THE USE OF AUDITORY PROMPTS TO DIRECT DRIVERS' ATTENTION TO AN IN-VEHICLE VISUAL DISPLAY IN A DUAL-TASK SIMULATED COMMERCIAL TRUCK ENVIRONMENT

by

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(ABSTRACT)

A simulated driving experiment was conducted to assess the potential benefits of using an auditory prompt to assist in target acquisition of in-vehicle navigational information, presented as a secondary task in commercial truck cab noise. Dual-task (driving in addition to performing a secondary task) and secondary task scenarios were presented, and acquisition time and accuracy on the secondary task were measured under three prompt types, three levels of information density, and three noise types. A subjective workload rating was also obtained from participants following each unique treatment condition. Accuracy was significantly higher for both auditory prompt types as compared to visual prompts under the dual-task configuration, but not significantly different under the secondary task configuration, suggesting that the increased visual demand of the primary task affected performance during the visual-only trials, but not during the trials in which prompts were presented auditorially. Under all levels of information density in the secondary task scenarios, acquisition time was significantly faster for the trials during which information was presented using the auditory-directional

prompt, compared with the auditory-diotic and visual trials, suggesting that the aural lateralization cues helped drivers locate information more quickly.

The techniques explored in the study have resulted in the benefit of presenting information more efficiently to a driver experiencing a high degree of visual workload. The potential exists to expand upon these findings, toward the goal of improving information display techniques which minimize the inherent visual burden with which many commercial truck drivers must contend.

ACKNOWLEDGMENTS

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I would also like to thank my parents and grandparents for their inspiration, motivation, and patience throughout my life. In addition, I would like to thank Onkel Friedhelm for instilling in me a curiosity and appreciation for automobiles which has led to years of fascination and ultimately, motivated me to pursue this area of research. Finally, I would like to thank my wife, Kristen, for her loving support and encouragement throughout the first of our many years of happiness together.

TABLE OF CONTENTS

TABLE OF CONTENTS
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TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF TABLES

LIST OF TABLES
(continued)

LIST OF TABLES
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INTRODUCTION

Background

The emergence and integration of Intelligent Vehicle-Highway Systems (IVHS) technology into the commercial truck cab is now inevitable. Because of the increased number of vehicles occupying roadways, an increase in the amount of goods delivered by commercial trucks, and difficulty experienced by the U.S. Department of Transportation to build roads fast enough, solutions have been explored to alleviate the substantial traffic problem (Committee on Public Works and Transportation, U.S. House of Representatives, 1989; Highway Users Federation, 1993). As of 1989, U.S. traffic levels have reached more than two trillion vehicle-miles, and will continue to increase by four percent per year. Estimates for 2020 are a staggering four trillion vehicle-miles (Banks, 1991). Although IVHS research has been conducted in the automobile industry for decades, Commercial Vehicle Operations (hereafter referred to as CVO) concepts have only recently begun to evolve (Canahan-Bowers, 1991; Chen and Ervin, 1989). The Federal Highway Administration has proposed that improving the efficiency of trucks and other highway vehicle fleets can be increased through the addition of vehicle identification, communications, and safety advisory systems (Manuta, 1992). Many similar devices designed to increase road capacity, profit, customer service, and enhance safety in the trucking industry are currently being investigated, and some have recently reached the consumer market (Boehm-Davis and Mast, 1992; Ervin, 1992).

IVHS systems are being developed in the commercial sector to assist the driver with problems which result from overcrowded roadways, information overload in the cab environment, and ambitious scheduling deadlines. Concepts such as motorist service information, real-time routing information, in-vehicle telephone yellow pages services, trip recorders, crash recorders, on-board diagnostic equipment, automatic vehicle identification, weigh-in-motion, automated toll collection, maintenance schedule displays, vehicle positioning systems, HUDs, navigational displays, in-vehicle warning devices, active suspension systems, electronic noise cancellation, and autonomous vehicle navigation have all been discussed in the development of the truck cab of the future (Banks, 1991; Bishel, 1987; Chen and Ervin, 1989; Conroy, 1992; Herman, 1990; Manuta, 1992; Schmidt, Wright, and Zwerner, 1990). It is difficult to imagine the extent to which the driver will be affected by the incorporation of some or all these devices into the cab. Furthermore, if the inherent increase in workload is not satisfactorily addressed, driver acceptance issues may be sufficient to call into question the value of such systems (Morlok, Bedrosian, Zarki, and Hallowell, 1989).

