which previously demanded considerable attention become more automatic and can be performed with little or no attentional requirements (Anderson, 1990; Coren and Ward, 1989).

For example, Schneider and Shiffrin (1977) tested the ability to visually scan for letters or numbers and found that if the target was in a different category (the target was a letter and other characters were numbers, or vice-versa), the time to reach 95 percent accuracy was five times quicker (80 ms verses 400 ms) than if the target was in the same category. They attributed this difference to the fact that scanning for letters in a numerical background was already an automatic process. Shiffrin and Schneider (1977) tested the theory of automatic processing by having subjects practice searching for target letters within one set of letters (B, C, D, F, G, H, J, K, L) within the context of another set of letters (Q, R, S, T, V, W, X, Y, Z). Following 2100 trials, subjects were as efficient in the letter-only condition as they were when searching for a number target within a letter background. This result demonstrates that some tasks can become automatic with adequate repetition.

Driving tasks such as holding a steady speed, staying within a lane, and braking when approaching a red light are performed so frequently that they are usually done without conscious attention. Introducing new tasks, such as those related to ITS, into the truck cab will most likely initially require more attention because of the novelty of the activity. Once the driver becomes accustomed to the task, it will become part of the automatic repertoire. Ideally, ITS technologies will be designed so drivers will not need to divert their attention away from driving, and will often be virtually unaware of the new systems. On the other hand, it is a safe assumption that many ITS technologies will introduce new tasks that must be performed by the driver. These tasks should be designed to be unobtrusive and have applications requiring frequent repetition. Ideally, frequent repetition will enable these tasks to become automated processes. In addition, it is important to design the systems so that during the transitional learning process they do not consume the driver's attentional resources to the extent that driving performance is compromised.

Measurement techniques for driver workload. Cognitive processing of visual cues is very efficient, but is limited to one stimulus at a time. If navigation information is presented on a visual display, the driver must divert his or her attention away from the road to attain the navigational information. Extensive research has been conducted on driver's eye movements for several navigational devices. Although individual glances at a display may be as long as 4.80 s (Labiale, 1989), mean glance duration varied from 0.58 s (Verwey, 1991) to 1.66 s (Dingus, Antin, Hulse, and Wierwille, 1989). Mean glance duration variability may be due to differing experimental conditions (such as differing display complexities or locations) of each of the navigational displays tested. In a test of a moving-map navigational display, a strong positive relationship was found between display glance frequency and the percent of trials in which lane crossings occurred (Antin, Dingus, Hulse, and Wierwille, 1990). Furthermore, navigational displays incorporating auditory cues have been shown to decrease the frequency of glances to dashboard-mounted displays (Labiale, 1989; Walker, Alicandri, Sedney, and Roberts, 1991). This is an important finding which lends strength to the need for additional research to further investigate the benefits of auditory displays.

Stimulus Presentation Issues

Modality - Auditory versus visual. Deatherage (1972) offered general guidelines to help system designers decide when auditory displays are appropriate (see Table 1). These design guidelines lend strength to the argument for presenting information to the driver through the use of the auditory modality in some driving applications. Some examples of displays which may lend themselves to auditory presentation include: driver-dispatcher communication, collision avoidance warning devices, and critical vehicle status information systems. Because sound is omnipresent, the operator need not face the display to receive the information being presented. It is also important to decide whether to use speech or coded signals for presentation of auditory information. Table 2 specifies certain instances which are better for tonal or noise signals than for speech messages (Deatherage, 1972).

Retention - Auditory versus visual information. The limited capacity of working memory may also affect display modality selection. There are several techniques aimed at reducing load and increasing the efficiency of working memory. One classical method is information chunking. Miller (1956) defined the maximum number of items in working memory to be seven plus or minus two chunks of information. An example of chunking information can be seen in the grouping of telephone numbers for easy memorization. The numbers 9075551212 would be difficult for most to memorize in this

TABLE 1

Appropriateness of Visual or Auditory Presentation of Information (taken from Deatherage, 1972, p.124)

Use auditory presentation if:	Use visual presentation if:
The message is simple.	The message is complex.
The message is short.	The message is long.
The message will not be referred to later.	The message will be referred to later.
The message calls for immediate action.	The message does not call for immediate action.
The visual system of the person is overburdened.	The auditory system of the person is overburdened.
The receiving location is too bright, or dark-adaptation integrity is necessary.	The receiving location is too noisy.
The person's job requires continual movement.	The job requires the person to remain in one position.

TABLE 2

Choosing the Form of Auditory Presentation (adapted from Deatherage, 1972)

Use of tonal or noise signals is preferred over speech in the following conditions:

1. For simplicity.
2. When listeners are trained to understand coded signals.
3. For designating a point in time that has no absolute value.
4. When immediate action is desired.
5. In conditions unfavorable for receiving speech messages.
6. When security of the message is desired.
7. If speech communication channels are overloaded.
8. If speech will mask other speech signals or annoy listeners for whom the message is not intended.

Use speech rather than tonal or noise signals in the following conditions:

1. For flexibility.
2. To identify a message source.
3. When listeners are without special training in coded signals.
4. There is a necessity for rapid two-way exchanges of information.
5. The message deals with a future time requiring some preparation.
6. Situations of stress might cause the listener to "forget" the meaning of a code.

10-digit chain, but when broken up into an area code, a prefix, and a suffix, the number essentially becomes three chunks of information. Thus, the phone number (907) 555-1212 can be easily recalled.

Iconic memory (for visual information) and echoic memory (for auditory information) both have the ability to "hold onto" a briefly presented stimulus before the information is processed by working memory. Iconic storage usually lasts less than one second, while echoic storage can last for several seconds before the representation fades (Sanders and McCormick, 1993; Wickens, 1992). The longer retention time of auditory information lends strength to the argument of presentation of certain types of information via the auditory sensory modality.

Auditory versus visual presentation. It is also important to consider how auditory and visual cues differ with respect to directing a person's attention to a specific location. The auditory sense is good at localizing a sound source. A unique feature of the auditory domain is that a listener's head orientation does not affect his or her ability to localize sounds; listeners can process auditory information received from any source located in three-dimensional space. Conversely, the ability to acquire targets in the visual field is dependent upon head and eye orientation (Coren and Ward, 1989). Although the visual system does not allow simultaneous access of stimuli in a 360° domain, it is extremely accurate within a limited range. Once a target is found by visually scanning the environment, an exact location can be determined by focusing in on that target. By contrast, the auditory sense can provide only a general stimulus location. In terms of target acquisition, the auditory modality is very efficient in directing attention to the general area of the target, at which time vision can then search for the exact location of the stimulus (Makous and Middlebrooks, 1990). The ability to lead visual search via directional auditory messages has practical implications with respect to in-vehicle auditory displays. This was demonstrated by Micheal (1995a), who showed that response time to targets on a secondary task display was significantly reduced when drivers were given directional auditory cues.

Auditory displays in vehicles. There has recently been increased research emphasis on the development of auditory displays for many in-vehicle information systems. A few of the areas for which in-vehicle auditory displays could be used are collision avoidance warnings, route guidance information, severity of vehicle diagnostic warnings, and vehicle dynamic-state information. Additional research is needed to maximize the efficiency of this method of information presentation.

In an experiment comparing auditory and visual displays for an in-vehicle navigation system, Kishi and Sugiura (1993) presented auditory or visual cues telling the driver which way to turn at upcoming intersections. Although no reduction of individual glance duration was shown between verbal and visual conditions, glance frequency was reduced when verbal cues were presented, and thus the cumulative glance duration was reduced.

Heart rate data (beats/minute) were also collected during the experiment as a measure of mental workload. Drivers' baseline heart rates were collected while they drove on a straight stretch of road for 30 seconds. Experimental data consisted of drivers' heart rates collected over the 30 seconds preceding each turning point. Kishi and Sugiura (1993) found that subjects' heart rates were reduced near intersections when they were given auditory information as compared to when they were not given auditory information. However, the difference in heart rate between the control subjects and the ones with the auditory cue variable were not statistically significant. The results may have been significant had more drivers been tested (only four drivers participated in the experiment). Results of this study may have been further confounded because the experiment was conducted in a uncontrolled "on-road" environment, with traffic situations varying between subjects. Kishi and Sugiura (1993) recommended that a similar study be conducted in a controlled environment (i.e., a simulator or a test track) to validate their results.

Another source of information on auditory navigational displays comes from an extensive field test of the TravTek vehicle navigation and route guidance system. This experiment tested several methods of presenting navigational information. The goal of the TravTek study was to perform a detailed evaluation of driving and navigation performance, system usability, and safety of the TravTek system (Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman, 1995). Using both local and out-of-town drivers as subjects, participants were asked to drive to specific locations in the

Orlando, Florida metropolitan area using various configurations of the TravTek system. Experimental conditions included the TravTek route-map display, TravTek route-map display with supplementary voice guidance, TravTek symbolic guidance-map display, TravTek symbolic guidance-map display with supplementary voice guidance, paper map, and text-on-paper directions. The general results showed that the TravTek route-map display with supplementary voice guidance condition and the text-on-paper directions condition resulted in the best overall navigation performance. In contrast, the TravTek route-map without voice resulted in the most driving errors of all the conditions tested.

The TravTek study also provides an important glimpse into the types of errors committed by users of an advanced guidance system. Descriptions of these errors were broken down into general categories (braking, glance time over 2.5 s, merging or lane changing errors, intersections, etc.) and were assigned a potential severity (marginal, critical, catastrophic). Two hundred and ninety separate errors were reported in the final TravTek report (Dingus et al., 1995). Although specific causes of these driving errors were not reported, it is possible that time-sharing of attentional resources between the driving task and the navigational information may have contributed to some of the errors. A more controlled study of time-sharing associated with navigational prompts should be conducted to investigate driving performance at varying levels of driver workload to better understand driver errors.

Background noise levels. An important factor to consider when studying auditory displays is the background noise level present in the working environment. Therefore, during testing of auditory displays in the commercial truck cab environment, it is necessary to mimic those noise levels present in the truck cab. In addition, due to the increased noise exposure experienced by commercial truck drivers (Robinson, Casali, and Lee, 1997), it is also important to examine the extent to which commercial truck drivers' hearing levels differ from the general population.

Nerbonne and Accardi (1975) found that there was a steady increase in drivers' hearing levels with increased driving time. In comparison with the average male population of similar age, male truck drivers exhibited hearing loss of 10-20 dB from 250 to 4000 Hz (Nerbonne and Accardi, 1975). This was an important finding because this band encompasses the 1000 to 4000 Hz frequencies that are critical for detection and intelligibility of speech (Coren and Ward, 1989; Morrison and Casali, 1994).

Several studies have measured noise exposures within commercial truck cabs. Although the commercial vehicle industry does not fall under OSHA regulations, these regulations can be used to better understand the noise exposure of driving a commercial vehicle. Of particular concern in these studies was whether occupational exposure exceeded standards for maximum allowable noise exposure of 90 dBA time-weighted average (TWA) during an 8 hour day (OSHA, 1990).

In a study conducted in heavy trucks from the early 1980's, Reif and Moore (1983) found 40% of the trucks had 8-hour equivalent levels higher than 90 dBA TWA for a normal 10-hour driving shift. They also found 90% of the trucks exceeded the OSHA action level of 85 dBA TWA in the average 10-hour day.

In a more recent study (Micheal, 1995b), background noise was measured and recorded from four different commercial truck cab configurations. These configurations combined two engine types (Cummins Model N14 or a Detroit Diesel Series 60) with two cab types (cab-over-engine or a conventional cab). Measurements were performed in accordance with SAE standard J336 (1988) to determine the interior noise levels during acceleration, along with average noise levels when the truck was traveling on the freeway. Results of the SAE testing revealed interior noise levels to be between 77.9 and 84.5 dBA for the upper range of engine speeds. With the trucks traveling at a constant speed of 62 mph, equivalent noise levels (Leq) ranged between 74.3 and 78.8 dBA, a considerable reduction from those levels measured by Reif and Moore (1983).

Recognition of synthesized speech. Morrison and Casali (1994) used the Modified Rhyme Test (ANSI, 1989) to investigate the effect of background noise on the intelligibility of synthesized voice messages. Three types of background noise were used: recorded truck cab noise, truck cab noise plus background speech, and pink (flat-by-octaves) noise, all presented at the same overall level (78.8 dBA) as the average truck cab noise. Synthesized speech-to-noise (S/N) ratios were varied at levels of 0 dB, 5 dB, 10 dB, and 15 dB. The results showed a linear relationship. Intelligibility ranged from 16.8% at 0 dB S/N ratio to 58.4% in the 15 dB S/N ratio condition. The condition in which truck cab noise was mixed with speech resulted in significantly lower intelligibility than either the pink noise or truck cab noise conditions. Clearly, the truck cab noise environment was found to be a decrement to the intelligibility of synthesized speech.

Speech message recall. A study conducted by Mollenhauer, Lee, Cho, Hulse, and Dingus (1994) tested recall of information presented while subjects drove an automobile simulator. Subjects were asked to recall relevant information consisting of either the current speed limit, the current route, or the information on the last sign. Street sign information was presented either visually (via a three square inch dash-mounted LCD display) or aurally (via a digitized voice). The simulator, a Systems Technology Incorporated driving simulator (STISIM), recorded various driver performance behaviors including lane deviation variance, speed variance, steering wheel rate, and heading error.

Results showed that presenting sign information aurally increased free recall of information compared to visual presentation. The increased ability to recall auditory versus visual information may be attributable to the inherently visual nature of the driving task, and the intrusive nature of auditory prompts (i.e., an inability to ignore the presented information). On the other hand, driving performance (as measured by lane deviation variance, steering wheel rate, road-heading error, and speed deviation) decreased when subjects were presented with auditory information. Mollenhauer et al. (1994) expected that subjects would perform better on the driving task when given sign information aurally rather than visually. Although not explained by the experimenters, the decrease in driver performance could be due to the novelty of attending to auditory information while driving. Subjective information gathered after each experimental session indicated that subjects found visual information less distracting than auditory information. The limited acceptance of the auditory condition may be explained by drivers' unfamiliarity with auditory cues.

Speech message length. The length of speech messages should also be considered when designing ITS technologies. Simpson (1976) tested word recognition based on the presence or absence of contextual cues. Subjects were given key words such as "fuel low" individually or within a carrier sentence such as "your fuel is low." Recognition was best for words presented within a carrier sentence. One interesting result was that the presence of a sentence had less of an effect on multisyllabic words. For example, words such as "skid," "point," and "lab" would be recognized less frequently than longer (multisyllabic) words such as "coconut," "restaurant," and "carpenter." Apparently, the additional syllables in more complex words create contextual cues similar to those created by the carrier sentence. This result implies a minimum level of verbal context needed for optimal speech recognition.

Another consideration with speech recognition is that in noisy conditions, comprehension is increased by using a standardized vocabulary within the system (Wickens, 1992). In practice, presenting vital information within a set of standardized words enables operators who do not hear the entire message to fill in the remainder of the message. Practical implications of these findings translate into the specification of software requirements which use a limited vocabulary and the integration of appropriate context for auditorily displayed information.

Timing of message information. Given that the presentation of auditory information may be used for navigation or collision-avoidance warnings, it is critical to consider the timing of the presentation of this information. Although both Ito, Azuma, and Sumiya (1993) and Kishi and Sugiura (1993) studied auditory displays used in advanced navigation systems, neither directly tested differences in timing of information presentation. Ito et al. (1993) presented auditory information based on the distance to the upcoming turn. Four auditory messages were presented at predetermined distances to each turn. These messages came at distances of 5 km, 700 m, 300 m and just prior to the turn. An example of an intermediate auditory cue is "turn to the left at the ABC street about 700 meters ahead". Examples given by Ito et al. (1993) of when to give navigational cues appear in Figure 2.

Kishi and Sugiura (1993) tested auditory versus visual display of navigation information and found that drivers were less likely to glance at the display when turn information was presented audibly (even though distance to the next turn was on the display). An example of auditory presentation from Kishi and Sugiura (1993) showed a similar presentation pattern to that used by Ito et al. (1993). Although the focus of these studies was not to validate timing of auditory information, it is an important variable that should be further investigated. Specification of timing parameters for commercial trucks must not only consider variables such as the speed of the vehicle and safe and

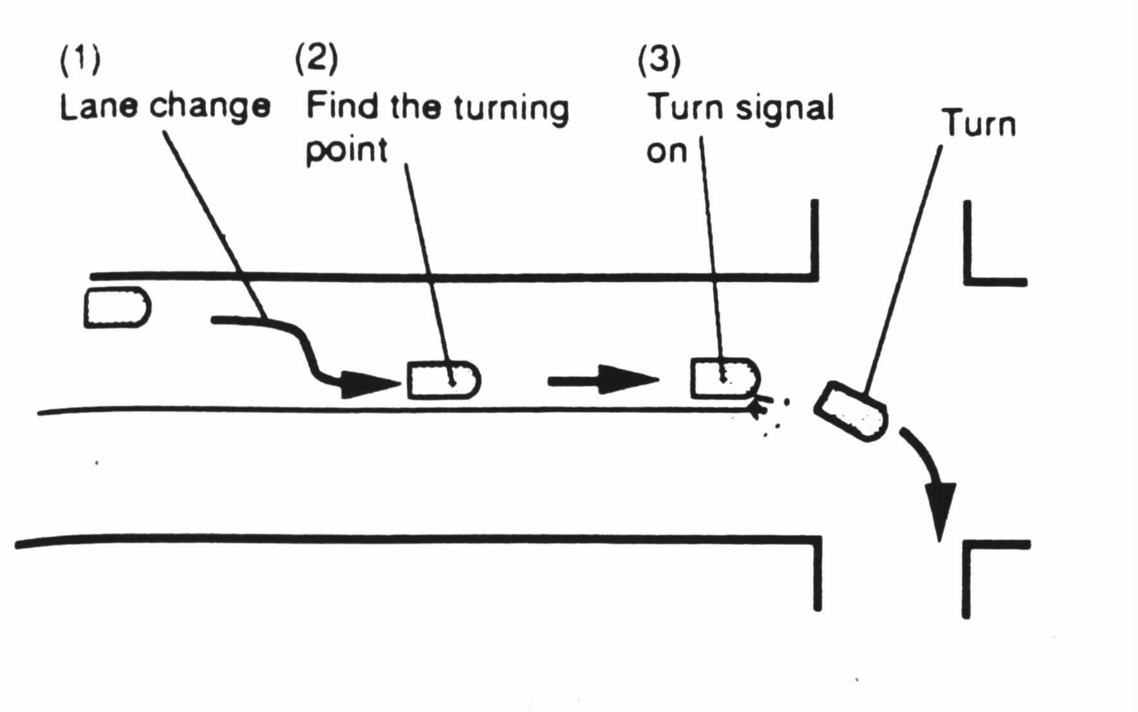


Figure 2. Presentation of multiple auditory cues in a turn.

(adapted from Ito, Azuma, and Sumiya, 1993) comfortable slowing rate before turning, but must also account for the increased weight of the vehicle, different handling characteristics, increased effects of inclement weather conditions, terrain, and the nature of the cargo.

Another way timing of navigational information is important is how it may affect driving performance. A logical conclusion from workload research is that if the driver is visually overloaded, he or she will show decreased driving performance. When time-sharing between multiple tasks, drivers sometimes focus too much on tasks of secondary importance, negatively affecting their performance on the primary task. In the driving domain, if the driver is overloaded and still attends to systems such as navigational displays, serious consequences could result. Research is needed to evaluate how the timing and sensory modality of navigational information presentation affects driver performance.

Navigation and guidance message content. Navigation systems currently on the market make use of large databases of city roads, interstate systems, tourist attractions, and consumer services. Most of these systems use both visual displays and auditory cues (Walker et al., 1991; Kishi and Sugiura, 1993; Ito et al., 1993). Information contained in the verbal directions consists of relevant street names, directions, and distance to turn (Ito et al., 1993). Although street names are vital to the mapping of cities and towns, the actual street signs are often difficult to read because of possibly poor location, the use of ALL CAPITALS, and the thickness of the font (Garvey, Pietrucha, & Meeker, 1998). When using a paper map, the convention is to check the road names which precede the desired turn so that the driver can better estimate when he or she is approaching the desired turn (Dingus et al., 1995). Otherwise, the driver has to slow down at each intersection to check often illegible, and sometimes missing road signs.

An alternative method of giving route guidance is to use landmarks to give location information. Navigation using landmarks is a common practice for many people today (Kishi and Sugiura, 1993). Even in a society of high technology, people still describe how to get to specific locations by the relevant landmarks they will pass along the way. Kishi and Sugiura (1993) suggested using multiple auditory cues (leading up to a directional change) and believed that it is appropriate to present landmarks auditorily when the driver is visually searching for the turning point (see Figure 3).

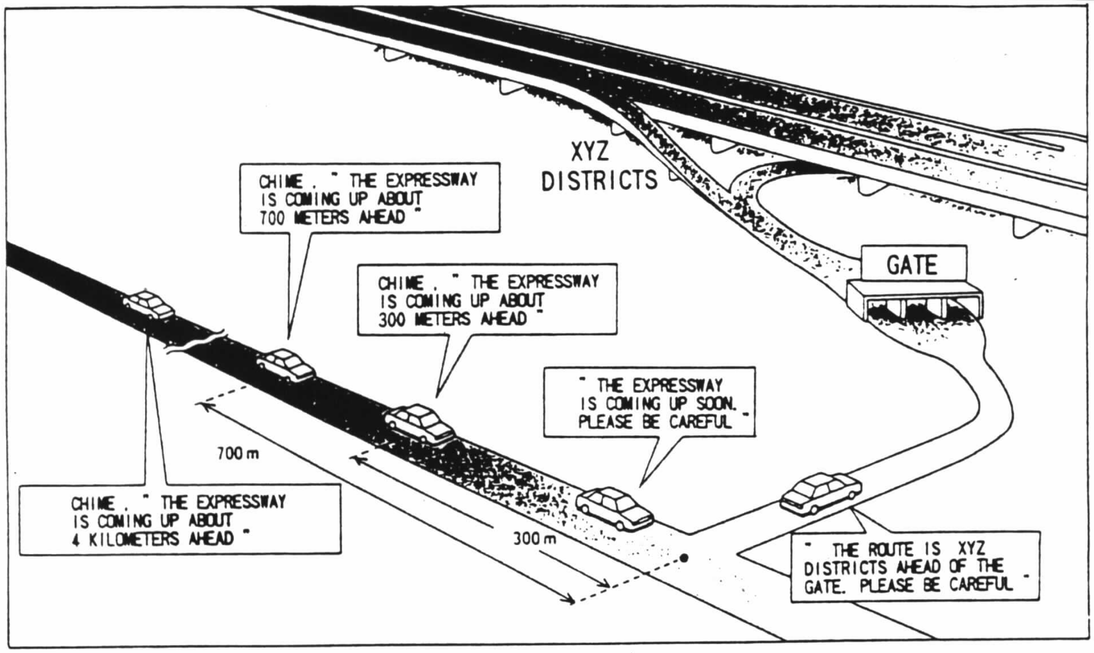


Figure 3. Presentation of auditory cues in a turn.

(adapted from Kishi and Sugiura, 1993)

Localization cues. An important attribute of the auditory domain is the ability to localize the source of the sound. The ability to localize sounds, such as one's visual attention to a loudspeaker, is used frequently. Localization is aided by pinna (outer ear) reflections and refractions which alter sounds in subtle, frequency-dependent ways. Due to wavelength differences in sounds of differing frequencies, these reflections and refractions are different for each wavelength. The unique shape and dimensions of the head, pinna, and auditory canal amplify sound waves by 10-15 decibels in the 2-4-kHz region (Berger, Ward, Morrill, and Royster, 1988). This amplification is important because it is in the same frequency range in which critical speech frequencies lie. In addition to pinna effects, localization is also aided by the intensity differences created when a sound source emanates from the left or the right side of a listener. These intensity differences are due to the sound source going directly to the near ear, while the far ear is in an area referred to as a head or sound shadow, which requires sounds to bend around the head to reach the far ear (Sanders and McCormick, 1993; Coren and Ward, 1989). As a sound source is moved more to one side or the other, the intensity differences become greater, with the most pronounced differences shown when sounds are located 90º azimuth in either direction (directly into one ear). When a sound source is 90º azimuth in either direction, the sound reaches the near ear 0.8 msec sooner than it reaches the far ear. Time differences to each ear are less for sounds which are less than 90º azimuth, until they reach a point that they contact both ears at the same time (when the source is directly in front or behind the listener).

The head shadow effect is also frequency dependent. Low-frequency sound waves (less than 3000 Hz) bend around the head very easily, while high-frequency sounds are usually only detected by the far (or shadowed) ear if they are deflected back to that ear (Coren and Ward, 1989). These differences exaggerate the head shadow effect for high-frequency sounds.

Another area of research that should be considered is the recent research on 3-D auditory displays. Experimentation directed at integrating 3-D auditory displays into the aircraft industry can be related to advanced navigation systems for use in the CVO environment. To make use of the ability to localize sound, it is imperative to determine the effect at the eardrum of variations in sound position. This can be accomplished by activating a tone in several locations and recording the outputs of very small probe microphones which are placed within an individual's (or acoustical manikin's) ear canals. The mathematical equivalent of this physical process is referred to as a head-related transfer function (HRTF), Wrightman and Kistler, 1989a. The application of HRTFs to a sound source, and subsequent projection through headphones, results in the perception of sounds from locations in 3-D space where they were recorded. One problem with HRTFs is that of individual differences. Localization of virtual sound sources is more successful for individualized HRTFs due to the variability of pinna size and structure, (Wightman and Kistler, 1989a; Wenzel, 1992) than nonindividualized HRTFs (Wenzel, Arruda, Kistler, and Wightman, 1993). A more detailed description of HRTFs can be found in Wightman and Kistler (1989b), and successful validation of individualized HRTFs can be found in Wightman and Kistler (1989a).

Wenzel (1992) may have best described a method for auditory display selection in the following recommendation: "a good rule of thumb for knowing when to provide acoustic cues is to recall how we naturally use audition to gain information and explore the environment; that is, the function of the ears is to point the eyes" (emphasis added). Recent studies in the airline industry have focused on the possible utilization of 3-D displays for pilots (Bronkhorst, Veltman, and van Breda, 1996; Begault, 1993). Another possible application of 3-D audio cues is in the domain of air traffic control (Begault and Wenzel, 1993). It is believed that 3-D auditory displays would enhance communication between air traffic controllers and pilots in a manner which would allow air traffic controllers to more critically attend to instances in which two signals come from the same direction (Wenzel, 1992; Wenzel et al., 1993; Begault and Wenzel, 1993).

A representative example of the use of a 3-D auditory display in aviation is reported by Bronkhorst et al. (1996). Bronkhorst et al. (1996) used individualized HRTFs and tested target acquisition using various displays. Displays that were tested included a standard 3-D tactical display (only useful within a limited field of view), a bird's-eye-view radar display, and a 3-D auditory display. Using a fighter aircraft simulator, subjects were instructed to follow a target aircraft until the target instantaneously disappeared, at which time the pilot was instructed to track (using available displays) the missing aircraft until it reappeared on the tactical display.

Performance was measured by the time it took to re-acquire the target aircraft in the visual field. Results indicated that both the 3-D auditory display and the radar display had a similar, significant reduction in target acquisition time (compared to the tactical display). In addition, the combination of the 3-D auditory display and radar display resulted in a further reduction in target acquisition time. This study is an indication of the level of operator efficiency possible in a system which uses 3-D auditory cues. Similar benefits may be realized in the automotive environment. In terms of an advanced navigation system, it may be possible to use directional auditory cues to direct a driver to either side of the visual display.

Since it is generally acknowledged that in many ITS applications there will be some type of visual display added to the in-vehicle environment, the ability to make a more efficient visual search of these displays will be crucial to workload reduction. One interesting quality of acoustically-aided visual search is that even when the visual target is inside an individual's central visual field, search time is still enhanced by complementary acoustical signals (Makous and Middlebrooks, 1990; Perrott, Sadralodabai, Saberi, and Strybel, 1991). "The primary function of the auditory spatial system may be to provide information that allows the individual to redirect the eyes in order to bring the fovea into line with an acoustically active object" (Perrott et al., 1990).

Recent research has focused on the effect that presentation of auditory information has on visual search and acquisition time (Micheal and Casali, 1995). The main objective of this study was to compare prompting of auditory versus visual information for navigational search in an environment acoustically similar to a commercial truck cab. The primary task in this experiment was manual vehicle control. This task was provided through the use of a low-fidelity driving simulator. Roadway images were displayed on a 14-inch monitor placed directly in front of the subject. An accelerator and brake pedal assembly, combined with a steering wheel control provided inputs and thus closed-loop aspects which approximated the manual control process of driving. Because the scenario required subjects’ frequent attention to avoid negative consequences such as speeding tickets or collisions, this experimental condition was seen as an acceptable primary task.

Secondary task information was displayed visually or auditorily. A 14-inch touch-screen was used for the secondary search task. This touch-screen was located to the right of the primary task CRT and positioned at a 20º downward visual angle to simulate a dash-mounted display. Auditory information was presented through a two-channel headrest loudspeaker apparatus. Two three-inch loudspeakers were placed approximately four inches from the participant and positioned at 45º angles (about a vertical axis) in relation to the participant's ear canal entrances, as recommended by Pachiaudi and Blanchet (1990). Auditory information was presented either diotically (same sound to both ears) or directionally (sound to only the left or right headrest loudspeaker). Participants were asked to press one of several buttons on the touch-screen corresponding to the information presented in the auditory message. Response time, measured in milliseconds, and accuracy, measured in percent of correct selections, were recorded for the various background noise type conditions. The number of touch-screen buttons available on any given trial was varied in order to create different levels of information density. These levels consisted of four, eight, or 12 items, and were based on a previous study by Noy (1990).

The directional presentation of auditory cues led to quicker response times to the corresponding side of the visual display ($p < 0.05$). For example, if the auditory message "touch the letter A," was given through the left headrest speaker, response time to touch the letter "A" on the left side of the screen was faster than if the participant was given a diotic auditory or a visual cue. It may be inferred that reducing acquisition time by giving directional auditory cues may reduce driver attentional demand to subsidiary driving tasks, thereby reducing the workload associated with these tasks. Furthermore, presentation of auditory cues (whether diotic or directional) resulted in significantly higher accuracy of button selections when compared to the visual-only presentation mode ($p < 0.05$).

Results showed response time was similar for both visual and diotic auditory presentation modes, but as previously discussed, auditory directional presentations resulted in significantly faster response times than auditory diotic presentations. Micheal (1995a) suggested that further investigation under similar conditions was needed in order to determine if directional presentation of auditory information can be beneficial in various ITS applications.

User capabilities and characteristics. To adequately propose designs that will be implemented into the commercial truck cab, it is important to understand the physical characteristics of the drivers. Knowledge of population age and gender distributions can be used to calculate anthropometric data, which are in turn used to estimate drivers' fields of view. Anthropometric differences are known to exist between the truck driver and general driver populations (Shaw and Sanders, 1985). Extensive anthropometric descriptors of the physical aspects of the truck driver population in the United States have been obtained by Sanders (1983) and Shaw and Sanders (1985). Although collection of anthropometric data is an ideal measurement tool for determining population differences, it is also expensive and somewhat impractical. Perceived changes in ethnic and gender composition led Kinghorn and Bittner (1993) to use estimation techniques to provide an up-to-date description of the commercial driver population. Commercial driver gender composition changed from 4% female in 1985 (Shaw and Sanders) to an estimated 13.2% in 1993 (Kinghorn and Bittner, 1993). Ethnic composition in the "black and other" category of male truck drivers is believed to currently be 22.6%, compared to 18.4% in 1983 (Sanders, 1983). Complete anthropometric estimates taken from Kinghorn and Bittner (1993) are listed in Table 3. In general, truck drivers are taller and heavier than the general driving population.

Knowledge of basic anthropometric measurements in and of itself does not sufficiently enable us to understand how an operator interacts with the truck cab environment. One important design issue to be considered is the driver's forward field of view. Forward field of view can be determined using the Society of Automotive Engineers (SAE) Motor Vehicle Driver's Eye Range Standard (SAE J941, 1992). Use of the SAE J941 standard allows an estimation of eye position ranges for the majority of drivers (usually encompassing 95 percent of the drivers). This range is drawn from the lower part of the eyellipse to the closest visible point in front of the truck to determine minimum forward visibility. One problem with this technique is that it requires a fixed seated height, regardless of the height of the driver. Reynolds and Bowers-Carnahan (1993) proposed that shorter drivers raise their seats higher to gain more visibility. Using

TABLE 3

Estimates of 1993 Commercial Vehicle Operator Anthropometry (adapted from Kinghorn and Bittner, 1993)

	PERCENTILES (female/male)			
	5th (F/M)	50th (F/M)	95th (F/M)	SD (F/M)
HEIGHTS (in cm)				
Stature	153.5/165.0	164.2/176.2	174.4/186.0	6.36/6.78
Height, sitting	81.0/85.9	87.1/92.1	92.7/97.9	3.34/3.44
Eye height, sitting	69.2/73.7	75.1/79.4	80.4/85.2	3.3/3.7
Shoulder height	50.4/53.2	57.1/60.0	63.3/66.4	3.9/4.06
Elbow rest height	19.2/20.2	24.0/24.9	28.8/30.0	2.8/2.78
Knee height	46.1/50.8	50.8/55.6	55.4/60.5	2.8/2.8
Popliteal height	36.3/40.5	40.6/45.4	44.9/49.9	2.6/2.67
Thigh clearance	11.0/12.6	14.3/15.7	18.4/19.5	1.9/1.88
DEPTHS (in cm)				
Elbow-fingertip	39.4/45.1	43.1/49.1	52.6/57.3	2.2/2.2
Buttock-knee	52.7/55.5	57.9/60.7	63.7/65.7	3.14/2.9
Buttock-popliteal	43.6/45.1	48.9/50.5	54.4/56.1	3.1/3.15
Forward/functional reach	65.5/78.1	72.6/84.5	80.8/90.5	4.6/5.1
BREADTHS (in cm)				
Elbow-elbow	32.2/37.3	38.3/44.2	49.4/53.4	5.28/4.81
Hip breadth, sitting	32.2/32.9	37.3/37.8	44.8/43.3	3.79/2.97
Biacrominal breadth	32.8/36.9	36.3/40.9	39.7/44.5	1.97/2.1
LENGTHS (in cm)				
Foot length	22.8/25.4	24.6/27.6	26.8/29.7	1.2/1.3
Hand length	16.7/18.1	18.4/19.5	20.3/21.1	1.06/0.95
OTHER (in cm)				
Iliocristale height	94.2/99.8	102.0/108.8	110.5/117.9	5.15/5.5
Functional leg height	97.8/105.9	105.7/114.4	119.5/122.7	4.7/5.09
Cervical height	132.6/141.2	141.5/151.7	151.0/162.5	5.62/6.43
Trigion height	148.8/155.1	158.0/164.6	167.5/174.6	5.52/5.76
Weight (in kg)	51.1/69.1	65.7/90.4	99.4/118.7	15.9/15.2

a limited sample of drivers from the 1st through 95th percentiles, Reynolds and Bowers-Carnahan (1993) were able to estimate a more appropriate eyellipse measurement. Eyellipse measurements were then directly translated into visibility parameters for 95 percent of the truck driver population.

The eyellipse diagram and visibility parameters can be seen in Figures 4 and 5 respectively. The adjusted eyellipse in Figure 4 corresponds to the visibility parameter labeled "A" in Figure 5. The original eyellipse is labeled "B". As shown graphically in Figure 5, average driver visibility is increased by 1.2 m when the adjusted eyellipses are used. Physical descriptors such as those in Figures 4 and 5 are important to consider when designing displays for commercial trucks. Eyellipse data are also viable descriptors of where the driver's ears are located and can lead to optimal loudspeaker placement for a headrest speaker system. Although navigation systems to be used in the commercial truck cab are similar to those being designed for use in consumer automobiles, it is critical that designers base their decisions on the population that will use the systems and for the environment in which they will be used.

Drivers' responses to traffic signs. It is important to briefly review some relevant research on how drivers respond to traffic signs. A discussion of this area will reveal what type of information drivers currently find conspicuous and/or salient. To gain information on the salience of traffic signs, early studies consisted of stopping cars after they passed a traffic sign and asking them what was on the sign (Johansson and Rumar, 1966; Johansson and Backlund, 1970). Overall recall of signs was found to be quite poor, which was explained in part by the stress associated with being pulled over by a police officer. It was found that drivers correctly recalled traffic signs more often when the perceived importance of the sign was high. For example, speed-limit signs were reported correctly 78% of the time, road-damage signs were reported correctly 55% of the time, and pedestrian crossing signs were correctly reported only 17% of the time (Johansson and Rumar, 1966).

Although it is beneficial to determine what signs drivers deem important, another critical factor is whether drivers responded to traffic signs regardless of their perceived importance. In a uniquely designed experiment, Summala and Hietamaki (1984) determined drivers' immediate response to three different road signs (Danger, Children,

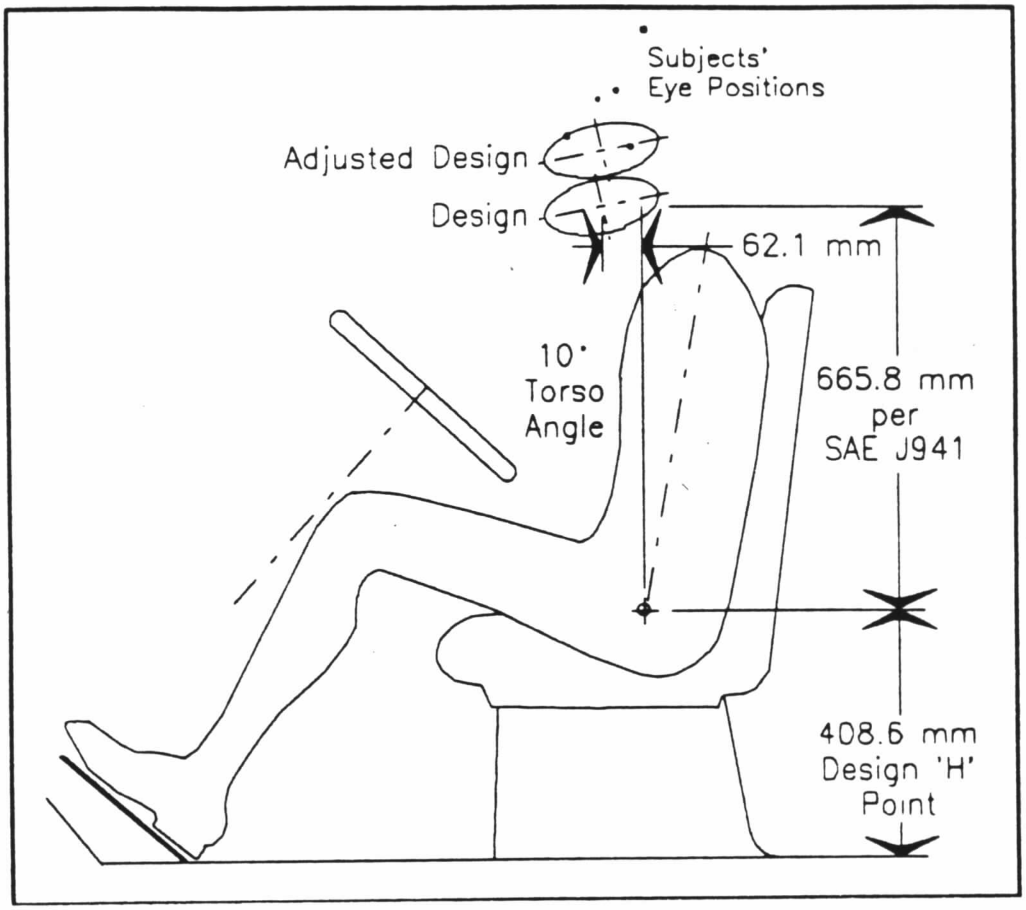


Figure 4. Scale diagram of actual eye positions and eyellipse locations.

(adapted from Reynolds and Bowers-Carnahan, 1993)

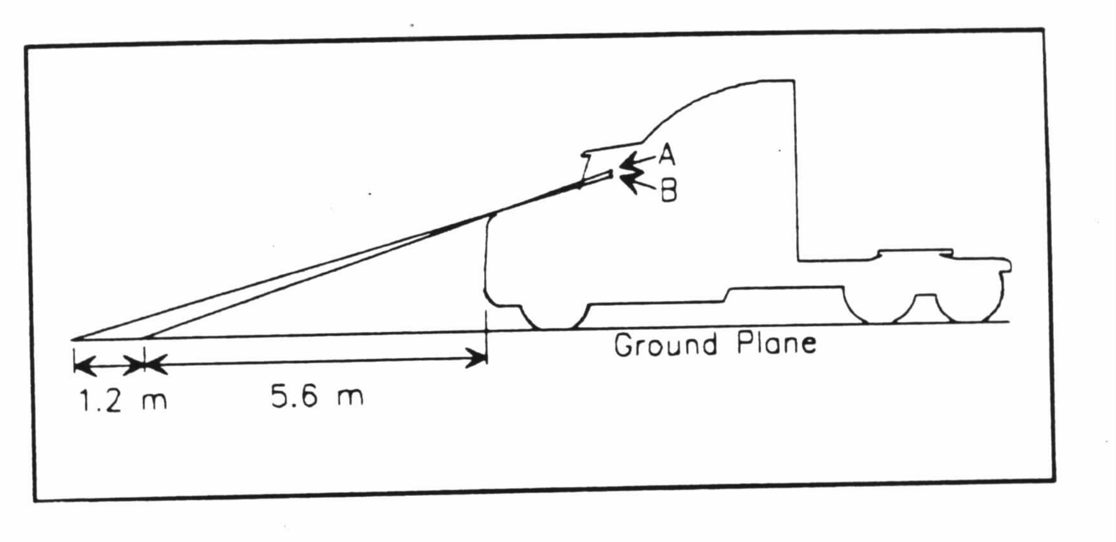


Figure 5. Visibility at ground plane with change in eye height.

(adapted from Reynolds and Bowers-Carnahan, 1993) and Speed Limit 30) in two conditions (with or without an overhead flashing light). Each sign was randomly presented on the same section of rural road. A total of 2,185 drivers' responses were observed during the experiment over six, 8-10 hour days. The signs were located along a curve in the road, in such a way that they were not visible until drivers were (on average) 2.2 seconds from reaching it. Each car's speed was measured over seven intervals starting before the sign became visible, and concluding after passing the sign. Drivers in all sign conditions slowed at a rate at least equal to releasing their foot from the accelerator pedal when compared with the no-sign control condition ($p < 0.01$). Overall speed reduction was greatest for the speed limit sign (as expected) due to the relevance of reducing driving speed in adherence with the speed limit.

The important finding in this study is that drivers always reduced their speed when the sign became visible. Even though they might not be able to recall what was on the sign, they do respond to the sign when they see it. This finding has practical implications in workload research. It may be inferred that if drivers do not respond to signs presented in a driving task, they may be overloaded and possibly allocating too much attention to a side task. Although drivers often have spare visual resources that they can use to periodically view displays and controls, ITS technologies need to be designed in such a way that they do not divert the driver's attention away from the road when the driver has no visual resources to spare.

Incomplete Areas of Investigation

Throughout the literature, experimenters have tested many aspects of concern that will hopefully lead to the optimal design of ITS technologies for commercial vehicle applications. Most of the preceding discussion has focused on those aspects relating to auditory presentation of information. While it has been shown that auditory presentation of navigational information shows promise, gaps remain in the literature. Issues needing further examination include timing of information presentation, message length, and stimulus-task compatibility.

The timing of information delivery requires further research to determine when and how many pre-turn messages should be given as well as the optimal lead time and distance to the turn for each message. Such research could eventually lead to software specifications for auditory presentation of navigation information. As Verwey (1991) suggests, one type of additional investigation should be whether drivers are able to recognize and respond properly, and in time, to critical situations when they perform other tasks than driving. Research is also needed to determine the specific guidelines for optimum message length. Furthermore, it is also important to determine if standardized carrier sentences should be used to maximize comprehension of auditorily-displayed information. Lastly, more research is needed to understand which specific tasks might benefit from directional presentation of auditory cues, and whether directional cues can be beneficial in a variety of typical ITS applications.

RESEARCH OBJECTIVES

The current experiment was conducted to fill some of the voids existing in the literature. One of the more promising ITS technologies envisioned for use by commercial motor vehicle operators is a navigation system. A navigation system that is easy to use and which provides relevant information has the potential to reduce driver stress and fatigue, decrease fuel consumption, shorten delivery time, and reduce truck wear. This experiment was conducted to help designers of navigation and other advanced information systems optimize the presentation of information through the use of the auditory sensory modality, if and when appropriate. The main objective of this experiment was to examine the effect of aurally presented navigational information on a drivers' ability to perform the primary task of driving. A secondary objective of the experiment was to verify the findings of Micheal (1995a) who showed that response time is shortened when auditory prompts are given in a directional format verses when prompts are given visually or audibly without directional cues.

EXPERIMENTAL DESIGN AND METHODOLOGY

Experimental Design

The experimental design was a three-factor, within-subjects complete factorial design. In addition, a single control condition with no secondary task was included. Participants were treated as a random-effect variable and independent variables were treated as fixed-effect variables. Independent variables included Secondary Task Presentation Mode (auditory diotic, auditory directional, visual), Secondary Task Information Density (low, medium, high), and Timing of Secondary Task Presentation (zero, two, and four seconds before speed limit changes). The control condition was randomly presented an average of once for every three secondary task presentations to control for learning effects of secondary task presentation with speed limit changes. All of the experimental conditions were replicated five times for each participant. Figure 6 is a graphic representation of the experimental design. Table 4 shows each of the independent variables.

Independent variables. As shown in Figure 6 and Table 4, three independent variables were manipulated in the experiment. Three levels of presentation mode were used, two auditory and one visual. Auditory messages were presented either simultaneously to both ears (diotically) or only to the left or right ear (directionally). The visual presentation mode consisted of presenting information via a text message displayed on the secondary task screen. All messages were worded the same except for the highway route number to be selected. The carrier sentence "Select Highway Route Number" preceded the specific two-digit number that was to be selected. An example of the visual prompt appears in Figure 7.

Three levels of secondary task density were used, as suggested by Noy (1990). These levels were high (12 highway icons), medium (8 highway icons), and low (4 highway icons). Examples of each density level and the highway icon used appear in Figure 8. The third independent variable was the timing of the prompts. Secondary task messages prompting drivers to select highway routes were presented in conjunction with the presentation of speed limit signs into the visual scene. Pretesting determined that speed limit signs were rarely legible at 500 feet, but were always legible at 320 feet and

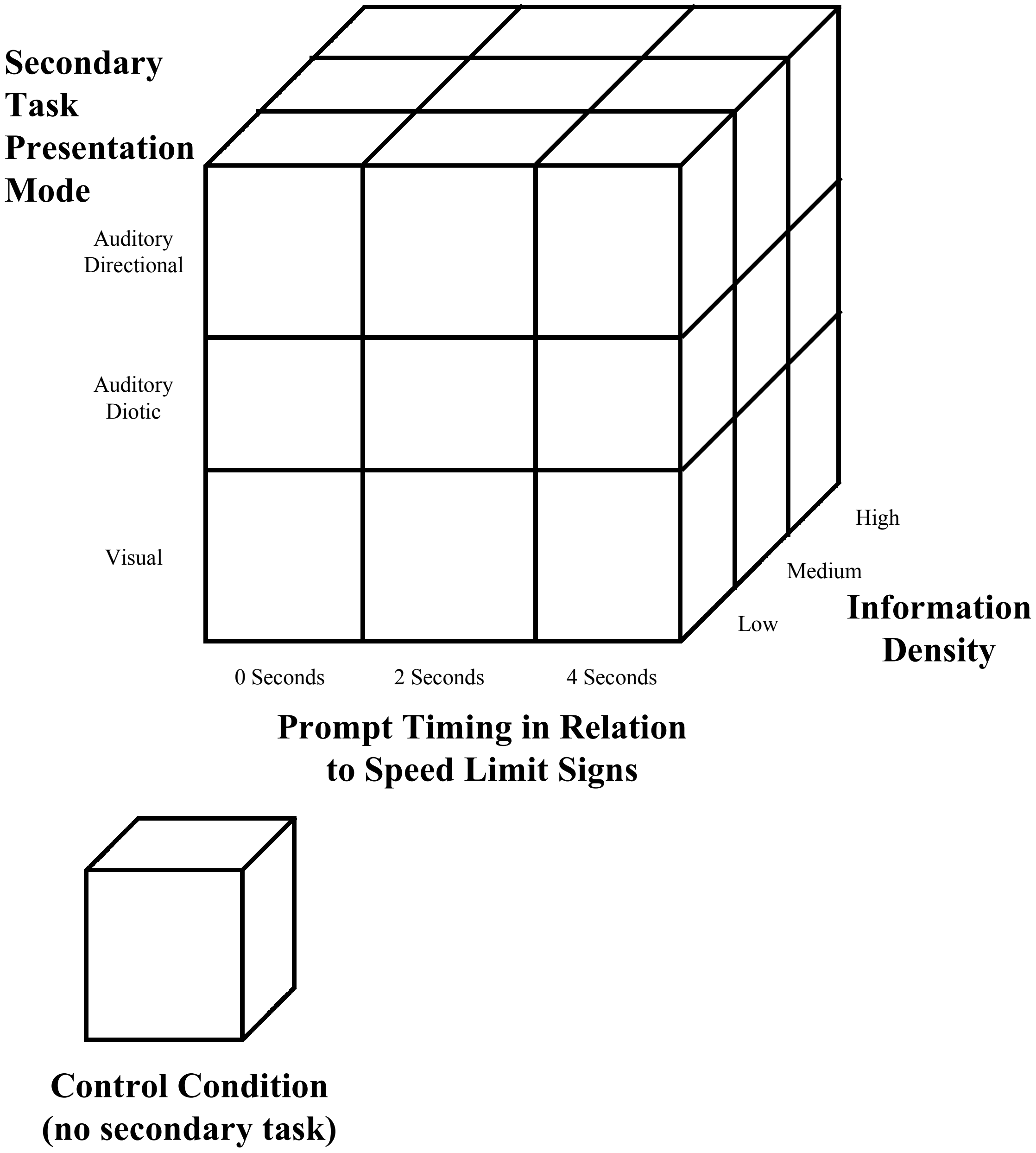


Figure 6. Experimental design.

TABLE 4

Independent Variables (Factors Manipulated)

Secondary Task Presentation Mode

- Auditory - Directional
- Auditory - Diotic (non-directional)
- Visual

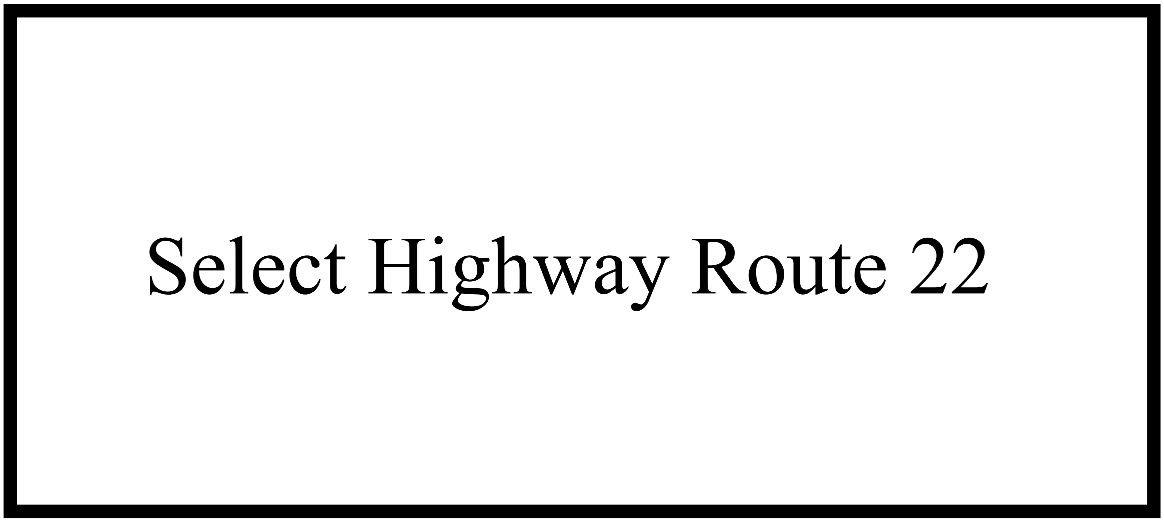
Information Density

- Low (4 possible selections)
- Medium (8 possible selections)
- High (12 possible selections)

Timing of Prompts

- Prompt (auditory directional, auditory diotic, visual) presented coincident with the appearance of a speed limit sign requiring an increase or decrease in vehicle speed
- Prompt presented two seconds before the appearance of a speed limit sign
- Prompt presented four seconds before the appearance of a speed limit sign

Control Condition (no secondary task presented when speed limit sign appeared)



Select Highway Route 22

Figure 7. Example of a secondary task visual prompt.

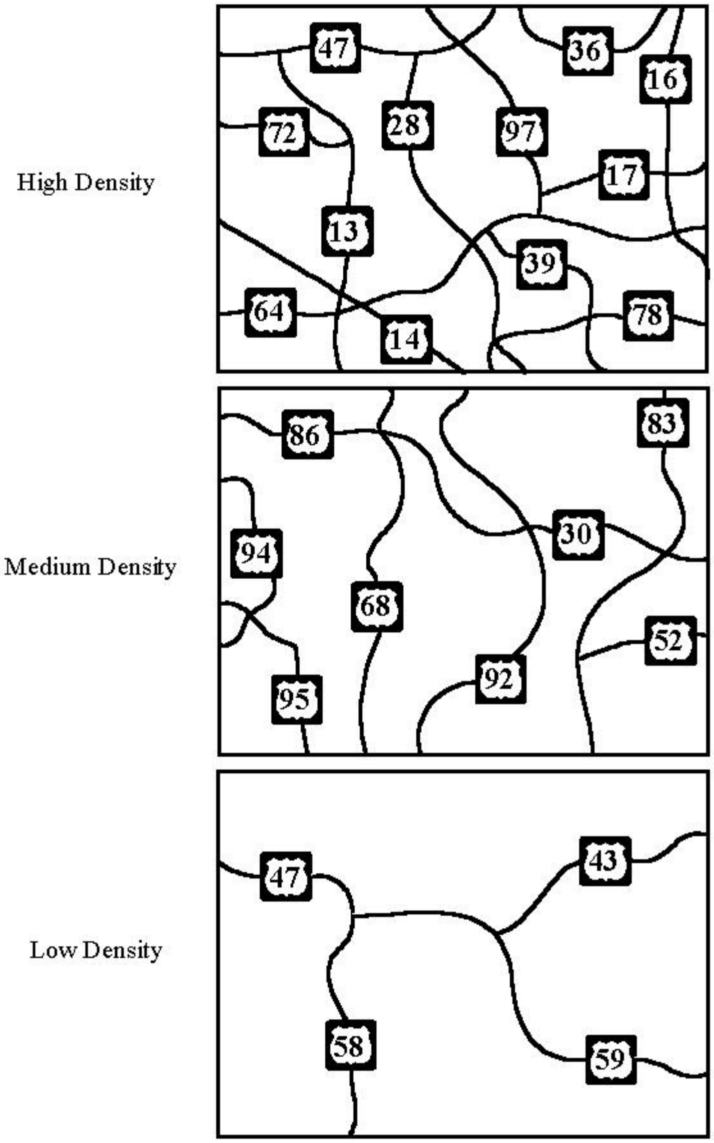


Figure 8. Samples of secondary task density levels and highway icons.

closer. Prompts were presented at three timing levels: the same time the speed limit became legible (0 second condition), two seconds before the speed limit became legible (2 second condition), and four seconds before the speed limit became legible (4 second condition).

Dependent variables. Two secondary task dependent measures were collected: response time and accuracy. The secondary task was presented in all experimental conditions except for the control condition. Response time (in hundredths of seconds) was defined as the time between presentation of the secondary task map and the time the participant selected a highway route icon. If the driver did not select an icon within nine seconds, the recording of the secondary task timed-out. The nine-second time limit was determined during pretesting as sufficient time to collect all possible responses.

Accuracy was also recorded to determine whether or not the participant selected the appropriate highway route icon. Each response was scored as a "one" for a correct selection or as a "zero" for an incorrect selection. Secondary tasks that timed-out were considered incorrect selections.

Five driving performance measures (lane deviation, steering wheel angle, road heading angle error, accidents, and adherence to the speed limit) were also collected. Driving performance data were collected at a rate of 10 Hz by the STISIM computer in a continuous data stream examined for a period of 12 seconds following each secondary task prompt. Each of the driving performance measures is described below.

Lateral lane deviation was indicated by the distance between the roadway dividing line and the vehicle center line. Positive numbers indicated the vehicle was to the right of the dividing line while negative numbers indicated the vehicle was to the left of the dividing line. A lane position standard deviation was calculated for each driving segment. The standard deviation was used because it is the measure that is most sensitive to lane position movement.

Steering wheel angle was indicated by the number of degrees the steering wheel was off its center position. The standard deviation of steering wheel angle was used as the actual dependent measure because of its sensitivity to the number and severity of each steering reversal.

Road heading angle error is defined as the degree to which the vehicle deviates from a path parallel to the roadway. A vehicle heading slightly toward the right shoulder would produce a positive heading angle error while a vehicle heading slightly to the left shoulder would produce a negative heading angle error. Once again, the standard deviation of road heading angle error was used as the dependent measure.

Accident data were also collected during each driving segment. An accident was registered if the vehicle traveled off the road or if it collided with an oncoming vehicle. Each 12 second driving segment was either given a value of 0 (for no accidents) or 1 (for one or more accidents). For some run off the road accidents, the simulator had a tendency to run off the road twice (registering two accidents) before the driver was able to regain normal operation. Therefore, more than one accident was considered a single accident.

The final dependent measure associated with driving performance was driver adherence to the speed limit. This measure was used to determine if the driver ignored the driving scene due to time spent attending to the secondary task. The STISIM scripting language uses distance (in feet) to define where buildings and other objects or events occur within a scenario. With distance traveled forming the basis for scenario scripts, the time at which secondary task prompts were presented depended on the speed the participant was traveling as he approached the speed limit sign. It was determined during pretesting that the speed limit became legible when the driver was 320 feet from the sign and the timing variable was based on this distance. The scenarios were written assuming the drivers would be traveling at the correct speed limit. The secondary task would be presented: 1) when the sign became legible, 2) two seconds before the signs became legible, or 3) four seconds before the signs became legible.

Control condition. A control condition was included in the experiment to examine the effect of a secondary task on driving performance. Control segments were identical to experimental segments, except that no secondary task was presented. Data analysis of the control condition was conducted for the same five driving performance dependent measures as the factorial design analysis. Control condition data collection began when each speed limit sign became legible (in the same manner as the 0 second timing condition). Control condition driving segments were randomly included among those for each experimental condition. Driving segments for the control condition were presented, on average, one time for every three experimental condition presentations. The increased number of control condition presentations compared to experimental condition presentations (the control condition was presented nine times in each scenario) was done to control for learning effects of secondary task presentation with speed limit changes. However, only one control condition replication (chosen at random) was used in the analysis for each driving session.

Pilot study. Before the experiment could be conducted, the number of replications
necessary for each experimental condition had to be determined. For this purpose, a pilot test was performed using a subset of the experimental design. The two extreme levels of each variable were used to create a 2x2x2 factorial design. Independent variables included density (high and low), prompt type (auditory directional and visual), and prompt timing (simultaneously and 4 seconds prior to presentation of speed limit signs). Each of the eight experimental conditions was replicated 12 times. Two driving scenarios were developed, each containing three replications of each experimental condition. Pilot subjects were tested over a two-day period with each subject driving each scenario on both days. Pilot subjects read and signed the informed consent and experiment description forms but were not screened for vision or hearing levels. The pilot subjects experienced the same training scenarios as would actual experimental subjects, but drove through only two driving scenarios. The second day consisted of driving through the two scenarios a second time. Pilot subjects were paid $5.00 per hour for their participation.

Since the goal of pilot testing was to find out how many replications were needed for reliable results, the data were arranged in graphical format. One graph was made for each dependent measure for each subject. Graphs consisted of 12 data points, each representing a cumulative average value for the dependent measure being analyzed. These graphs were used to visually inspect the variability associated with increased replications. As expected, larger changes were seen at the low ends of the graphs. Toward the mid-range of number of replications, values gradually leveled off due to the decreased influence of adding a single observation to a larger sample. A sample graph of the effect of multiple replications on lane deviation appears in Figure 9.

A compromise was necessary between the number of replications and the total length of the experimental session. Variables considered were the effect of multiple replications on participant attention and fatigue, how long each replication would take, and the trade off of running more replications but requiring the driver to participate in the experiment on two separate days. Although it was apparent from the graphs that 12 replications would be ideal, the increased benefit had to be weighed against the drawbacks. It was estimated that it would take about 45 minutes for the participants to undergo the screening procedures. Training on the simulator and the secondary task were estimated at 15-30 minutes. A major limiting factor regarding experimental session length was a desire to stay under three hours to avoid problems with fatigue which could confound experimental results. In an effort to adhere to a three hour maximum, only two hours remained in which to run the actual experiment. Since each replication would take about 20 minutes with short rest breaks between each scenario, a maximum of six replications could be performed in a one-day experiment.

Dividing the experiment into two days and running half the replications one day and half the next was considered. The choices were either to perform a two-day experiment and run at least 10 replications, or to limit the number of replications and have a single experimental session. Due to the participants' time constraints and the potential for attrition if the experiment were split across two days, it was decided to complete the experiment in one day. As such, it was estimated that six replications were possible, but that five replications would be better to allow for some leeway for session overrun.

Each experimental condition was replicated five times. Five driving scenarios were programmed into the simulator to present each of the 27 experimental conditions once and the control condition nine times, resulting in a total of 36 driving segments per scenario. Random presentation of all 36 driving segments was used within each scenario to control for differential transfer. Differential transfer is a concern associated with within-subject designs that occurs when performance on one experimental condition

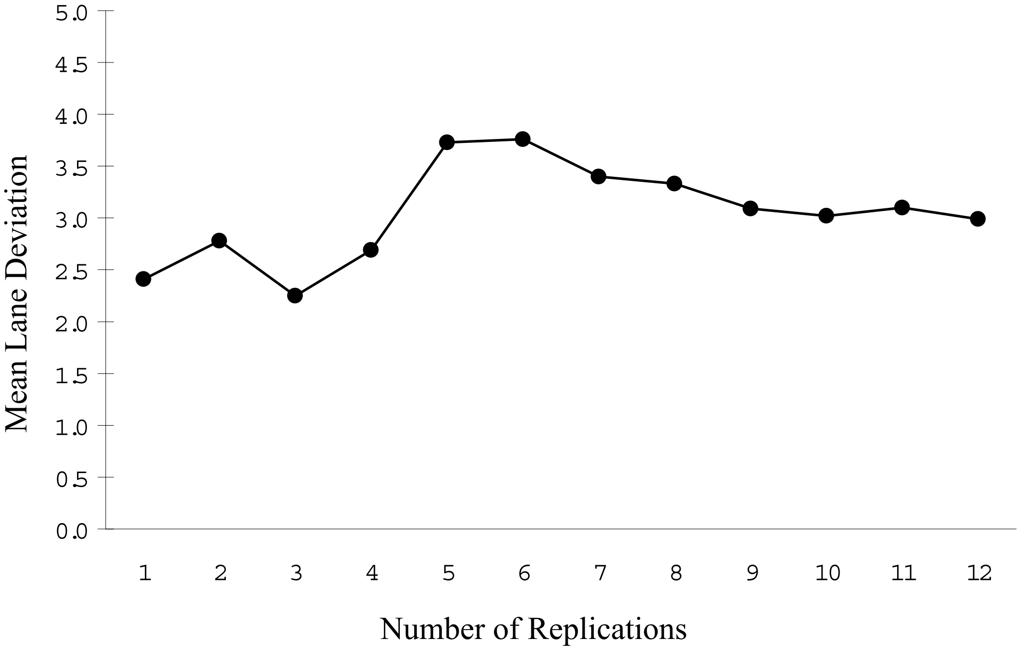


Figure 9. Example graph of the effect of multiple replications on mean lane deviation.

affects performance on other conditions. Random assignment was also used to determine the presentation order for each of the five scenarios for each driver.

Experimental Facility and Apparatus

The experiment was conducted in two rooms located in the Environmental and Safety Laboratory in the Human Factors Engineering Center at Virginia Tech. The main experimental room housed the simulator buck, the secondary task touch-screen, the headrest speaker apparatus, and two loudspeakers. The simulator buck consisted of an air-actuated driving seat, a full-size tractor-trailer steering wheel (attached to a torque motor), accelerator and brake pedals, and a 21-inch monitor for the roadway display. Figure 10 shows a diagram and Figure 11 shows a photograph of the simulator room layout.

Two-inch thick Sonex sound-absorbing foam lined the walls of the experimental room to approximate the reverberation characteristics of a commercial truck cab. Reverberation Time (T60) is the time (in seconds) that it takes the sound stimulus pressure level in a room to drop 60 dB from original level when a noise stimulus is stopped abruptly. Since a decay of 60 dB was not achievable, a 15 dB decay was measured (as done by Morrison, 1993). The resultant time was then multiplied by 4 to estimate the T60. Table 5 presents reverberation times for conventional and cab-over-engine truck cab configurations (Morrison, 1993), as well as reverberation times measured in the experimental facility.

An adjoining room served as the experimenter station and contained all of the simulator support equipment. The simulator was visible from the control room via a one-way mirror. A two-way intercom system allowed communication between the experimenter and the participants. Figure 12 is a photograph of the experimenter station.

Primary Task Apparatus - STISIM Simulator

A Systems Technology Incorporated Driving Simulator (STISIM) fixed-base driving simulator was used for the primary driving task. The STISIM simulator is a fully interactive, closed-loop simulator which includes an automatic transmission, variable vehicle dynamics, and simulated engine noise. The physical arrangement of the

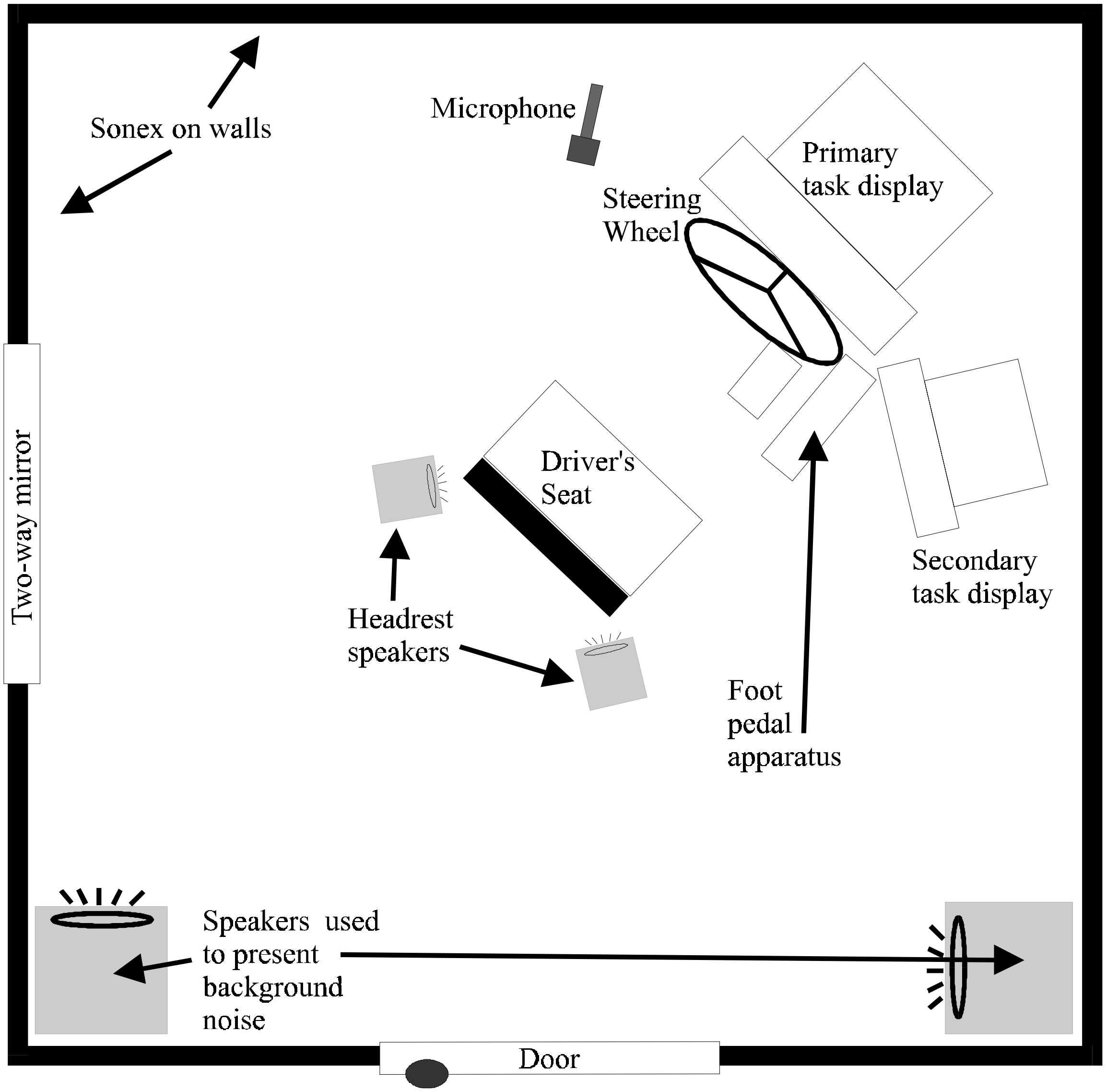


Figure 10. A top view diagram of the simulator room.

Figure 11. A photograph of the simulator buck configuration.

TABLE 5

Truck Cab and Experimental Room Reverberation Times

Octave Band (Hz)	Conventional Cab T60 (s)	Cab-over-engine T60 (s)	Experimental Room T60 (s)
63	0.29	0.39	0.22
125	0.26	0.23	0.49
250	0.16	0.16	0.36
500	0.16	0.16	0.25
1000	0.15	0.16	0.20
2000	0.16	0.16	0.19
4000	0.16	0.16	0.18
8000	0.15	0.16	0.18

Figure 12. A photograph of the experimenter station.

simulator buck was modeled after the interior of a commercial truck cab, based on measurements taken from two 1996 Volvo Conventional Cab commercial trucks (models WIAG4T and WCAG4T). The full-sized, 21-inch steering diameter wheel was positioned at a 25° angle with the center 33.5 inches above the floor. The accelerator pedal was mounted six inches to the right of the seat center axis, with the heel point of the pedal four inches in front of the vertical axis of the steering wheel. An accelerator pedal from a 1974 Mack truck was adapted to work with the STISIM pedal assembly to mimic the floor mounted accelerator pedal commonly found in heavy trucks. Volvo Heavy Truck Corporation donated the driver's seat. Compressed air tanks stored in the experimenter room were used to supply air to the pneumatic seat controls.

One important feature of the STISIM is its variable vehicle dynamics. By changing values in the STISIM Gains file, the simulator can be configured to mimic the response characteristics of many different vehicles (e.g. acceleration, braking, steering). For purposes of the present study, the simulator was configured to mimic the response of a large commercial vehicle. The appropriate gains file settings were obtained from the Battelle Human Factors Transportation Center, in Seattle, WA (S. Stone, personal communication, December 27, 1995) and were the same settings as used by Kantowitz (1995).

Just as vehicle dynamics were important to make the simulator feel like a commercial truck, it was also necessary to closely approximate the auditory environment of the truck cab to accurately test auditory message presentation. The truck cab noise used as the experimental background noise was recorded in a 1995 Volvo extended sleeper tractor equipped with a Caterpillar 3406 engine. To achieve a consistent background noise, a 15-second segment of the original recording was digitally copied and used to create a 45-minute sound file. This file was then recorded onto an analog tape for use in the experiment.

Truck noise was played at the same level (74.9 dBA, +/- 0.5 dBA) as was measured in the on-road tests (Micheal, 1995b) and was consistent with the truck noise levels (72-76 dBA) used by Micheal (1995a). A Yamaha equalizer (Model GE-60) was used to adjust the noise spectrum presented during the experiment to approximate that of the actual truck noise measured on-road. Two Infinity Model SM 155 loudspeakers were used to play simulator and truck noise and were positioned in the experiment room to approximate a diffuse sound field around the head of the driver. During experimental set-up, pink noise was played through the loudspeakers and six SPL measurements were taken from the head-center position (left/right, up/down, front/back). The up/down and front/back measurements were within +/- 5dB of one another. A stricter requirement of +/- 2dB was used for the left/right measurements due to the directional component in the experiment.

In addition to the prerecorded truck noise, the sound files built into the simulator software were used to add cues of acceleration, deceleration, braking, and crashing. STISIM auditory cues were mixed with the background truck noise so that they were just audible without significantly increasing the overall sound pressure level. To accomplish this, five pilot subjects drove the simulator at speeds varying from 20 to 60 miles per hour and instructed the experimenter to adjust the noise level so they could clearly hear the acceleration and deceleration cues. These individuals were instructed that the desired level was one that was always audible, yet did not overpower the background truck noise. Following each test, the simulator was run on auto-pilot at 45 MPH and a two-minute Leq measurement was taken. The mean of the five Leq measurements (61.4 dBA) was used for daily calibration of the STISIM noise cues. Mixing the simulator sounds with the truck noise did not significantly change the overall sound level or noise spectrum (< 2 dB).

Primary Task

The simulated driving environment consisted of a two-lane highway in a rural setting during daylight hours. Participants were instructed that safe and lawful driving was their most important task, which included maintaining legal speeds posted on roadside signs. Participants experienced five unique driving scenarios, each lasting 15-20 minutes. The speed limit was changed on a regular basis during each scenario by standard speed limit signs (black numbers on a white background), or by "curve ahead" speed limit signs (diamond shape sign with black numbers on a yellow background).

The driving scene was also varied in an appropriate manner depending upon the nature of the speed limit change. For instance, scenery associated with speed reductions included a school zone, a construction zone, a town, a cross-walk, and an intersection. Speed limits increased as the driver passed by these scenes. Speed was displayed on the bottom edge of the driving display. A steady stream of oncoming traffic (at a rate of one car every 2-10 seconds) was also included throughout each scenario. A diverse driving scene which included buildings, pedestrians and traffic, not only made speed increases and decreases seem logical, it also created a more realistic driving scene.

Secondary Task

The secondary task consisted of a search task of a road map display. The search task was presented on a 15-inch Sony Triniton Multiscan touch-screen, model CPD-15SF1. The touch-screen was located to the right of the driver and positioned at a visual angle approximately 20° below the driver's horizontal line-of-sight. Placement of the touch-screen (measured from the farthest part of the map) was within thumb-tip reach for a 5th percentile male, 74.3 cm (NASA, 1978). This configuration mimics a dashboard-mounted navigational display and is consistent with the layout of the previous study (Micheal, 1995a). Figure 13 shows an example of the secondary task being performed.

Participants were instructed by auditory or visual prompts to select highway icons on the touch-screen while driving the simulator. The carrier sentence "select highway route" preceded the number to be selected. The presence of a standardized carrier sentence was based on optimal speech recognition parameters recommended by Simpson (1976). Three different types of highway selection prompts were used in the experiment: visual, auditory diotic and auditory directional. Diotic auditory prompts presented the same information to both ears simultaneously. Directional auditory prompts presented information to only the left or right ear, corresponding to the side of the display in which the highway icon to be selected was located. For example, a directional prompt presented to the left ear would indicate that the desired highway icon was on the left half of the map display. Auditory prompts were recorded in the anechoic chamber of the Auditory Systems Laboratory at Virginia Tech. A Sony DAT and an Audio-Technica ATM-10 microphone were used to record all of the prompts in the left channel microphone input.

Figure 13. An example of the secondary task being performed.

Given the desire to have a natural sentence flow, each prompt was digitally sampled in full ("select highway route 10, select highway route 11, ..."). All of the prompts were recorded three times and the best of the three was used in the experiment.

All auditory prompts were presented through small loudspeakers (Optimus® XTS 3) located behind and to either side of the driver's head, similar to Pachiaudi and Blanchet (1990) and Michael (1995a). Headrest loudspeakers were positioned at a 45° angle, 3-4 inches away from each of the driver's ears, as illustrated in Figure 14. Auditory prompts were controlled by a HyperCard^{TM} program and amplified by a Realistic SCR-3010 stereo receiver. An AudioControl Low Noise Octave Equalizer was used to filter out frequencies outside the human speech region.

Visual prompts contained the same information as the auditory prompts but were displayed as text on the touch-screen. The text message, appearing as black text on a white background, was presented in 36-point Times font to make it clearly legible. Visual prompts were displayed on the touch screen for three seconds, followed by presentation of the map. The three second time limit was chosen to be consistent with the length of the auditory prompts, which lasted about three seconds. As with the auditory diotic prompts, visual prompts gave no indication of the target's location on the display.

Maps were created in Canvas^{TM} then imported into HyperCardTM, which controlled the secondary task. All maps were 15 x 20 cm in size and the highway icons were 2.15 cm square. Display area not used by the map was blacked out, leaving visual prompts and highway maps as the only objects appearing on the secondary task display.

Twenty maps were designed for each density level. Roads were numbered using the standard U.S. Highway icon to add realism to the map display. It was posited that visual search may be affected by the number of digits presented in the highway number (Coren and Ward, 1989; Salvendy, 1997). Therefore, to avoid confounding the results only double-digit numbers from 10-99 were selected. Highway numbers were randomly assigned subject to the limitation that, within an individual map, no more than three numbers started or ended with the same digit. This was done to avoid possible confusion resulting from having too many similar choices on the display screen.

Figure 14. A photograph of the headrest loudspeaker apparatus.

Each map displayed randomly winding roads. The roads in the maps were fictitious, but the display complexity was similar to navigation displays used by Labiale (1989) and Walker et al. (1991). To ensure separation between the left and right sides of the display, a 2.5 cm wide section in the middle of the map was always free of highway icons, although highway lines often crossed the mid-point of the display.

An extension from the previous study by Micheal (1995a) was that the secondary task used in this study involved searching a map display for specific highway numbers, whereas the search task in the study by Micheal involved searching for letter buttons on a blank background. Whenever a highway route number was selected, the icon reversed colors (white numbers on a black background became black numbers on a white background) and a simple auditory beep was presented, after which the touch screen display went blank.

Participants

Twelve licensed male commercial truck drivers participated in the study. Only male drivers were tested due to the high percentage of males (estimated 86.7 percent) in the industry (Kinghorn and Bittner, 1993). Mean participant age was 36 years with a range of 23 to 47 years. Commercial driving experience ranged from 1 to 20 years, with a mean of 9.4 years. An effort was made to recruit a balanced mix of participants who normally drove interstate routes and those who normally drove local business routes. Seven of the participants drove less than 500 miles per week while the other five drove over 1500 miles per week. The primary vehicle driven on the job varied from small delivery trucks to Class 8 tractor-trailers.

Procedures

Participant recruitment. Participants were recruited by phone. A list of commercial truck driving businesses was generated using the local yellow pages. Several large and small businesses were contacted to determine if they had any drivers interested in participating in the study. Typical businesses included moving companies, furniture companies, long-haul trucking companies, and bottling distributors. Subsequently, drivers were either contacted at home or work and were interviewed using a structured telephone questionnaire, Appendix A.

The telephone questionnaire was used to collect demographic information as well as determine eligibility for the study. Qualifying participants were male, held a valid commercial drivers license, had driven regularly in the previous three months, had no history of excessive hearing loss, and were able to read text on a computer screen without difficulty. Other questions related to the number of miles driven per week, percent of night-time driving, years of commercial driving experience, age, and type of vehicle most often driven. If the driver qualified for the experiment, he was informed of the experimental protocol and told that his continued participation would depend upon meeting the prescribed hearing and vision criteria. Drivers were informed that they would be paid $50.00 if they completed the entire experiment, but would receive $5.00 if they did not meet the hearing or vision criteria. If a driver passed the telephone screening and was still interested in participating, an experimental session was scheduled.

Screening procedures. Upon arriving at the Auditory Systems Laboratory participants were asked to read a written description of the experiment, Appendix B. If the prospective participant was still interested in participating, he was asked to read and sign the informed consent form, Appendix C. Each participant was screened to ensure that his hearing and vision met the Federal Highway Administration (FHWA) regulations (FHWA, 1994). FHWA requires commercial vehicle operators to have a pure tone average hearing threshold of at least 40 dBHL (for 500 Hz, 1000 Hz, and 2000 Hz) in the driver's better ear. It should be noted that the FHWA requirement also includes the provision of passing the hearing requirement by the use of a forced-whispered test. The forced-whisper test requires the driver “first perceives a forced-whispered voice in the better ear at not less than 5 feet with or without the use of a hearing aid”. The use of this method has many shortcomings, documented by Robinson, Lee, and Casali (1997) and therefore was not chosen as the testing method. The criteria for participation in the experiment was made more stringent by requiring participants to have hearing levels of at least 40 dBHL for each ear at 500 Hz, 1000 Hz, and 2000 Hz. Participants’ hearing was checked using a Beltone Model 114 clinical pure-tone audiometer in conjunction with TDH 50 earphones.

Vision was also tested during the screening process. A Stereo OPTEC 2000 vision tester was used to ensure each driver possessed 40/20 far vision, consistent with the FHWA vision requirement (FHWA, 1994). If a prospective participant did not meet all of the screening criteria or chose not to participate after completing the screening process, he was paid $5.00 and thanked for his time. All drivers passed the vision exam, but four drivers did not meet the hearing criteria. If the driver qualified and chose to continue, simulator training and experimental procedures began. Examples of the screening forms appear in Appendix D.

Experimental procedure. Experimental procedures were the same for each participant. A detailed checklist of set-up and experimental procedures followed by the experimenter appears in Appendix E. Sound levels were calibrated daily. Calibration levels for ambient noise, background truck noise, simulator noise, and the auditory prompts appear in Table 6. All levels were from A-weighted Leq measurements, with the exception of the auditory prompt level. Auditory prompts were calibrated using an A-weighted Lmax measurement due to the transient nature of human speech. A RION NA-29E octave band analyzer was used for all calibration measurements with the microphone positioned at the participants' head center position (equidistant from each headrest speaker) and with the driver's seat in the lowest position.

Ambient noise level measurements were taken with the simulator and all sound equipment turned on, but not playing any prompts or background noise. The ambient noise level ranged from 37 to 42 dB for all participants, well below the other sound levels used in the experiment. A two-minute Leq measurement was taken for calibration of the prerecorded truck noise. Truck noise calibration for all participants was within ± 0.2 dB of the desired level of 74.9 dBA. A two-minute Leq was also taken for simulator noise calibration. As was done in pretesting, simulator noise levels were calibrated by running the simulator on auto-pilot at 45 mph. Actual simulator noise levels were within ± 0.1 dB of the desired 61.4 dBA level.

Secondary task prompts consisted of the message "Select Highway Route" followed by a random number between 10 and 99. When determining how loud to present the secondary task prompts, it was important to consider design standards for auditory warnings and alarms, such as ISO 7731 (1986), due to similarities in effectively

TABLE 6

Daily Sound Calibration Data (all data are A-weighted Leq measurements, unless otherwise noted)

Participant	Room Ambient Noise Level	Truck Noise Level (74.9)	Simulator Noise Level (61.4)	Auditory Prompt Level* (82.2)
1	39.1	74.8	61.4	82.3
2	38.8	74.7	61.5	82.8
3	41.2	75.0	61.5	82.2
4	38.6	74.8	61.4	82.2
5	38.3	74.9	61.5	82.2
6	38.5	74.9	61.5	82.6
7	39.9	74.9	61.5	81.1
8	37.8	74.5	61.4	82.5
9	37.8	74.5	61.4	82.5
10	37.9	74.9	61.5	82.5
11	38.6	75.1	61.4	82.4
12	38.6	75.1	61.4	82.4
Mean	38.8	74.8	61.5	82.4

* Auditory prompts were calibrated using A-Weighted Lmax due to the transient nature of the stimulus.

presenting auditory information (loud enough, but without startle effects). During pretesting, participants instructed the experimenter to either increase or decrease the level of the secondary task prompts so that they were clearly audible above, but not overwhelming to, the background and simulator noise. After a level was chosen, SPL measurements were taken to define the appropriate level. These measurements showed that the best audibility was 82.2 dBA Lmax. All 18 auditory prompts were played during calibration with the resulting levels falling within ± 0.6 dBA of the desired level of 82.2 dBA.

To allow the subjects to become accustomed to driving a simulator, they were asked to practice driving the simulator for five to ten minutes prior to the start of the experimental scenarios. The scenario used for the first training run was one of the scenarios that had been developed for pilot testing. Prior to beginning the practice run, participants were specifically instructed to conform to the rules of the road, including adhering to the posted speed limits and driving in a safe manner similar to their normal driving habits. The training period concluded when, in the judgment of the experimenter, the driver exhibited acceptable driving behavior (he followed the speed limit signs and rules of the road) and properly controlled the simulator. Participants were then asked if they felt comfortable with the driving task. If so, the practice trial was ended; if not, they were given additional driving time until they felt comfortable.

Once participants became comfortable with the simulated environment they were asked to familiarize themselves with the secondary task. Practice on the secondary task took place while the simulator was stationary. Participants were asked to position themselves looking toward the roadway display with their hands on the steering wheel. Several secondary task prompts were presented during the practice trial, including examples of all prompt types and density levels. After practicing the secondary task by itself, the participant drove the simulator again while simultaneously performing the secondary tasks. Once the participant felt comfortable with the combined tasks, experimental trials began.

Before beginning the experiment, subjects were again informed that the driving task was to be taken seriously, just as during normal commercial driving and that they were expected to obey the rules of the road and adhere to posted speed limits. The experimenter then solicited and answered any additional questions concerning the experiment. Participants were told they could ask questions throughout the experiment, but if possible, to wait until the end of a scenario to do so.

Participants drove for each of the five experimental scenarios, in random order, with short rest breaks between each scenario. Upon completion of all of the experimental scenarios, participants were paid $50.00 for their time and debriefed. In keeping with the experimental goal of reducing the likelihood of problems due to driver fatigue, boredom, and repetition of tasks, the total time to complete the experiment (including screening tests and training drives) was just under three hours. After the participant left, data files were backed-up and the experimental equipment was turned off.

RESULTS

Data Manipulation and Reduction

Raw data used in the analysis were gathered from the 12 seconds of driving time following presentation of the secondary task. Data for the driving performance measures (lane deviation, steering wheel angle, road heading angle error, accidents, and adherence to the speed limit) were collected from the STISIM driving simulator at a rate of 10 Hz. Data for the secondary task measures (accuracy and response time of highway route icon selection) were collected using HyperCard^{TM} and transferred to an Excel^{TM} spreadsheet.

The twelve seconds of raw driving data resulted in 120 lines of data for each condition (times five replications). Each line of data included basic values for each dependent measure. The 120 lines of data were used to calculate standard deviations for steering wheel angle, road heading angle error, and lane deviation. The number of accidents that took place within these 12 seconds were also recorded for later analysis. Values used in the analysis were an average of the five replications for each experimental condition.

As discussed earlier, correct timing of the secondary task prompts depended on the driver traveling at the correct speed as he approached a speed limit sign. In an extreme case, if a driver were going half the speed limit, the secondary task would be presented eight seconds (in the four second condition) or four seconds (in the two second condition) prior to his reaching the point at which the speed limit sign became legible. In such a case, the timing variable would be subject to improper driver behavior and thus not equally presented across subjects and conditions.

To control for this potential timing confound, a data reduction program giving the exact timing of each secondary task prompt was written. Since the STISIM sampling rate was 10 Hz, timing data were reliable to 1/10 of a second. A decision was made prior to running the experiment that prompts had to occur within ± 0.5 seconds of their intended time to be acceptable. Some variation was necessary to allow for slight, unavoidable variations in driving speed. Prompts occurring outside this range were not included in the data.

For each driver/scenario combination a file listing the correct speed limit and the participant's actual speed for the entire scenario was created and used to determine if the driver had maintained an appropriate speed for each condition and responded correctly to each speed limit change. The intended speed and the driver's actual speed were plotted for all experimental sessions. Three “experts” who were familiar with the simulator and the goals of the research evaluated each graph using a structured set of decision rules (Appendix F). Three possible ratings could have been assigned to a driving segment. If the driver changed his speed in accordance with the new speed limit, a correct rating of one was assigned. If the driver did not change his speed in accordance with the new speed limit, a rating of zero was assigned. In those instances in which the driver's speed was already close to the new speed limit before the sign appeared (in which case the sign did not necessitate a change in speed) the segment was eliminated from the data set. Each expert first rated all of the driving scenarios independently. In cases where all three experts did not rate a segment identically (5-10% of all ratings), these ratings were discussed in a formal meeting to reach a consensus opinion as to the appropriate rating. Speed limit adherence data consisted of the percent of the time a driver changed his speed when a speed limit change was required.

Roughly 10 percent of the replications were eliminated due to inappropriate driver behavior. Although five replications of each condition for each participant were collected, this number was sometimes reduced through the filtering procedure described above. However, there were no fewer than three replications in any condition for any subject.

During the practice sessions with one participant, it was evident that he simply could not perform the driving task and the secondary task simultaneously. He had problems each time the secondary task was presented. Although he became frustrated with his frequent crashes, he still attended to the secondary task to the extent that it severely compromised his driving performance. Even after considerable practice and his assertion of comfort with the dual task, his frustration was still apparent. Although it would have been appropriate to stop the experiment at this point, the session was continued in case the experimenter's perception of poor performance was incorrect.

During the five experimental trials this participant's performance did not improve. He averaged over eight accidents per replication, and his total of 41 accidents was considerably greater than the next highest total for any other participant (six). In addition, his speed was extremely variable, often 25 mph over or under the posted speed limit. Because of this subject's obvious inability to perform the experimental tasks, his data were not used and another driver was recruited to replace him.

Multivariate Analysis of Variance (MANOVA)

The data from the seven dependent measures were first analyzed using multivariate analysis of variance (MANOVA) with all main effects and interactions investigated. The Wilks' Lambda criteria was used to determine significant effects at the $\alpha = 0.05$ level. Significant results found in the MANOVA included the main effects of prompt type ($F = 4.46$; $p < 0.001$) and density ($F = 6.94$; $p < 0.001$), the two-way interactions of prompt-by-density ($F = 1.994$; $p = 0.005$) and prompt-by-timing ($F = 1.717$; $p = 0.022$), and the three-way interaction of prompt-by-density-by-timing ($F = 1.384$; $p = 0.041$). These results are summarized in Table 7.

Analysis of Variance (ANOVA)

An analysis of variance (ANOVA) was performed for each dependent measure (seven in total) to determine the loci of significance for main effects and interactions found significant in the MANOVA analysis. The Geisser-Greenhouse correction for homogeneity of variance was used to determine ANOVA significance at $G\text{-}G\ p = 0.05$ level in order to account for possible violations of the ANOVA sphericity assumption (Keppel, 1991).

Significant interactions in each ANOVA were investigated using simple effect *F*-tests followed by application of the Newman-Keuls procedure to determine the loci of the interaction. The Newman-Keuls procedure was also used to examine the main effects. A summary of the significant ANOVA results appears in Table 8. Complete ANOVA summary tables for each dependent measure in the factorial design appear in Appendix G.

TABLE 7

Summary of MANOVA *p*-values for Significant Main Effects and Interactions for the Factorial Design

Wilks' Lambda Criteria	*F*	Degrees of Freedom Numerator	Degrees of freedom denominator	*p*
Prompt	4.455	14	32	< 0.001*
Density	6.943	14	32	< 0.001*
Timing	1.113	14	32	0.384
Prompt-by-Timing	1.717	28	138	0.022*
Prompt-by-Density	1.994	28	138	0.005*
Timing-by-Density	0.869	28	138	0.657
Prompt-by-Timing-by-Density	1.384	56	447	0.041*

* significant at $p \leq 0.05$

TABLE 8

Summary of ANOVA *p*-values for Significant Main Effects and Interactions for the Factorial Design (from Appendix G)

Source of Variance Dependent Measure	*F*	*p*	*G-G p*
Prompt			
Accuracy	5.92	0.009	0.013*
Response Time	14.59	< 0.001	< 0.001*
Density			
Steering Wheel Angle	21.06	< 0.001	< 0.001*
Lane Deviation	14.45	< 0.001	< 0.001*
Road Heading Error	18.52	< 0.001	< 0.001*
Response Time	79.59	< 0.001	< 0.001*
Prompt-by-Timing			
Response Time	3.42	0.016	0.038*
Prompt-by-Density			
Response Time	9.79	< 0.001	< 0.001*

* significant at $p \leq 0.05$

Prompt-by-timing interaction. The prompt-by-timing interaction was significant only for response time ($F = 3.42$, *G-G* $p = 0.038$). Simple-effect F-tests indicated significant simple main effects of prompt at the timing levels of 0 seconds ($F = 7.66$, $p = 0.001$) and 2 seconds ($F = 20.64$, $p < 0.001$), but not for 4 seconds ($F = 1.49$, $p = 0.236$). Newman-Keuls test applied to timing levels 0 and 2 seconds revealed that response time was significantly faster for directional auditory prompts than for diotic auditory or visual prompts. Newman-Keuls results are shown in Figure 15 and specific values used in the procedure appear in Appendix H.

Simple-effect F-tests were also performed on timing for each prompt type. Results indicated that simple main effects of timing existed for the diotic auditory prompt ($F = 5.15$, $p = 0.010$), and the visual prompt ($F = 3.54$, $p = 0.037$), but not for the directional auditory prompt ($F = 1.01$, $p = 0.372$). Newman-Keuls analysis showed that response time for the diotic auditory prompt to be faster for timing levels of 0 and 4 seconds than for 2 seconds. The Newman-Keuls procedure did not find any significant difference between timing levels for the visual prompt. The results are illustrated in Figure 16 and the specific values appear in Appendix I.

Prompt-by-density interaction. As was the case for the prompt-by-timing interaction, the prompt-by-density interaction was significant only for response time ($F = 9.79$, *G-G* $p < 0.001$). Post-hoc comparisons again consisted of simple-effect F-tests followed by Newman-Keuls tests to determine the loci of the interaction. Simple-effect F-tests indicated that a simple main effect of prompt type existed for the high density condition ($F = 38.95$, $p < 0.001$), but not for the medium ($F = 2.10$, $p = 0.135$) or low density conditions ($F = 1.55$, $p = 0.224$). Newman-Keuls tests indicated that in the high density condition, response time was faster when directional auditory prompts were used than when either diotic auditory or visual prompts were used. Newman-Keuls results are shown in Figure 17. A table of values used in the Newman-Keuls procedure for the high density condition appears in Appendix J.

Simple-effect F-tests were also performed to determine differences in density for each prompt type. Results indicated that simple main effects of density existed for all prompt types: directional auditory prompt ($F = 13.85$, $p < 0.001$), diotic auditory prompt ($F = 62.63$, $p < 0.001$), and visual prompt ($F = 81.08$, $p < 0.001$). For the visual and

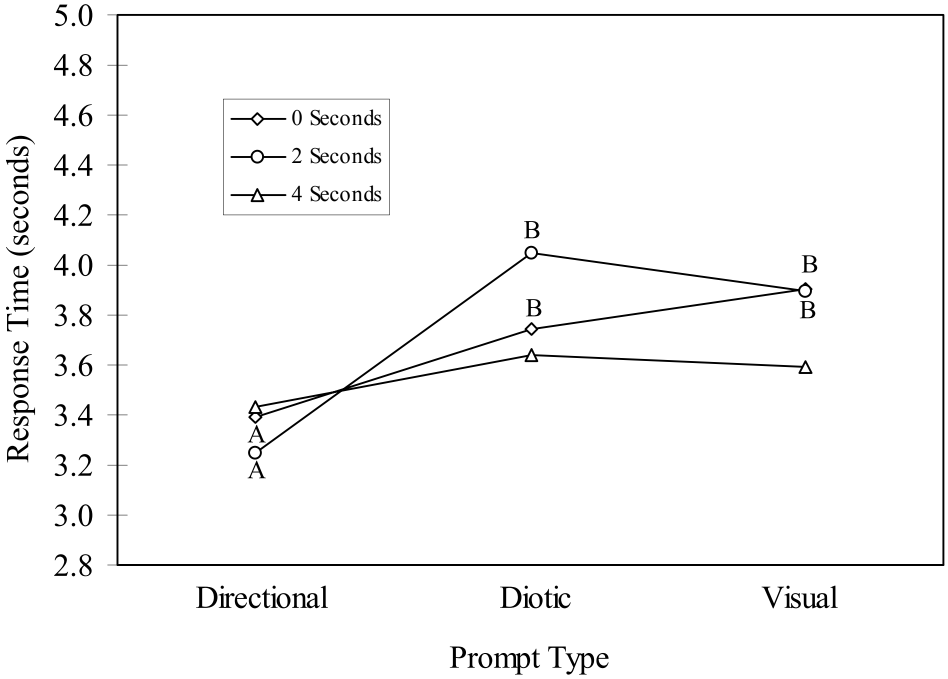


Figure 15. A simple main effect of Prompt at two levels of Timing for the Response Time dependent measure. (For a given level of timing, levels of prompt type with different letters are significantly different from each other. The 4 second timing condition was not significant in the simple effect *F*-test.)

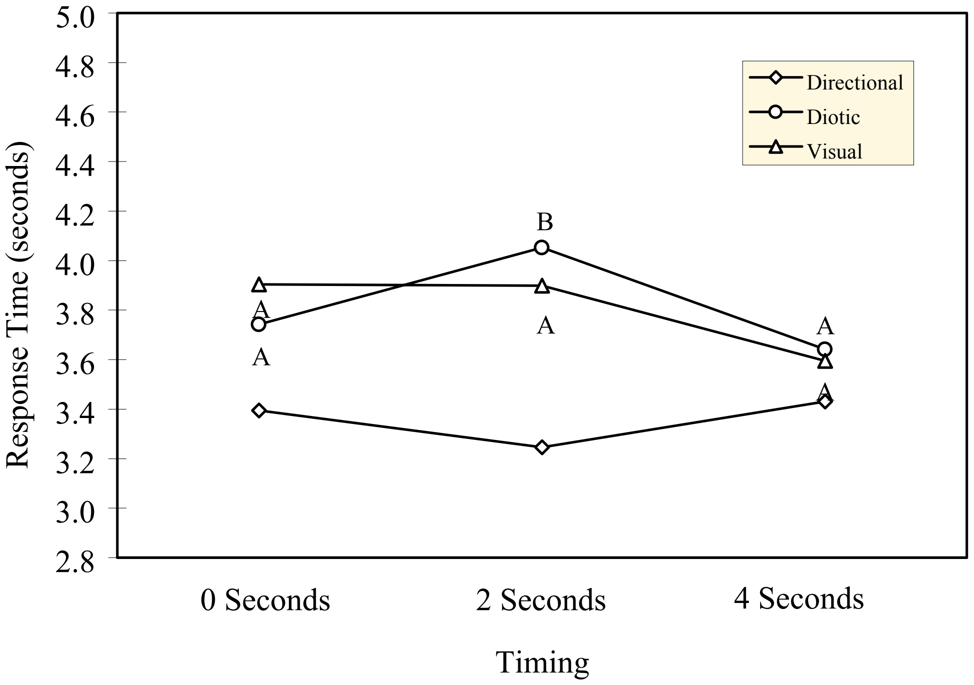


Figure 16. A simple main effect of Timing for two Prompt types for the Response Time dependent measure. (For a given Prompt type, Timing levels with different letters are significantly different from each other. The directional prompt was not significant in the simple effect *F*-test.)

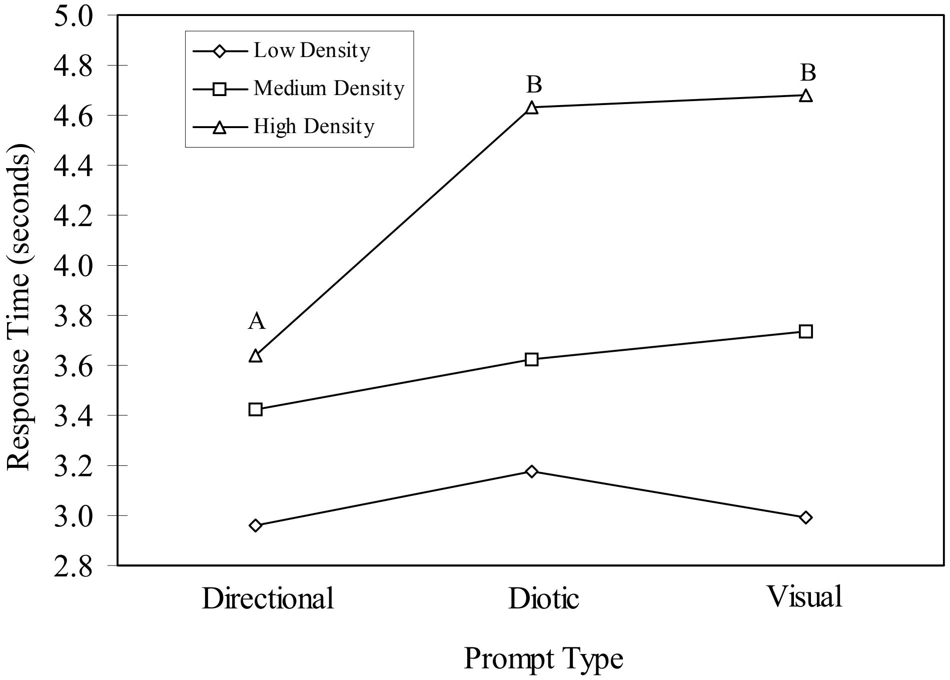


Figure 17. Simple main effects of Prompt at one level of Density for the Response Time dependent measure. (For a given level of Density, Prompt types with different letter labels are significantly different.)

diotic auditory prompts, response times increased significantly at each level of density. For the directional auditory prompt condition, response times for the low density condition were significantly shorter than for either the medium or high density condition. This interaction is illustrated in Figure 18. Values used for the Newman-Keuls tests appear in Appendix K.

Density main effect. The density main effect was found to be significant for four of the seven dependent measures: lane deviation (F = 14.45, G-G $p < 0.001$), steering wheel angle (F = 21.06, G-G $p < 0.001$), road heading angle error (F = 18.52, G-G p <0.001), and response time (F = 79.59, G-G $p < 0.001$). Newman-Keuls tests were used to determine the nature of the main effect for each dependent measure. For steering wheel angle, Figure 19, the high density condition resulted in greater mean steering wheel angle than did the low or medium density conditions. Lane deviation was significantly lower in the low density condition than in either the medium or high density conditions (Figure 20). Figures 21 and 22 show results for road heading angle error and response time, respectively. As can be seen, significant differences were found between each level of density for both dependent measures. Specific values used for all four Newman-Keuls tests for the main effect of density appear in Appendix L.

Prompt type main effect. The main effect of prompt type was found to be significant for both secondary task dependent measures: accuracy ($F = 5.92$, *G-G* $p = 0.013$) and response time ($F = 14.59$, *G-G* $p < 0.001$). The Newman-Keuls post-hoc test revealed that participants selected the correct highway route icon more often when given either a directional or diotic auditory prompt than when given a visual prompt (Figure 23) and that they responded significantly faster when directional auditory prompts were given than when either diotic auditory or visual prompts were given (Figure 24). Values for both Newman-Keuls tests appear in Appendix M.

Control Condition

To determine if driving performance in any of the experimental conditions differed from that in the control condition, the data were arranged into a single-factor experimental design with 28 levels. Twenty-seven levels represented each experimental condition in the 3x3x3 factorial design, and the last level represented the control

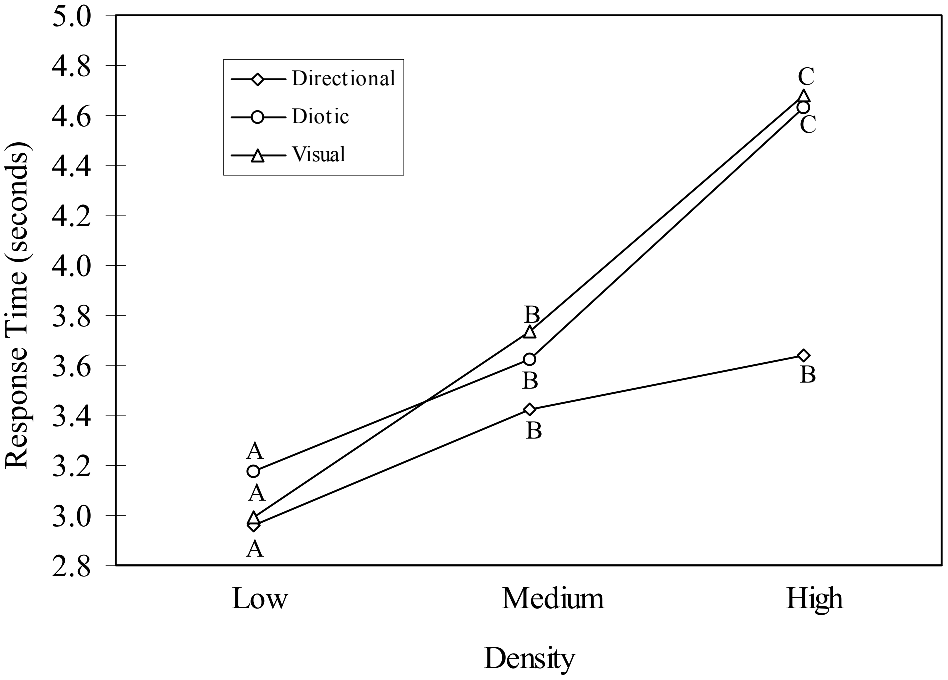


Figure 18. Simple main effects of Density at each level of Prompt for the Response Time dependent measure. (For a given Prompt type, levels of Density with different letter labels are significantly different.)

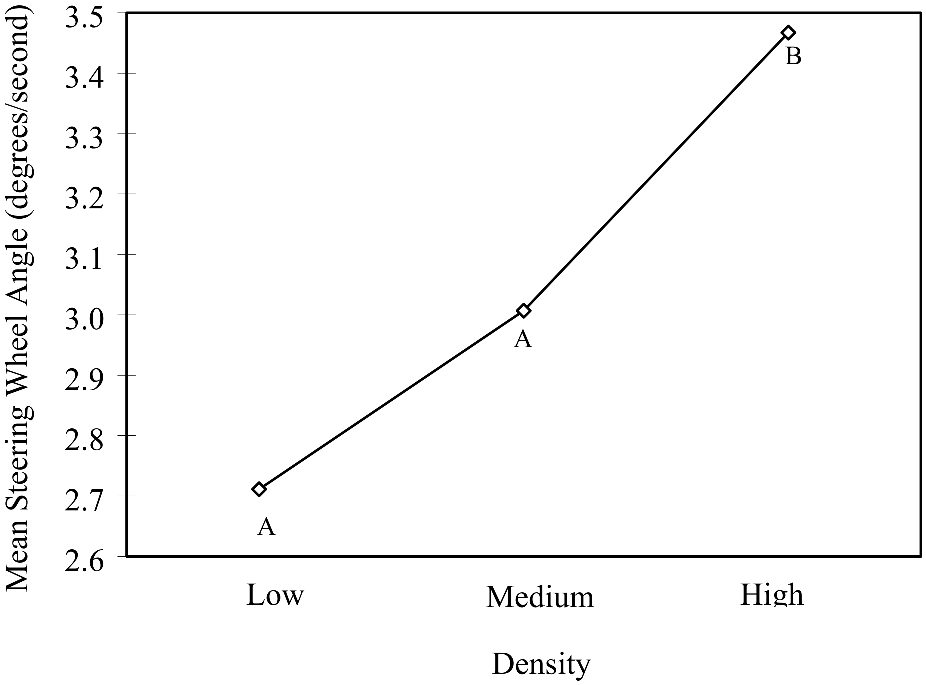


Figure 19. Main effect of Density for the Steering Wheel Angle dependent measure. (Density levels with different letters are significantly different from each other.)

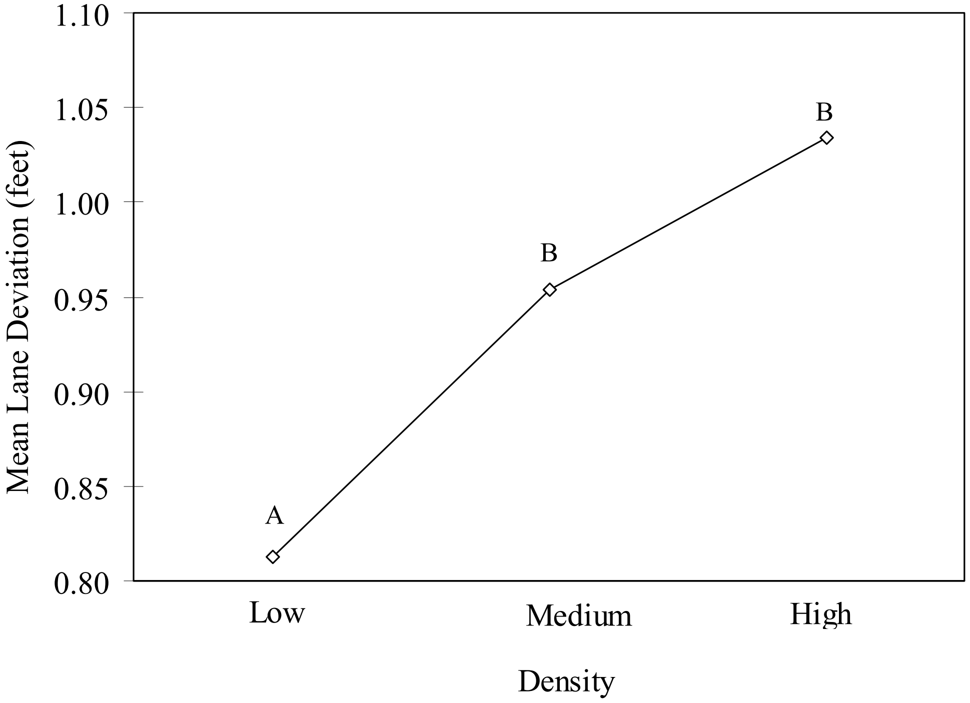


Figure 20. Main effect of Density for the Lane Deviation dependent measure. (Density levels with different letters are significantly different from each other.)

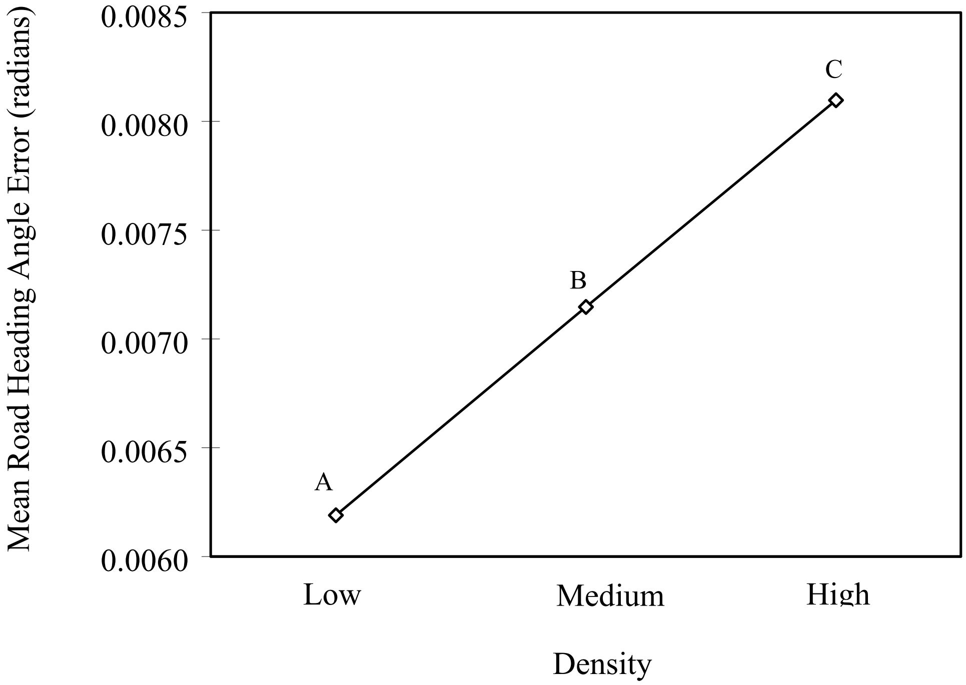


Figure 21. Main effect of Density for the Road Heading Angle Error dependent measure. (Density levels with different letters are significantly different from each other.)

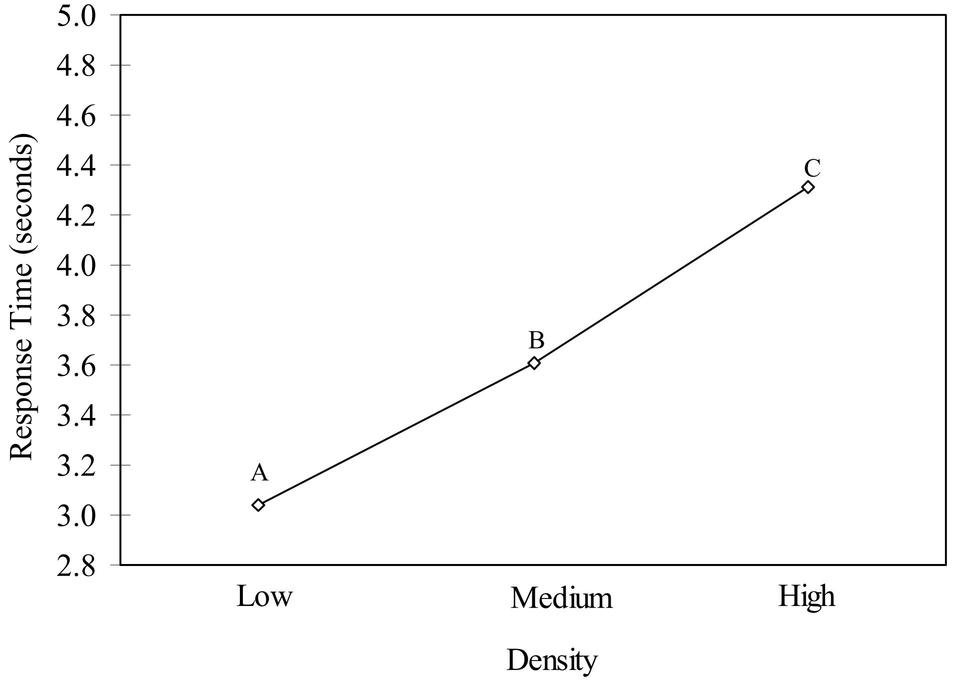


Figure 22. Main effect of Density for the Response Time dependent measure. (Density levels with different letters are significantly different from each other.)

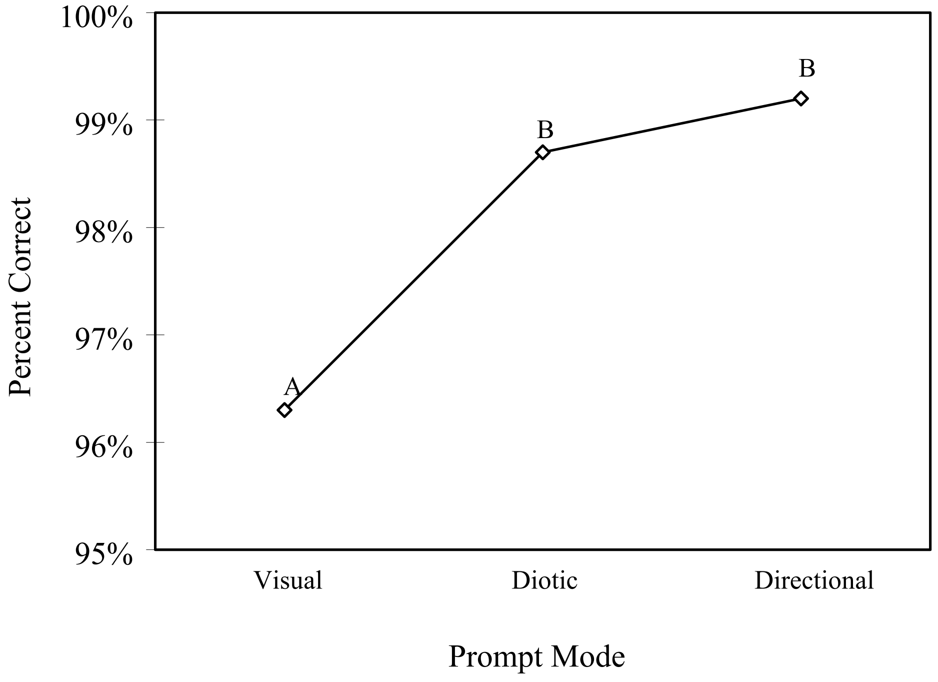


Figure 23. Main effect of Prompt Type for the Accuracy dependent measure. (Prompts with different letters are significantly different from each other.)

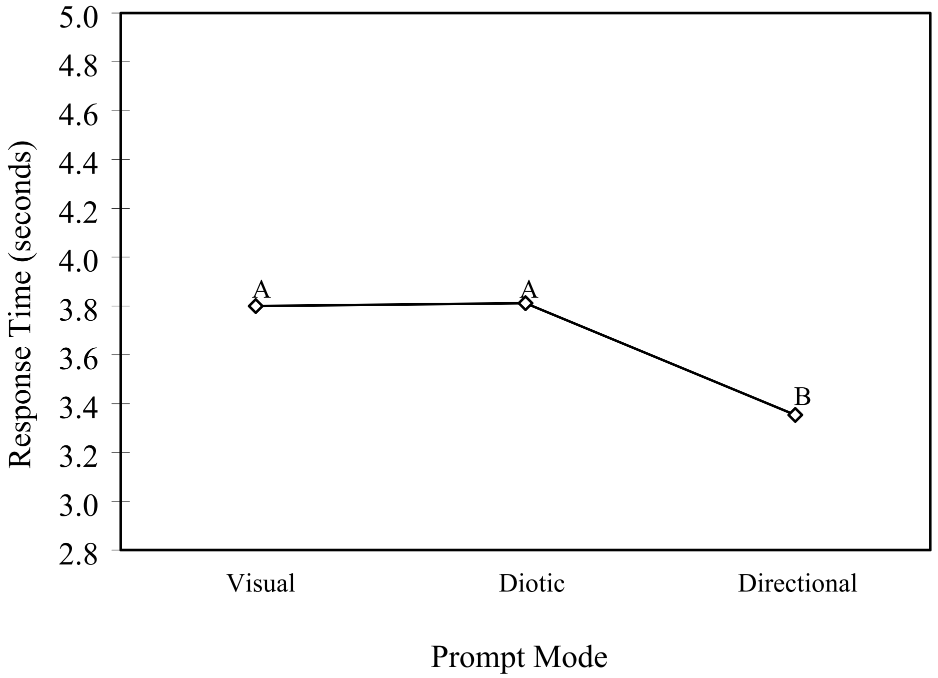


Figure 24. Main effect of Prompt Type for the Response Time dependent measure. (Prompts with different letters are significantly different from each other.)

condition. The analysis was restricted to driving performance measures (lane deviation, steering wheel angle, road heading angle error, accidents, and adherence to the speed limit) because there was no secondary task in the control condition. A MANOVA was applied to the single factor design, resulting in a significant main effect ($F = 1.65$; $p < 0.0001$). The MANOVA summary table appears in Table 9. The Wilks' Lambda criterion was used for determination of significance at the $\alpha = 0.05$ level.

As was done with the factorial design, MANOVA significance was investigated using separate ANOVAs for each dependent measure. ANOVAs performed for each dependent measure resulted in significant main effects for lane deviation ($F = 2.90$; *G-G* $p = 0.011$), steering wheel angle ($F = 3.79$; *G-G* $p = 0.004$), and road heading angle error ($F = 3.41$; *G-G* $p = 0.005$). A summary table of each of the significant ANOVA *p*-values (Greenhouse-Geisser correction) appears in Table 10. Complete ANOVA summary tables for each dependent measure appear in Appendix N.

Post-hoc analyses of significant ANOVA results was conducted differently for the control condition analyses than for the factorial design. In the factorial design, simple effect *F*-tests and the Newman-Keuls procedure were used to test the loci of significance of each interaction and main effect. The goal of the control condition analyses was to determine if there was a difference in driving performance when the secondary task was present compared to when no secondary task was present. The most appropriate post-hoc analysis is the Dunnett test, which is designed to test for significance between a single condition (usually the control condition) and several other conditions (Dunnett, 1955; Dunnett 1964; Keppel, 1994; Winer, B. J., Brown, D. R., and Michels, K. M., 1991). The Dunnett t-test also controls for increased Type I error which exists in multiple comparison tests (Keppel, 1994). The result of the Dunnett test is a critical difference value. If the difference between the control condition mean and an experiment condition mean exceeds the critical difference value, then that experimental condition is considered to be significantly different from the control condition. A two-tailed Dunnett test was employed in the post-hoc analysis for each significant dependent measure. The Dunnett test results for lane deviation, steering wheel angle, and road heading angle error are shown in Tables 11 through 13. Dunnett test results show that of the 27 experimental

TABLE 9

MANOVA summary table for the Control Condition Analysis

Source of Variance: CONTROL CONDITION

Error Term: CONTROL CONDITION*Subject

Statistic	*F*	Numerator df	Denominator df	*p*
Wilks' Lambda	1.651	135	1450.17	< 0.0001*

* significant at $p \leq 0.05$

TABLE 10

ANOVA summary table of Significant Main Effects for the Control Condition Analysis

ANOVA	*F*	*p*	*G-G p*
Steering Wheel Angle	3.792	< 0.001	0.004*
Lane Deviation	2.904	< 0.001	0.011*
Road Heading Error	3.407	< 0.001	0.005*

* significant at $p \leq 0.05$

TABLE 11

Lane Deviation Dunnett test results

Factorial Design Condition				Control Condition Mean	Difference
Prompt Type	Timing Level	Density Level	Mean		
Directional	0 seconds	Low	0.81267	0.69968	+ 0.11299
Directional	0 seconds	Medium	1.03277	0.69968	+ 0.33309 *
Directional	0 seconds	High	1.12132	0.69968	+ 0.42163 *
Directional	2 seconds	Low	0.81380	0.69968	+ 0.11411
Directional	2 seconds	Medium	0.99614	0.69968	+ 0.29646 *
Directional	2 seconds	High	0.88546	0.69968	+ 0.18578
Directional	4 seconds	Low	0.76641	0.69968	+ 0.06673
Directional	4 seconds	Medium	0.89986	0.69968	+ 0.20018
Directional	4 seconds	High	0.96070	0.69968	+ 0.26102 *
Diotic	0 seconds	Low	0.77795	0.69968	+ 0.07827
Diotic	0 seconds	Medium	0.97095	0.69968	+ 0.27126 *
Diotic	0 seconds	High	1.05966	0.69968	+ 0.35998 *
Diotic	2 seconds	Low	0.77648	0.69968	+ 0.07680
Diotic	2 seconds	Medium	0.87691	0.69968	+ 0.17723
Diotic	2 seconds	High	0.98642	0.69968	+ 0.28674 *
Diotic	4 seconds	Low	0.89508	0.69968	+ 0.19540
Diotic	4 seconds	Medium	0.90694	0.69968	+ 0.20725
Diotic	4 seconds	High	0.86113	0.69968	+ 0.16144
Visual	0 seconds	Low	0.85145	0.69968	+ 0.15177
Visual	0 seconds	Medium	0.93890	0.69968	+ 0.23921 *
Visual	0 seconds	High	1.05250	0.69968	+ 0.35282 *
Visual	2 seconds	Low	0.79244	0.69968	+ 0.09276
Visual	2 seconds	Medium	0.96625	0.69968	+ 0.26657 *
Visual	2 seconds	High	1.23235	0.69968	+ 0.53267 *
Visual	4 seconds	Low	0.83242	0.69968	+ 0.13274
Visual	4 seconds	Medium	0.99788	0.69968	+ 0.29820 *
Visual	4 seconds	High	1.14694	0.69968	+ 0.44725 *

Dunnett CD = 0.21062

* significant at $p \leq 0.05$

TABLE 12

Steering Wheel Angle Dunnett test results

Factorial Design Condition				Control Condition Mean	Difference
Prompt Type	Timing Level	Density Level	Mean		
Directional	0 seconds	Low	2.49552	1.61959	+ 0.87593 *
Directional	0 seconds	Medium	3.09317	1.61959	+ 1.47358 *
Directional	0 seconds	High	3.49550	1.61959	+ 1.87591 *
Directional	2 seconds	Low	2.39431	1.61959	+ 0.77472 *
Directional	2 seconds	Medium	3.32215	1.61959	+ 1.70256 *
Directional	2 seconds	High	3.24762	1.61959	+ 1.62803 *
Directional	4 seconds	Low	2.45469	1.61959	+ 0.83510 *
Directional	4 seconds	Medium	2.65670	1.61959	+ 1.03711 *
Directional	4 seconds	High	3.71413	1.61959	+ 2.09454 *
Diotic	0 seconds	Low	3.28056	1.61959	+ 1.66097 *
Diotic	0 seconds	Medium	3.22608	1.61959	+ 1.60650 *
Diotic	0 seconds	High	3.61800	1.61959	+ 1.99841 *
Diotic	2 seconds	Low	2.44006	1.61959	+ 0.82047 *
Diotic	2 seconds	Medium	2.81875	1.61959	+ 1.19916 *
Diotic	2 seconds	High	3.35874	1.61959	+ 1.73915 *
Diotic	4 seconds	Low	2.86279	1.61959	+ 1.24320 *
Diotic	4 seconds	Medium	2.51900	1.61959	+ 0.89941 *
Diotic	4 seconds	High	3.06786	1.61959	+ 1.44827 *
Visual	0 seconds	Low	2.86109	1.61959	+ 1.24150 *
Visual	0 seconds	Medium	3.17603	1.61959	+ 1.55644 *
Visual	0 seconds	High	3.36396	1.61959	+ 1.74437 *
Visual	2 seconds	Low	3.16922	1.61959	+ 1.54963 *
Visual	2 seconds	Medium	3.23989	1.61959	+ 1.62030 *
Visual	2 seconds	High	3.72631	1.61959	+ 2.10673 *
Visual	4 seconds	Low	2.43822	1.61959	+ 0.81863 *
Visual	4 seconds	Medium	3.01538	1.61959	+ 1.39579 *
Visual	4 seconds	High	3.61000	1.61959	+ 1.99041 *

Dunnett CD = 0.71878

* significant at $p \leq 0.05$

TABLE 13

Road Heading Angle Error Dunnett test results

Factorial Design Condition				Control Condition Mean	Difference
Prompt Type	Timing Level	Density Level	Mean		
Directional	0 seconds	Low	0.00586	0.00428	+ 0.00158
Directional	0 seconds	Medium	0.00758	0.00428	+ 0.00330 *
Directional	0 seconds	High	0.00844	0.00428	+ 0.00416 *
Directional	2 seconds	Low	0.00559	0.00428	+ 0.00131
Directional	2 seconds	Medium	0.00781	0.00428	+ 0.00353 *
Directional	2 seconds	High	0.00713	0.00428	+ 0.00285 *
Directional	4 seconds	Low	0.00568	0.00428	+ 0.00140
Directional	4 seconds	Medium	0.00635	0.00428	+ 0.00207 *
Directional	4 seconds	High	0.00812	0.00428	+ 0.00384 *
Diotic	0 seconds	Low	0.00666	0.00428	+ 0.00238 *
Diotic	0 seconds	Medium	0.00749	0.00428	+ 0.00321 *
Diotic	0 seconds	High	0.00828	0.00428	+ 0.00400 *
Diotic	2 seconds	Low	0.00587	0.00428	+ 0.00158
Diotic	2 seconds	Medium	0.00664	0.00428	+ 0.00236 *
Diotic	2 seconds	High	0.00777	0.00428	+ 0.00349 *
Diotic	4 seconds	Low	0.00677	0.00428	+ 0.00249 *
Diotic	4 seconds	Medium	0.00640	0.00428	+ 0.00212 *
Diotic	4 seconds	High	0.00700	0.00428	+ 0.00272 *
Visual	0 seconds	Low	0.00653	0.00428	+ 0.00225 *
Visual	0 seconds	Medium	0.00733	0.00428	+ 0.00305 *
Visual	0 seconds	High	0.00801	0.00428	+ 0.00373 *
Visual	2 seconds	Low	0.00677	0.00428	+ 0.00248 *
Visual	2 seconds	Medium	0.00729	0.00428	+ 0.00301 *
Visual	2 seconds	High	0.00930	0.00428	+ 0.00502 *
Visual	4 seconds	Low	0.00598	0.00428	+ 0.00170 *
Visual	4 seconds	Medium	0.00743	0.00428	+ 0.00314 *
Visual	4 seconds	High	0.00881	0.00428	+ 0.00453 *

Dunnett CD = 0.001691

* significant at $p \leq 0.05$

conditions 13 showed significance for lane deviation, all 27 showed significance for steering wheel angle, and 23 showed significance for road heading angle error.

DISCUSSION

The main goal of this experiment was to examine the effect of aural verses visual presentation of navigational information on a drivers' ability to perform the primary task of driving. A secondary goal of the experiment was to verify the findings of Micheal (1995a) who showed that response time is shortened when auditory prompts are given in a directional format. This study represents an extension of Micheal's (1995a) in that driving performance data (lane deviation, steering wheel angle, road heading angle error, accidents, and adherence to the speed limit) was collected that could be used to objectively test changes in driving performance due to different prompt types.

Control Condition Analysis

The control condition (no secondary task) was included in the experimental design to determine if performing the secondary task had an effect on driving performance. As shown in Tables 11 through 13, it is very clear that driving performance (lane deviation, steering wheel angle, road heading angle error) was degraded when participants were asked to perform the secondary task. These results indicate that a secondary task such as interacting with a navigation system can adversely affect driving performance. A closer look at Tables 11 through 13 reveals another very important insight: of the experimental conditions in which driving performance was not significantly different, most were conditions of auditory prompts. The total number of nonsignificant conditions for the lane deviation and the road heading angle errors as shown in the Dunnett tables totaled 8 directional auditory, 7 diotic auditory, and only 3 visual prompt types. These totals seem to indicate that driving performance was less affected when auditory prompts were used. These results are important due to the lack of significance for any of the driving performance measures in the factorial design of the overall experiment analysis.

Factorial Design Analysis

The main results of interest from this experiment are those from an analysis of the Prompt-by-Timing-by-Density factorial design. Each of these factors had three levels which resulted in 27 experimental conditions. The dependent measures for the factorial design analysis were the two secondary task measures (response time and accidents) as well as the five driving performance measures mentioned earlier.

The Prompt-by-Timing interaction was significant for response time and can best be understood by viewing Figure 15. Figure 15 shows that directional auditory prompts led to faster response times than either auditory diotic or visual prompts. The mean response time for directional auditory prompts was 3.35s compared to 3.80s for visual prompts and 3.81s for diotic auditory prompts. The interaction is shown by the fact that this relationship was only significant for timing levels of 0 and 2, but not for 4 seconds. The reason the 4 second timing level was not significant may be an indication that drivers were able to respond to the secondary task without also having to attend to speed changes when prompts were presented 4 seconds before the speed limit sign became legible. This assertion is supported by the fact that the average response time for all conditions was less than 4 seconds and the average time to respond in the 4 second condition was less than the average for either of the other two conditions.

Response time was also the only statistically significant dependent variable for the Prompt-by-Density interaction. Although Figure 18 shows a near linear relationship between density level and response time (with increases in response time at each increase in density level), the interaction is best described by Figure 17. Figure 17 shows that prompt type only had a significant effect in the high density condition. This effect showed response time to be significantly faster when directional auditory prompts were used than when either diotic auditory or visual prompts were used in high density displays. These results indicate that directional auditory prompts have their greatest utility in complex displays.

The only effect in the factorial design that was statistically significant for any of the driving performance measures was the main effect of density. The main effect of density was significant for lane deviation, steering wheel angle, road heading angle error, and also response time. All of these measures show that increases in density lead to decreases in performance (although this relationship was not statistically significant between all levels for lane deviation and steering wheel angle). The main effect of density shows that increasing display complexity not only decreases secondary task performance, but also degrades driving performance. The practical implication of this result is that ITS technologies should be designed with minimal visual search requirements or they may lead to degraded driving performance.

As mentioned earlier, one of the main objectives of this experiment was to determine if prompt type had an effect on driving performance and secondly to verify the results of Micheal (1995a) who showed improvements in response time and accuracy when directional prompts were used. Thus, the hypothesis of this research that directional auditory prompts would result in better driving performance and lead to quicker and more accurate responses to the secondary task than when either auditory diotic or visual prompts were used was supported by the test results.

As predicted, the main effect of prompt type was significant for accuracy, with either directional or diotic auditory prompts resulting in more accurate driver selections than did the visual prompt. These results are consistent with Micheal's (1995a). It is also interesting to note that these results are similar to the findings of Mollenhauer et al. (1994), who reported increased ability to recall sign information from aural versus visual information.

Although prompt type was only found to be significant for the above secondary task measures, this effect was nearly statistically significant for the same three driving performance measures as were significant for the control condition analysis. The ANOVA summary tables (Appendix G) show that lane deviation ($F = 3.33$; $p = 0.055$), steering wheel angle ($F = 2.44$; $p = 0.111$), and road heading angle error ($F = 3.13$; $p = 0.064$) all approach significance. Since these measures were of interest, it is useful to examine the trend of the results produced. For this purpose, the means are shown graphically in Figures 25 through 27. Each dependent measure is graphed in the same format as was used to show the results of the Newman-Keuls test, but no test of significance was performed (or permitted) since the main effects were not significant. As the graphs show, it appears that driving performance is better with auditory prompts than visual prompts. Although not statistically significant, these graphs do seem to indicate a strong positive correlation between auditory prompts and driving performance. This trend is further supported by the results of the control condition analysis which showed fewer significant differences (via the Dunnett test) between the control condition and experimental conditions for these measures.

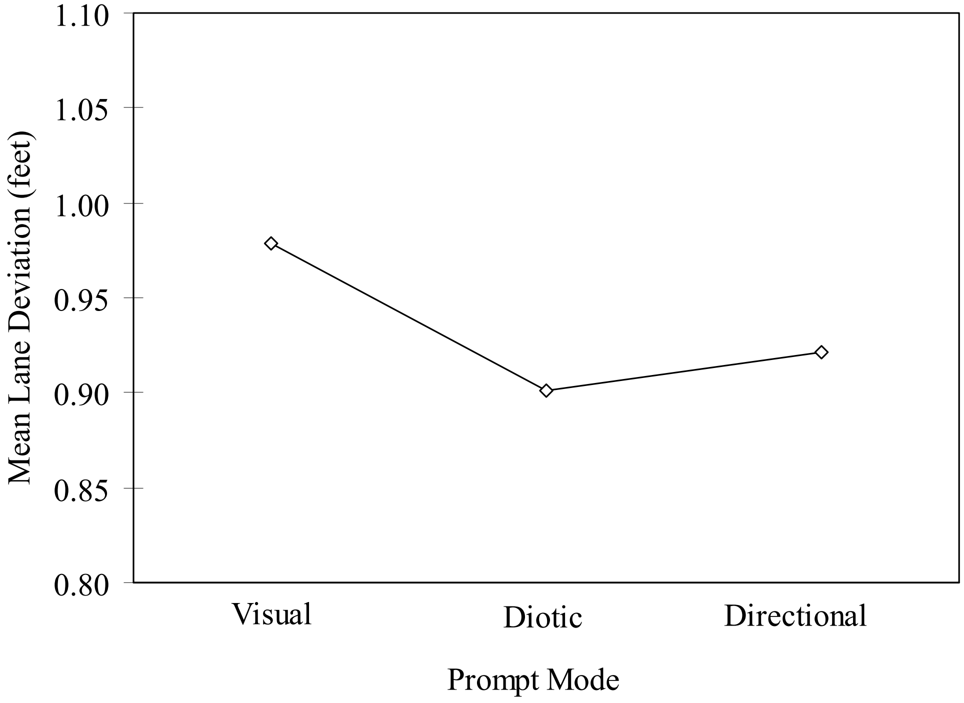


Figure 25. The effect of Prompt for the Lane Deviation dependent measure. (This graph shows a trend in the data; the main effect was not significant.)

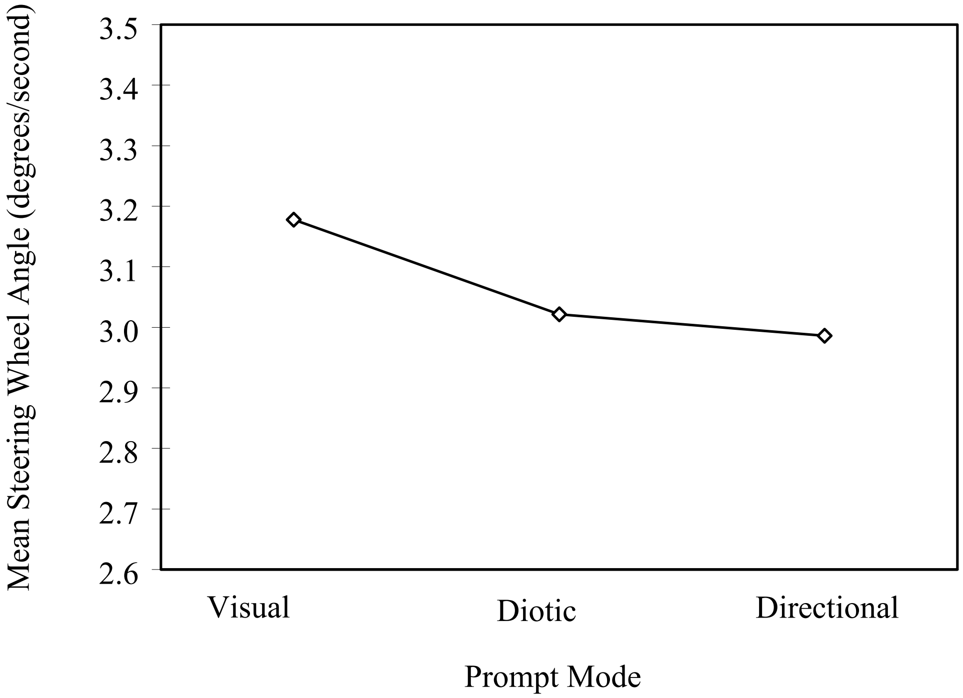


Figure 26. The effect of Prompt for the Steering Wheel Angle dependent measure. (This graph shows a trend in the data; the main effect was not significant.)

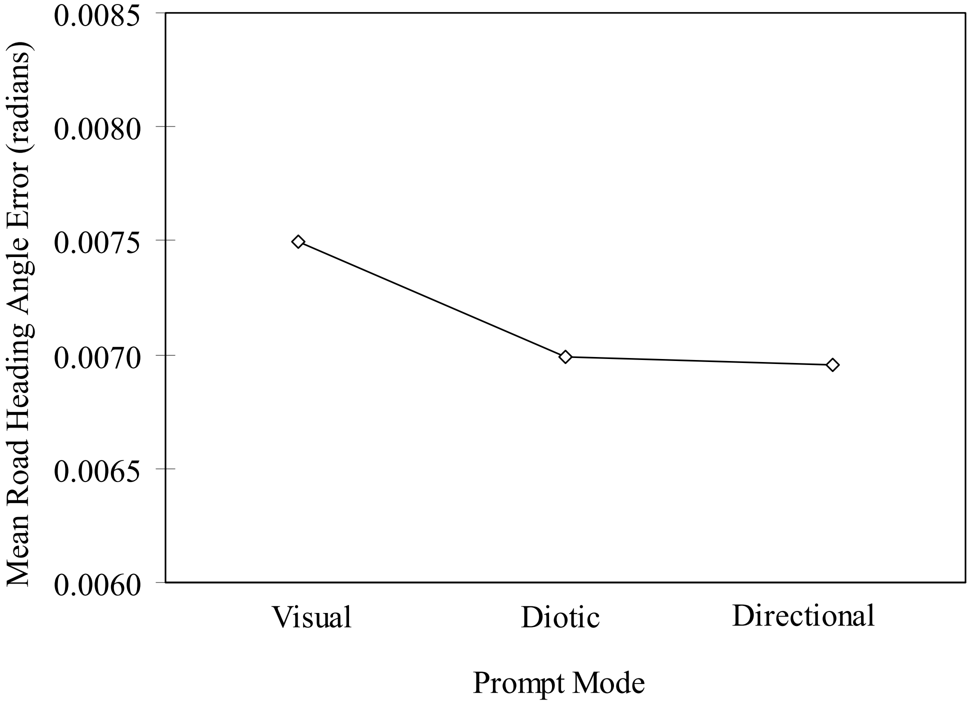


Figure 27. The effect of Prompt for the Road Heading Error dependent measure. (This graph shows a trend in the data; the main effect was not significant.)

The trend shown by the current results contrasts with some unexpected findings by Mollenhauer et al. (1994) who also used a STISIM for data collection. Mollenhauer found that driving performance decreased when road sign information was given aurally versus when the same information was given visually. These results were also surprising as improvement was seen in information recall in the auditory presentation conditions. Mollenhauer's results may be a good indication that some types of information are best displayed visually, whereas other types of information are better suited to aural presentation (as shown in the current study). Drivers in the Mollenhauer experiment also rated auditory presentation of information as more distracting than visual presentation of information. The high fidelity of the current auditory prompts (calibrated to always be audible) and the proximity of the presentation of these prompts to the driver may have had a positive effect that was not present in Mollenhauer's study. It should also be noted that Mollenhauer tested 16 drivers and only had two levels of prompt, thus increasing the power over the current study. Untimely or unclear auditory prompts, or simply the fact that the visual display was mounted atop the dash (an unlikely location if the system were integrated into a modern vehicle), could represent possible confounds that may have lead to this result. Regardless, the results from the present experiment are consistent with the results Mollenhauer expected to find.

A few key changes to the current experimental method would have resulted in a more powerful experiment and possibly significant results in the driving task measures. The most obvious change would have been to test more drivers. Twelve truck drivers were tested in this experiment, and although similar to many of the referenced studies (e.g. Micheal, 1995a; Kantowitz, 1995), other studies tested more drivers (e.g. Mollenhauer, 1994; Stein, Allen, and Parseghian, 1992). Another way to increase the power of the experiment would have been to increase the number of replications of each condition (each was replicated 5 times) in order to reduce the variance of the data. This could have been accomplished either by testing over 2 days (resulting in 10 replications) or by reducing the size of the experiment; thus being able to run more replications in a single session. Of these choices, either increasing the number of participants and/or reducing the number of cells in the experimental design would be preferable over testing for two days due to the attrition rate often found in two day experiments, and the heavy time demands of commercial truck drivers. Although lacking statistically significant findings, the results of this experiment provide some support to using auditory prompts for navigation systems.

In summary, the results of this experiment show some benefits of the use of the auditory displays for information presentation in commercial vehicles. It is clear that presenting information in a directional auditory format results in decreased response time and increased accuracy for a navigation search task. The results also suggest a potential trend towards significantly improved driving performance when auditory prompts are given as opposed to visually presented prompts. Although these results were not statistically significant, they certainly contradict the results of Mollenhauer et al. (1994) who showed decreased driving performance when information was presented auditorially. Another important finding of the current study is that driving performance degrades when display density increases, but the use of directional auditory prompts lessens this deterioration of performance for high density conditions. These results may provide some general guidance to system designers responsible to the design of ITS displays. Systems should be designed with lower levels of display density and the use of auditory prompts may reduce response time in such systems.

SUGGESTIONS FOR FUTURE RESEARCH

The discrepancy between the current results and the results from Mollenhauer et al. (1994) needs to be investigated. One meaningful way to test these differences would be to use the same tasks as Mollenhauer, yet use an optimal auditory display system along with a well designed visual display. In view of the need to integrate ITS technologies into current vehicles, the visual display should be moved from atop the dash to the instrument panel (or the visual display could be tested with a heads-up display). Also, given the lack of significant results of the main effect of prompt in this experiment, experiments with a larger sample of drivers should be conducted.

It is also important to test additional uses of directional auditory information. One potential use for directional auditory information display would be for collision warning systems such as the Eaton Vorad EVT300. Directional auditory warnings in a collision warning system may add significant safety enhancements over traditional auditory warning systems. Directional auditory displays may also prove useful for reconfigureable instrument panel displays, as they may direct drivers' attention to the source locations of new information. Although changing from the traditional analog gauge-dominated dash to a digitally reconfigureable one may be many years away, this latter display technology will almost certainly be employed as it provides large potential cost savings associated with the integration of ITS technologies in the truck cab. One noteworthy application for directional auditory displays in ITS may be seen in lane departure warning systems. Directional auditory warnings have the potential to quickly and accurately communicate unintended lane crossings without startling the driver.

One thing is certain. Drivers' abilities and limitations will remain relatively constant in comparison to the advancement of intelligent systems being integrated into commercial vehicles. If these abilities and limitations are carefully considered at the forefront of design, many of these systems will benefit drivers. If not, they could prove very harmful.

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APPENDIX A

Telephone Screening Questionnaire

Today's Date:

General Information

Participants name Age: Phone #:

Are you a licensed male commercial truck driver? Y / N
Have you had any history of tinnitus or head noises? Y / N
Do you have a history of excessive ear wax? Y / N
Do you have any excessive hearing loss? Y / N
Do you wear glasses or contacts? Y / N
Can your read text on a computer screen without difficulty
(with correction if needed)? Y / N

Employment History

How many years of experience do you have driving commercial trucks? ____ Years
Have you been involved in any accidents while driving commercially? Y / N
If so, were they during the day or at night? Day / Night
What percent of your current driving is night-time driving: ____%
How many miles do you drive commercially per week? ___ miles / week
Are you employed by a private carrier, an owner-operator, or other?
What type of commercial vehicle do you drive most often?

If Acceptable, Inform them:
The total experimental time will be about three hours.
When you first arrive, we will test your hearing and vision to ensure that you can adequately hear and see each part of the experiment. It is possible that you may not qualify for the experiment if you do not meet the hearing and/or vision

criteria. If you do not qualify, you will be paid $5.00 and thanked for coming in. Please realize, however, that the initial hearing and vision tests are not designed to assess or diagnose any physiological or anatomical hearing or vision problems, they will be used only to determine whether or not you will be able to participate in the experiment.

The experiment is divided into seven segments, and you will be paid a total of $50.00 for completion of the entire experiment. This payment will be made to you in cash immediately following your participation in the experiment.

Experimental session Time ______ & Date ______

When arriving at Virginia Tech, you need to stop by Parking Services in the Virginia Tech Visitors Center located off Highway 460 on Southgate Drive. Tell the receptionist that you need a visitors pass to participate in an experiment in Whittemore Hall They can also give you directions to Whittemore Hall and tell you where to park. Please meet me in the Auditory Systems Laboratory, room 538 (5th Floor) in Whittemore Hall at the scheduled time.

This office phone number is (231-9087) and my home number is (953-2291). Please call me if you have any questions or need to reschedule.

Thank you.

APPENDIX B

Description of the Driving Simulator Experiment
Written Instructions to the Participant

This experiment is intended to determine how drivers use in-vehicle navigational displays. If you agree to participate in this experiment, you will be asked to take part in one screening session (about 30 minutes), one training session (about 20 minutes), and five experimental trials (totaling about 2 hours).

In the screening session, you will be asked to read and sign an informed consent from, have your outer ears visually examined, and receive both vision and hearing tests. If you qualify as a participant, the experimenter will show you the equipment which will be used in the experiment and demonstrate its operation to you. You are encouraged to ask questions of the experimenter at any time. The experimenter will answer all of your questions to the best of his ability; however, there may be some questions regarding specifics of the study which can only be answered completely after you have finished your participation.

In the first part of the training session, you will be asked to familiarize yourself with the driving simulator. The controls (steering wheel, brake pedal, and accelerator pedal) work similarly to normal vehicle controls. Although driving the simulator is comparable to driving a real vehicle, there are differences to which you must become accustomed. You will be asked to practice driving the simulator until you feel comfortable doing so. It is very important that you follow the all of the rules of the road (obey traffic laws, posted speed limits, etc.) just as you normally do when operating a motor vehicle.

After you are comfortable driving the simulator, the experimenter will explain and demonstrate the secondary task to you. You will be asked to look at the simulator's roadway display and place your hands on the steering wheel while awaiting further instructions. Periodically, you will be asked to respond to an auditory or visual message instructing you to select a particular highway number appearing on the secondary-task display by touching the appropriate icon with your index finger. Respond to these messages as quickly as possible. For some of these trials, you will see a one sentence message instructing you to look for a particular highway number on the secondary-task display. The visual message will appear as: "Select highway route __." In other trials, you will hear the message rather than seeing it on the screen. The auditory messages will come from the two small loudspeakers located directly behind and to either side of your head. You are asked to listen closely to the auditory messages. Some of the messages will be presented using both loudspeakers, while other messages will be presented using only one of the loudspeakers (left or right). When you hear a message coming from only one loudspeaker, you should begin looking for the highway number on the same side of the display as the loudspeaker from which you heard the message. For instance, if the message comes from only the right loudspeaker, then you should look only on the right side of the screen for the highway number. The target highway number will always be on the same side of the display as the loudspeaker from which the message originated. If the message is heard through both loudspeakers, then the highway number may be located anywhere on the display.

In the final part of the training session, you will be asked to perform the secondary task while driving the simulator. Remember, the search task is a secondary task (much like adjusting the radio), and you should always attend to the driving scene just as you would normally. Remember, always give the highest priority to the driving task. Although it is necessary to respond to the instructions asking you to select a particular highway number as quickly as possible, safe and lawful driving is your most important task. Of course, this includes maintaining legal speeds posted on the roadside signs.

In each of the experimental trials you will be asked to perform both tasks just as you did in the final portion of the training session. Experimental trials will be divided into five 15 to 20 minute segments, with short rest breaks between each segment. Although you may ask questions at any time, please try to wait until a break to do so.

Please print and sign your name below to indicate that you have read and understand these instructions.

______________________________ ______________________________

Participant's Printed Name Participant's Signature

APPENDIX C

Participant Informed Consent

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL ENGINEERING (ISE)
AUDITORY SYSTEMS LABORATORY

Informed Consent for Participants of Investigative Projects

Title of Project: The Effect of Directional Auditory Navigation Cues on Driver Performance in a Simulated Truck Cab Environment.

Principle Investigator: Jared A. Powell

Faculty Advisor: Dr. John G. Casali, Professor, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a study which will investigate how drivers use in-vehicle information displays.

II. PRE-EXPERIMENTAL PROCEDURES

The following pre-experimental procedures will be used in this research. If you wish to become a participant after reading the description of the study and signing this form, you will begin with a screening process which involves checking your hearing and vision. The purpose of these screening tests is to determine if your hearing and seeing ability today qualifies you to participate in the experiment.

First, the experimenter will perform a visual examination of your ears using an otoscope to determine the condition of your outer ears. Next, the hearing in your right and left ears will be tested with very quiet tones presented through a set of headphones. These hearing tests are to ensure that you can hear the auditory messages which will be presented to you during the experiment. You must be very attentive and listen carefully for these tones. You will be asked to press the button on the hand switch and hold it down whenever you can hear the tone and release it when you do not hear the tone. The tones will be very faint, and you will have to listen very carefully to hear them. The hearing test will be conducted in a sound-proof booth with the experimenter sitting outside. The door to the booth will be shut but not locked; either you may open it from the inside or the experimenter may open it from the outside. There is also an intercom system through which you may communicate with the experimenter by simply talking (there are no buttons to push).

During the course of the experiment, you will be presented with written visual instructions in addition to verbal auditory instructions. Therefore, it is necessary that your vision also be tested to ensure that you can read the instructions and the letters on the displays involved in the experiment. Your vision will be tested using a Stereo Optical OPTEC 2000 vision tester. This test is similar to the vision test administered by the Department of Motor Vehicles during driver's license examinations. If qualified, you may choose to participate in a research experiment which will investigate how drivers use in-vehicle information displays.

There is no known risk posed to your well-being by participating in this experiment. Also, realize that the initial hearing and vision tests are not designed to assess or diagnose any physiological or anatomical hearing or vision problems. The tests will be used to determine whether or not you will be able to continue to the main part of the experiment.

III. EXPERIMENTAL PROCEDURES

After qualifying for the experiment, you will be given the opportunity to drive the fixed-base driving simulator. Although the simulator will react similarly to a commercial truck, there may be some differences to which you will have to become accustomed. Next, the experimenter will explain and demonstrate the secondary task. The secondary task consists of the presentation of either an auditory message (presented through loudspeakers located behind and to either side of your head) or a text message (displayed on the secondary task touch screen) directing you to touch a specific highway number on the map appearing on the secondary task display (touch screen). When you are comfortable performing both the primary driving task and the secondary task individually, you will be asked to practice both tasks simultaneously. Once you feel comfortable performing the combined tasks, the experimental trials will begin.

During the experiment, the noise and speech levels may seem loud. Prerecorded truck noise will be presented at levels ranging from 72 to 76 dBA to simulate the background noise levels found in currently available commercial trucks. Auditory prompts related to the secondary task will be presented at levels ranging from 78 to 80 dBA. None of these levels exceed the Occupational Safety and Health Administration (OSHA) legal limit for noise exposure. OSHA regulations allow U.S. industrial workers to be exposed to a 90 dBA time-weighted average (TWA) noise level for an 8-hour workday (corresponding to a 100% dose). In this experiment, the maximum levels to which you will be exposed will be well below 90 dBA for no longer than 3 hours. In fact, OSHA does not even include levels below 80 dBA in its noise exposure calculations.

The experiment will be divided into five 15 to 20 minute trials, with short rest breaks between each trial. In each experimental trail, you will be asked to drive the simulator and perform the secondary task concurrently. The total time necessary to complete the screening, training, and experimental trials will be approximately three hours.

IV. BENEFITS OF THIS RESEARCH

Your participation in this project will provide the following useful information. First, data obtained during the telephone interview will help characterize the population being studied (licensed, male commercial truck drivers). Second, it is the ultimate goal of this research effort to improve the safety and efficiency of commercial vehicle operations. This experiment represents a small step in the pursuit of that goal. It is expected that the results of this study will lead to further research which will continue to improve driving safety for all road users.

No guarantee of benefits has been made to encourage you to participate. You may wish to receive a summary of the results of this research when completed. If so, please leave a self-addressed envelope with the experimenter. To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.

You will also receive payment for each portion of the experiment that you complete as discussed below.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of your participation in this study will be kept strictly confidential. At no time will the researchers release any individual participant's results to anyone other than individuals working on the project without the written consent of the participant. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports of the research. A major goal of this research is to add to the current knowledge base relating to auditory displays in transportation. The findings of this research will be submitted for publication in professional journals that will be available to the general public in addition to the academic community. At no time will any individual's scores be discussed or written about in any of the written documents.

VI. COMPENSATION

For participation in this project you will receive $5.00 for each of the seven segments completed (the screening session, the training session, and the five experimental trials) for a total of $35.00. You will also receive a $15.00 bonus for completing the entire experiment, for a total of $50.00. This payment will be made to you in cash immediately following your participation in the experiment.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time you have spent in the study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant in this experiment. Such circumstances include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or equipment.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT'S RESPONSIBILITIES

I know of no reason I cannot participate in this study. I have the following responsibilities:

– To perform the tasks according to the instructions to the best of my ability.
– To notify the experimenter at any time about discomfort or desire to discontinue participation.

Signature of Participant

X. PARTICIPANT'S PERMISSION

Before signing the two signature pages of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on the following pages.

Experimenter's Copy Of Participant's Signature Page

I have read and understand the informed consent and conditions of this project. All the questions that I have asked have been answered to my satisfaction. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid for only the portion of time that I spend in the study.

Signature
Printed Name
Date

Witness Signature
Printed Name
Date

The research team for this experiment includes Jared A. Powell, a Master's student in Industrial and Systems Engineering, Dr. John G. Casali, Director of the Auditory Systems Laboratory, and Dr. Gary S. Robinson, Research Associate. They may be contacted at the following address and phone number:

Auditory Systems Laboratory
Room 538 Whittemore Hall
VPI & SU
Blacksburg, VA 24061
(540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Dr. Ernie Stout
Chair, University Human Subject's Committee
301 Burruss Hall
VPI & SU
Blacksburg, VA 24061
(540) 231-9359

Participant's Signature Page

I have read and understand the informed consent and conditions of this project. All the questions that I have asked have been answered to my satisfaction. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid for only the portion of time that I spend in the study.

Signature
Printed Name
Date

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Date

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(PLEASE TEAR OFF AND KEEP THIS PAGE FOR FUTURE REFERENCE)

APPENDIX D

Vision & Hearing Screening Forms

Pure-Tone Audiometric Tests for Normal Hearing

Participant: ________________________________ Age:_____ Sex:_____

Phone:____________________ Screening Date:_________ Qualify?____

Right Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125							
250							
500							
1000							
2000							
3000							
4000							
6000							
8000							

Left Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125							
250							
500							
1000							
2000							
3000							
4000							
6000							
8000							

SCREENING FORM

Otoscopic Data

Occluding wax?: ______________________________

Ear canal irritation?: ______________________________

Unusual canal characteristics: ______________________________

Eardrum perforations?: ______________________________

Eardrum scar tissue? ______________________________

Foreign matter?: ______________________________

SCREENING FORM

Vision Tests for Near and Far Acuity

Qualify? ___

Near Point (14") Test

Target	1	2	3	4	5	6	7	8	9	10
NEAR ☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	
Snellen	20	20	20	20	20	20	20	20	20	20
Equivalents	200	100	70	50	40	35	30	25	22	20

Far Point (20 Ft.) Test

Target	1	2	3	4	5	6	7	8	9	10
FAR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Snellen	20	20	20	20	20	20	20	20	20	20
Equivalents	200	100	70	50	40	35	30	25	22	20

APPENDIX E

EXPERIMENT PROCEDURES

Experiment Set-Up

Auditory Systems Lab

1. Enter room, turn on lights
2. Turn power on to:
   - Main surge protector
   - Stereo Optical OPTEC Vision Tester
   - Anachoic Chamber for audiogram
   - Audio Gram machine
   - Lights to the Anachoic Chamber

Environmental and Safety Lab

1. Enter room, turn on lights
2. Turn on power to:
   - PC
   - PC monitor
   - Power Mac
   - Stereo Mixing Board (turn on before any other stereo equipment)
   - Adcom pre-amp
   - Adcom amp
   - Yamaha equalizer
   - Sony Tape Deck
   - Realistic receiver
   - Audio Control equalizer
   - Subject Intercom
   - Experimenter Intercom
   - Driving Monitor
   - Steering wheel Torque motor (this must be off when booting the PC)

3. Turn on air and make sure it has at least 70 LBS pressure
4. Position microphone to room center and calibrate room with RION NA 29

Running Subject

Auditory Systems Lab

1. Meet subject in Auditory Systems Lab
2. Present subject experiment description (ask for questions)
3. Present subject informed consent form (ask for questions)
4. Sign witness part of informed consent and check that they have signed all forms
5. Perform otoscopic exam
6. Perform audiogram
7. Perform vision exam
8. If qualified, escort participant to Environmental and Safety Lab

Environmental and Safety Lab

1. Show participant STISIM Driving Simulator
2. Ask participant to sit in seat and adjust it to their normal driving position in relation to the steering wheel and pedals
3. Explain headrest apparatus and have participant sit in the seat in their normal driving posture, then position headrest speaker apparatus so that each speaker is centered to the side and 3-4 inches away from the participants ears.
4. Explain that the simulator should respond similarly to a tractor trailer for acceleration and braking. Tell the participant that if they should go off the road, or crash into another vehicle, there will be some tire squeal and a crash noise followed by and crash sound then their vehicle will be put back into the center of the roadway.
5. Have participant test-drive the simulator to get used to how it handles for 5-10 minutes. Emphasize that they should take the driving task seriously, as they would during normal driving, and tell them the importance of adhering to the speed limit. (POWER2.DEM scenario)
6. Describe the secondary task and how the touch screen works, emphasize

that they should take advantage of the directional prompt. Test using POWER TEST 2 HyperCard Stack.

7. Have participant drive with the addition of the secondary task for 5-10 minutes, emphasize that they should concentrate on the task of driving, but should also respond to the secondary task as quickly as possible. (POWER1.DEM & POWER TEST 1)
8. Ask participant if they are comfortable with the driving task and if so proceed to experimental trials
9. Enter appropriate SREP1-5.DEM file and scenario length based on replication order
10. Flip the cassette over and rewind to the beginning
11. Enter appropriate SREP1-5.DEM file and scenario length based on replication order
12. Enter appropriate SREP1-5.DEM file and scenario length based on replication order
13. Flip the cassette over and rewind to the beginning
14. Enter appropriate SREP1-5.DEM file and scenario length based on replication order
15. Enter appropriate SREP1-5.DEM file and scenario length based on replication order
16. Have participant fill out and sign payment form and pay subject in cash
17. Ask for any questions about the experiment, and debrief as needed
18. Ask participant if they know of any other co-workers that might be interested in the study
19. Back up all data files on disk
20. Turn off all experimental equipment

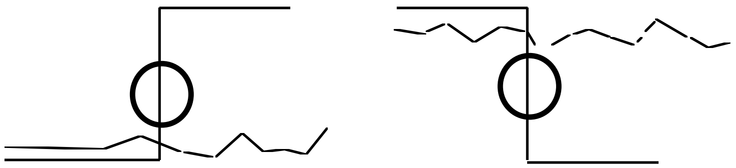
APPENDIX F

DECISION RULES FOR SPEED LIMIT ADHERENCE

Data displayed:

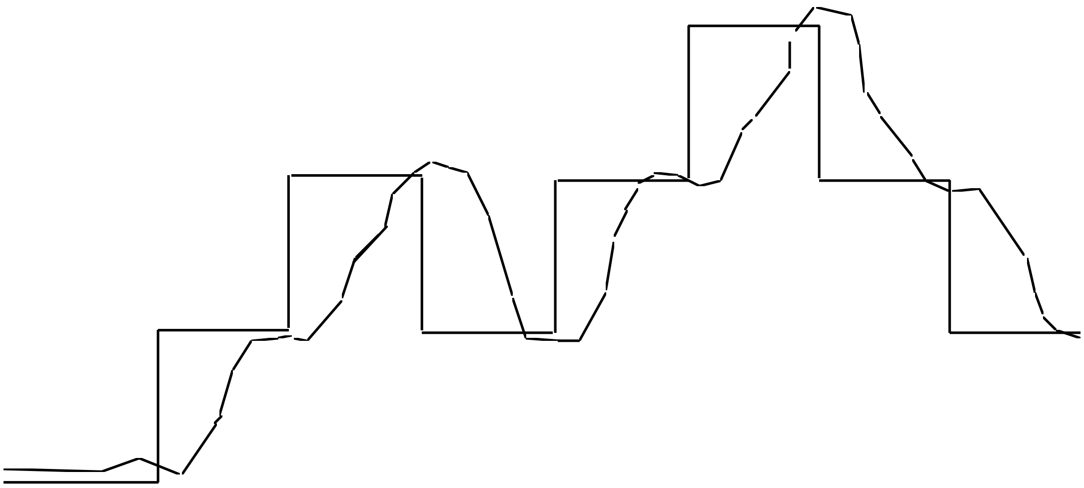
Solid Line = Current Speed Limit
Dashed Line = Drivers' Speed

0 = Driver did not Increase / Decrease his speed in accordance with the change in speed limit (circle this area on the graph)



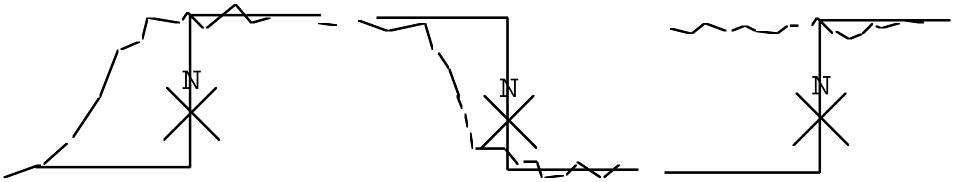
Rate a 0 = Driver did not change his speed in accorance with speed limit

1 = Driver Increased / Decreased his speed in accordance with the change in speed limit (no mark). Drivers must make a clear change in speed in response to the speed limit change before the next speed limit change. This change can take place in any part of the data line, as long as it occurs before the next speed limit change.



Rate a 1 = Driver changed speed

N = Not ratable due to next speed limit change requires no speed increase or decrease by the driver. Always rated (N) because there is no required speed change (x-out this area on the graph and write an (N) . This data will not be analyzed.



Rate an N = No speed change required

Two possible results if the driver does not obey the speed limit:

1) The speed limit change is an increase or decrease of 20 MPH
   May be rated a 0 or 1
2) The speed limit change requires no speed increase or decrease by the driver
   Always rated (N) because there is no required speed change

<u>Operational Definitions</u>

Clear Change in Speed = Steady driving followed by either a steady or sharp increase or decrease in speed before the next speed limit change

Steady Driving = some fluctuations in speed but having no overall increase or decrease over the length of the segment (the slope of a straight line drawn through the data would be essentially zero)

Sharp Increase or Decrease in Speed = a straight line increase or decrease preceded by and followed by steady driving segments (the slope of a straight line drawn through the data would be distinctly positive or negative)

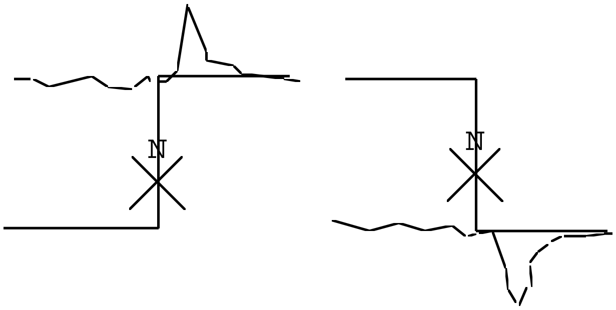
Steady Increase or Decrease in Speed = A steady increase or decrease may have some slight fluctuation but will exhibit an overall increase or decrease in speed (the slope of a straight line drawn through the data would be distinctly positive or negative).

<u>Possible Questionable Areas</u>

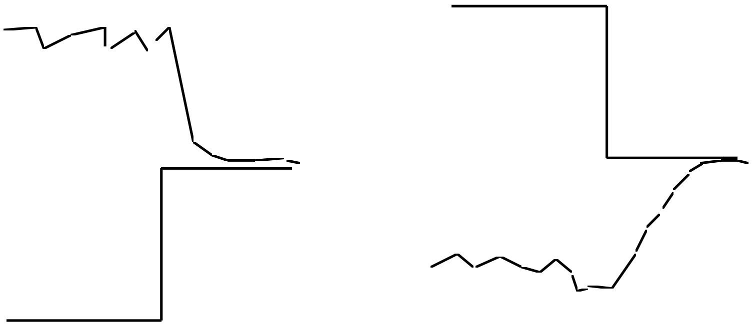
Peaks and Valleys: An increase followed directly by a decrease (or vice versa) with no steady driving in between. The first part is rated a 1 as long as it approached the desired speed limit, and the second part is rated a 1 as long as the change was in response to a new speed limit.

Double Increase (or Decrease): A sharp or steady increase (or decrease) followed by another sharp or steady increase (or decrease). The first increase (or decrease) should be rated a 1 if it approaches the goal speed limit, and the second increase (or decrease) is also rated a 1 if it also approaches the second speed limit. It is also acceptable to rate the second increase (or decrease) a 1 if the rate of change is distinctly different (the slope of each increase or decrease is different from one another)

Examples and rational for some questionable areas



Rate an N due to no change required even
though they seem to respond to the sign



Rate a 1 because even though it was not the intended change the driver did correctly respond to the speed limit sign

Three experts rated each data file and any rating that was not unanimous was discussed in a meeting to determine the most appropriate rating.

APPENDIX G

ANOVA SUMMARY TABLES FOR THE FACTORIAL DESIGN

TABLE G-1 ANOVA Summary Table for Steering Wheel Angle

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	18.379771			
Within-Subject					
Prompt (P)	2	1.125441	2.44	0.1108	0.1204
P x S	22	0.462095			
Greenhouse-Geisser Epsilon = 0.8594					
Timing (T)	2	1.745542	2.00	0.1594	0.1729
T x S	22	0.873443			
Greenhouse-Geisser Epsilon = 0.7562					
Density (D)	2	15.677218	21.06	0.0001	0.0001*
D x S	22	0.744312			
Greenhouse-Geisser Epsilon = 0.7736					
P x T	4	1.463109	1.97	0.1164	0.1340
P x T x S	44	0.744158			
Greenhouse-Geisser Epsilon = 0.7953					
P x D	4	0.974108	1.02	0.4070	0.3827
P x D x S	44	0.953985			
Greenhouse-Geisser Epsilon = 0.5631					
T x D	4	0.594262	0.78	0.5425	0.4870
T x D x S	44	0.759164			
Greenhouse-Geisser Epsilon = 0.5907					
P x T x D	8	0.730867	0.91	0.5081	0.4518
P x T x D x S	88	0.798805			
Greenhouse-Geisser Epsilon = 0.4180					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-2
ANOVA Summary Table for Lane Deviation

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	1.100372			
Within-Subject					
Prompt (P)	2	0.176326	3.33	0.0547	0.0758
P x S	22	0.053026			
Greenhouse-Geisser Epsilon = 0.7093					
Timing (T)	2	0.047056	0.95	0.4022	0.3957
T x S	22	0.049557			
Greenhouse-Geisser Epsilon = 0.9836					
Density (D)	2	1.350451	14.45	0.0001	0.0001*
D x S	22	0.093472			
Greenhouse-Geisser Epsilon = 0.9978					
P x T	4	0.071187	0.97	0.4332	0.4197
P x T x S	44	0.073343			
Greenhouse-Geisser Epsilon = 0.7702					
P x D	4	0.097898	1.51	0.2171	0.2379
P x D x S	44	0.065037			
Greenhouse-Geisser Epsilon = 0.6276					
T x D	4	0.028007	0.38	0.8245	0.7528
T x D x S	44	0.074491			
Greenhouse-Geisser Epsilon = 0.6830					
P x T x D	8	0.079183	1.19	0.3137	0.3269
P x T x D x S	88	0.066492			
Greenhouse-Geisser Epsilon = 0.5727					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-3
ANOVA Summary Table for Road Heading Angle Error

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.00005204			
Within-Subject					
Prompt (P)	2	0.00000999	3.13	0.0638	0.0888
P x S	22	0.00000319			
Greenhouse-Geisser Epsilon = 0.6700					
Timing (T)	2	0.00000447	1.18	0.3257	0.3230
T x S	22	0.00000378			
Greenhouse-Geisser Epsilon = 0.8995					
Density (D)	2	0.00009818	18.52	0.0001	0.0001*
D x S	22	0.00000530			
Greenhouse-Geisser Epsilon = 0.8461					
P x T	4	0.00000388	0.81	0.5237	0.4981
P x T x S	44	0.00000478			
Greenhouse-Geisser Epsilon = 0.7677					
P x D	4	0.00000465	0.89	0.4754	0.4411
P x D x S	44	0.00000520			
Greenhouse-Geisser Epsilon = 0.6292					
T x D	4	0.00000109	0.25	0.9093	0.8389
T x D x S	44	0.00000439			
Greenhouse-Geisser Epsilon = 0.6617					
P x T x D	8	0.00000442	1.09	0.3767	0.3745
P x T x D x S	88	0.00000405			
Greenhouse-Geisser Epsilon = 0.5717					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-4
ANOVA Summary Table for Speed Limit Adherence

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.007127			
Within-Subject					
Prompt (P)	2	0.000586	0.17	0.8488	0.7996
P x S	22	0.003549			
Greenhouse-Geisser Epsilon = 0.7913					
Timing (T)	2	0.000864	0.37	0.6924	0.6907
T x S	22	0.002312			
Greenhouse-Geisser Epsilon = 0.9916					
Density (D)	2	0.002785	0.74	0.4877	0.4776
D x S	22	0.003754			
Greenhouse-Geisser Epsilon = 0.9165					
P x T	4	0.005772	1.82	0.1429	0.1772
P x T x S	44	0.003179			
Greenhouse-Geisser Epsilon = 0.5987					
P x D	4	0.004325	1.00	0.4173	0.3964
P x D x S	44	0.004321			
Greenhouse-Geisser Epsilon = 0.6337					
T x D	4	0.003110	0.81	0.5237	0.4782
T x D x S	44	0.003825			
Greenhouse-Geisser Epsilon = 0.6248					
P x T x D	8	0.005135	1.32	0.2447	0.2781
P x T x D x S	88	0.003893			
Greenhouse-Geisser Epsilon = 0.4958					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-5
ANOVA Summary Table for Accidents

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.002331			
Within-Subject					
Prompt (P)	2	0.000239	0.11	0.8940	0.8352
P x S	22	0.002125			
Greenhouse-Geisser Epsilon = 0.7405					
Timing (T)	2	0.001906	1.02	0.3777	0.3776
T x S	22	0.001872			
Greenhouse-Geisser Epsilon = 0.9984					
Density (D)	2	0.001721	1.16	0.3323	0.3250
D x S	22	0.001485			
Greenhouse-Geisser Epsilon = 0.7917					
P x T	4	0.002126	0.92	0.4600	0.4288
P x T x S	44	0.002307			
Greenhouse-Geisser Epsilon = 0.6259					
P x D	4	0.002948	1.21	0.3198	0.3205
P x D x S	44	0.002434			
Greenhouse-Geisser Epsilon = 0.6521					
T x D	4	0.000413	0.15	0.9611	0.9187
T x D x S	44	0.002715			
Greenhouse-Geisser Epsilon = 0.7047					
P x T x D	8	0.001831	0.69	0.7013	0.6166
P x T x D x S	88	0.002662			
Greenhouse-Geisser Epsilon = 0.5476					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-6
ANOVA Summary Table for Secondary Task Accuracy

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.010951			
Within-Subject					
Prompt (P)	2	0.024468	5.92	0.0088	0.0131*
P x S	22	0.004131			
Greenhouse-Geisser Epsilon = 0.8481					
Timing (T)	2	0.008125	1.93	0.1685	0.1693
T x S	22	0.004202			
Greenhouse-Geisser Epsilon = 0.9838					
Density (D)	2	0.009190	2.50	0.1051	0.1329
D x S	22	0.003676			
Greenhouse-Geisser Epsilon = 0.6202					
P x T	4	0.008981	2.43	0.0617	0.1026
P x T x S	44	0.003695			
Greenhouse-Geisser Epsilon = 0.5683					
P x D	4	0.003900	1.03	0.4048	0.3893
P x D x S	44	0.003804			
Greenhouse-Geisser Epsilon = 0.6720					
T x D	4	0.008148	1.99	0.1121	0.1436
T x D x S	44	0.004087			
Greenhouse-Geisser Epsilon = 0.6542					
P x T x D	8	0.003831	1.14	0.3425	0.3469
P x T x D x S	88	0.003349			
Greenhouse-Geisser Epsilon = 0.4077					
Total	323				

* significance at $p \leq 0.05$.

TABLE G-7
ANOVA Summary Table for Secondary Task Response Time

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	19.062658			
Within-Subject					
Prompt (P)	2	7.336942	14.59	0.0001	0.0004*
P x S	22	0.502765			
Greenhouse-Geisser Epsilon = 0.7857					
Timing (T)	2	0.917628	3.68	0.0417	0.0422*
T x S	22	0.249039			
Greenhouse-Geisser Epsilon = 0.9908					
Density (D)	2	43.991226	79.59	0.0001	0.0001*
D x S	22	0.552732			
Greenhouse-Geisser Epsilon = 0.8059					
P x T	4	1.091969	3.42	0.0162	0.0382
P x T x S	44	0.319547			
Greenhouse-Geisser Epsilon = 0.6241					
P x D	4	3.122854	9.79	0.0001	0.0003*
P x D x S	44	0.318849			
Greenhouse-Geisser Epsilon = 0.6265					
T x D	4	0.160877	0.44	0.7767	0.6977
T x D x S	44	0.363041			
Greenhouse-Geisser Epsilon = 06528					
P x T x D	8	0.626135	2.17	0.0370	0.0827
P x T x D x S	88	0.288015			
Greenhouse-Geisser Epsilon = 0.5324					
Total	323				

* significance at $p \leq 0.05$.

APPENDIX H

NEWMAN-KEULS TABLES FOR PROMPT TYPE AT 0 AND 2 SECOND TIMING LEVELS FOR THE RESPONSE TIME DEPENDENT MEASURE

Condition: Prompt for Timing = 0 Seconds

MSerror = 0.320
N = 36

df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Prompt Type	Mean	3.394	3.742	3.904	C.D.
Directional	3.394		0.348*	0.510*	0.324
Diotic	3.742			0.162	0.269
Visual	3.904				

* significance at *p* ≤ 0.05

Condition: Prompt for Timing = 2 Seconds

MSerror = 0.320
N = 36

df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Prompt Type	Mean	3.246	3.899	4.052	C.D.
Directional	3.246		0.653*	0.806*	0.324
Visual	3.899			0.153	0.269
Diotic	4.052				

* significance at *p* ≤ 0.05

APPENDIX I

NEWMAN-KEULS TABLES FOR TIMING AT DIOTIC AND VISUAL PROMPT TYPES FOR THE RESPONSE TIME DEPENDENT MEASURE

Condition: Timing for Diotic Prompt

MSerror = 0.320
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Timing	Mean	3.642	3.742	4.052	C.D.
4 Seconds	3.642		0.100	0.410*	0.324
0 Seconds	3.742			0.310*	0.269
2 Seconds	4.052				

* significance at $p \leq 0.05$

Condition: Timing for Visual Prompt

MSerror = 0.320
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Timing	Mean	3.595	3.899	3.904	C.D.
4 Seconds	3.595		0.304	0.309	0.324
2 Seconds	3.899			0.005	0.269
0 Seconds	3.904				

* significance at $p \leq 0.05$

APPENDIX J

NEWMAN-KEULS TABLES FOR PROMPT TYPE AT HIGH DENSITY FOR THE RESPONSE TIME DEPENDENT MEASURE

Condition: Prompt for High Density

MSerror = 0.319
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Prompt Type	Mean	3.639	4.632	4.679	C.D.
Directional	3.639		0.993*	1.040*	0.324
Diotic	4.632			0.047	0.269
Visual	4.679				

* significance at *p*≤ 0.05

APPENDIX K

NEWMAN-KEULS TABLES FOR DENSITY AT EACH PROMPT TYPE FOR THE RESPONSE TIME DEPENDENT MEASURE

Condition: Density for Directional Prompt

MSerror = 0.319
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Density	Mean	2.963	3.461	3.639	C.D.
Low	2.963		0.498*	0.676*	0.324
Medium	3.461			0.178	0.269
High	3.639				

* significance at $p \leq 0.05$

Condition: Density for Diotic Prompt

MSerror = 0.319
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Density	Mean	3.177	3.627	4.632	C.D.
Low	3.177		0.450*	1.455*	0.324
Medium	3.627			1.005*	0.269
High	4.632				

* significance at $p \leq 0.05$

Condition: Density for Visual Prompt

MSerror = 0.319
N = 36
df = 44

r	q(r,44)	C.D.
3	3.44	0.324
2	2.86	0.269

Density	Mean	2.988	3.732	4.679	C.D.
Low	2.988		0.744*	1.691*	0.324
Medium	3.732			0.947*	0.269
High	4.679				

* significance at $p \leq 0.05$

APPENDIX L

NEWMAN-KEULS TABLES FOR THE MAIN EFFECT OF DENSITY PERFORMED ON STEERING WHEEL ANGLE, RESPONSE TIME, ROAD HEADING ANGLE ERROR, AND LANE DEVIATION DEPENDENT MEASURES

Dependent Measure: Steering Wheel Angle

MSerror = 0.744
N = 108
df = 22

r	q(r,22)	C.D.
3	3.58	0.297
2	2.95	0.245

Density	Mean	2.711	3.007	3.467	C.D.
Low	2.711		0.296	0.756*	0.297
Medium	3.007			0.460*	0.245
High	3.467				

* significance at $p \leq 0.05$

Dependent Measure: Response Time

MSerror = 0.744
N = 108
df = 22

r	q(r,22)	C.D.
3	3.58	0.297
2	2.95	0.245

Density	Mean	3.043	3.607	4.316	C.D.
Low	3.043		0.564*	1.273*	0.297
Medium	3.607			0.709*	0.245
High	4.316				

* significance at $p \leq 0.05$

Dependent Measure: Road Heading Angle Error

MSerror = 0.0000053
N = 108
df = 22

r	q(r,22)	C.D.
3	3.58	0.000793
2	2.95	0.000654

Density	Mean	0.006190	0.007147	0.008097	C.D.
Low	0.006190		0.000957*	0.001907*	0.000793
Medium	0.007147			0.000950*	0.000654
High	0.008097				

* significance at $p \leq 0.05$

Dependent Measure: Lane Deviation

MSerror = 0.093472
N = 108
df = 22

r	q(r,22)	C.D.
3	3.58	0.105320
2	2.95	0.086786

Density	Mean	0.813190	0.954067	1.034054	C.D.
Low	0.813190		0.140877*	0.220864*	0.105320
Medium	0.954067			0.079987	0.086786
High	1.034054				

* significance at $p \leq 0.05$

APPENDIX M

NEWMAN-KEULS TABLES FOR THE MAIN EFFECT OF PROMPT TYPE PERFORMED ON ACCURACY AND RESPONSE TIME DEPENDENT MEASURES

Dependent Measure: Accuracy

MSerror = 0.004
N = 108
df = 22

Prompt Mode	Mean	0.963	0.987	0.992	C.D.
Visual	0.963		0.024*	0.029*	0.022
Diotic	0.987			0.005	0.018
Directional	0.992				

r	q(r,22)	C.D.
3	3.58	0.022
2	2.95	0.018

* significance at $p \leq 0.05$

Dependent Measure: Response Time

MSerror = 0.004
N = 108
df = 22

Prompt Mode	Mean	3.354	3.799	3.812	C.D.
Directional	3.354		0.445*	0.458*	0.022
Visual	3.799			0.013	0.018
Diotic	3.812				

r	q(r,22)	C.D.
3	3.58	0.022
2	2.95	0.018

* significance at $p \leq 0.05$

APPENDIX N

ANOVA SUMMARY TABLES FOR THE CONTROL CONDITION ANALYSIS

ANOVA Summary Table for Steering Wheel Angle

Source	df	MS	*F*	*p*	*G-G p*
Between-Subjects					
Subjects (S)	11	18.0406			
Within-Subject					
Control Condition (CC)	27	2.9309	3.792	< 0.001	0.004*
CC x S	297	0.7729			
Greenhouse-Geisser Epsilon = 0.1938					
Total	335				

* significance at $p \leq 0.05$

ANOVA Summary Table for Lane Deviation

Source	df	MS	*F*	*p*	*G-G p*
Between-Subjects					
Subjects (S)	11	1.11505			
Within-Subject					
Control Condition (CC)	27	0.1927	2.904	< 0.001	0.011*
CC x S	297	0.0663			
Greenhouse-Geisser Epsilon = 0.2423					
Total	335				

* significance at $p \leq 0.05$

ANOVA Summary Table for Road Heading Error

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.00005143			
Within-Subject					
Control Condition (CC)	27	0.00001459	3.407	< 0.001	0.005*
CC x S	297	0.00000428			
Greenhouse-Geisser Epsilon = 0.2351					
Total	335				

* significance at *p*≤ 0.05

ANOVA Summary Table for Speed Limit Adherence

Source	df	MS	*F*	*p*	*G-G* *p*
Between-Subjects					
Subjects (S)	11	0.00687			
Within-Subject					
Control Condition (CC)	27	0.00392	1.103	0.334	0.369
CC x S	297	0.00355			
Greenhouse-Geisser Epsilon = 0.185					
Total	335				

* significance at *p*≤ 0.05

ANOVA Summary Table for Accidents

Source	df	MS	*F*	*p*	*G-G p*
Between-Subjects					
Subjects (S)	11	0.00225			
Within-Subject					
Control Condition (CC)	27	0.00169	0.733	0.833	0.619
CC x S	297	0.00230			
Greenhouse-Geisser Epsilon = 0.2118					
Total	335				

* significance at $p \leq 0.05$

VITA

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EDUCATION

M.S. in Industrial and Systems Engineering, Human Factors & Safety Option, Dec 1999
Virginia Polytechnic Institute and State University Blacksburg, VA

B.S. degree in Psychology, May 1992
University of Idaho Moscow, ID

EXPERIENCE

Research Scientist June 1996 - Present
DaimlerChrysler Research and Technology of North America
Vehicle Systems Technology Center Portland, OR

The current position within DaimlerChrysler research focuses on providing Freightliner with human factors expertise while also facilitating the exchange of human factors knowledge and expertise between research centers in the US and Germany. Tasks include the design and conduction of human factors studies with emphasis upon the integration of Intelligent Transportation Systems into current truck cabs in a safe, efficient, and effective manner. Primary projects have been the optimization of a current driver message display system to include driver control of information and a safety based priority system while integrating collision warning and advanced cruise control technologies. Recent work has focused on an in-vehicle computer that integrates even more driver information sources but also makes use of speech recognition and synthesis to reduce driver workload.

PATENTS PENDING

Integrated Message Display Systems For A Vehicle (No. 60/122,167)
Fuel Use Efficiency System For A Vehicle For Assisting The Driver To Improve Fuel Economy (No. 08/982,117)

PROFESSIONAL AFFILIATIONS

Human Factors and Ergonomics Society (HFES) Member	1992 - Present
Society of Automotive Engineers (SAE) Member	1997 - Present
SAE Safety and Human Factors Standards Committee Member	1998 - Present

ACTIVITIES

Jared grew up in Alaska and continues to enjoy many outdoor activities including fishing, skiing, hiking, playing softball, and golfing. Jared is also well known for his chocolate chip cookie-baking prowess. Above all, he cares for his friends and family and truly loves live.