IVHS Technology

Some principal objectives of IVHS are to improve the safety and efficiency of the nation's highways by combining in-vehicle information gathering technology with sophisticated highway traffic information gathering and communications equipment. Traffic congestion and a steady increase in the driver population have been the impetus for on-going research. Other goals include increased and higher quality mobility, reduced environmental impact, improved energy efficiency, improved economic productivity, and a viable U.S. IVHS industry (IVHS America, 1992b). Several different elements within the context of IVHS have been identified, and work conducted in the area of Advanced Traveler Information Systems has revealed a genuine need by the general driving population to be informed of upcoming roadway hazards and delays. Also of interest to drivers is the location of everything from automated teller machines to traffic regulations in towns along the chosen route. Route planning, weather updates, and emergency communications were also considered desirable by most drivers (Center for Transportation Research, 1993).

For the heavy truck drivers, traffic regulations, e.g., per axle weight limits, minimum tire tread thickness and trailer width and length are of particular concern because of the variation from state to state (Chapman, 1994; Maggio, Maze, and McCall, 1992). Much of the valuable time lost at weigh stations is due to determining the drivers' compliance with individual state regulations. Combining information displays and the weigh-in-motion concept could alleviate much of this delay. Because of scheduling demands, it would seem that the frequency of planning and arriving at unfamiliar destinations is more common for commercial drivers than those in the general driving population. Although discussion of telecommuting and traveling to destinations using the nation's generally underutilized mass transit system have been cited as inexpensive alternatives to IVHS development, the general driving population in the U.S. seems unprepared to relinquish the freedom the automobile offers during the daily commute; however, in the trucking industry, the need for solutions is even more critical. The trucking industry is responsible for much of the interstate volume, moving more than 75 percent of all goods in the U. S. (Highway Users Federation, 1993). Everything from tires to toothpaste are transported to thousands of destinations on the nation's overcrowded roadways, mostly by interstate tractor-trailer trucks.

Commercial Vehicle Operations

Several goals specific to CVO as discovered by McCallum and Lee (1993) are decreased vehicle operation costs, increased vehicle service coverage, increased efficiency of dispatch operations, improved timeliness of delivery, and decreased vehicle maintenance costs. Also of importance is the issue of special cargo hazards and the effect on the driver of extensive nighttime driving. Accordingly, the Strategic Plan for IVHS in the U. S., IVHS America (1992b) has suggested areas of CVO safety research which include driver/vehicle real-time safety monitoring, driver warning systems, hazardous material information systems, and site-specific highway warning systems for trucks. As an integral part of all research efforts, human factors issues to be addressed include information processing and driver workload (IVHS America, 1992b).

To ensure safety of all roadway users, commercial vehicle operators must also be accurately informed about and sufficiently able to respond to impending traffic bottlenecks, inclement weather, and whether they will reach their destination within the prescribed time. In addition, because of the inherent mass, size, and high center of gravity of the commercial truck, advanced warning of hazards is of particular concern to ensure adequate stopping or maneuvering time (Morrison, 1993). Although noncommercial drivers have similar needs, research in CVO must address fundamentally different characteristics than in the noncommercial driver population. Differences in motivation, skill level, driving frequency, user acceptance, vehicle stability, vibration, noise effects, and vigilance must all be considered over the course of a normal eight to 10 hour day of driving (IVHS America, 1992b).

Driver differences. Differences in the driver workspace and anthropometry have been addressed by Philippart, Kuechenmeister, and Stanick (1985) at General Motors. In general, their findings indicate a larger, heavier population comprised of 95 percent male and 5 percent female drivers. Statistics cited regarding the general driving population indicated an equal distribution of males and females. In describing the truck driver workspace, models of the driver's eyellipse (the elliptically-shaped spatial field that contains the visible region of the right and left eye when the head is in held in a static position), head contour, shin-knee contours, stomach contour, and selected seat position curves, assist researchers in the development of additional components for this unique user population.

Other studies conducted to assess the differences in driver anthropometry were conducted by Shaw and Sanders (1985). Their findings also indicated that the truck driving population was taller and heavier than the general driving population; however, 75.9 percent of the sample was male and 24.1 percent female. Other findings included ethnic background, age, geographic location, driver experience, type of company, driving area, type of truck driven, and truck cab accessories.

The ethnic background of males in the study consisted of 81.1 percent Caucasian and 18.4 percent African-American. Females' background consisted of 94 percent Caucasian, four percent African-American, and two percent were listed as "other". The mean age of males and females was 44.1 years and 32.8 years, respectively. Average truck driving experience ranged from 4.7 years for females, most of whom worked for private carriers, to 20.4 years for males, most of whom worked for contract or common carriers. Most females reported driving only locally, while most males drove over the road a distance greater than 200 miles (322 km) during a particular delivery. The type of truck driven was approximately equally divided between cab-over and conventional type for both males and females. Some of the more common accessories available to the drivers were a tilt (steering) wheel, suspension seat, and a vertically-adjustable seat (Shaw and Sanders, 1985). Because of the increased diversity of the commercial truck driver population as compared to the population 20 years ago, human factors professionals must account for these specialized needs in the design of future truck cabs.

The inherently visual nature of driving has produced research dealing with the relationship between visibility and seating position based on anthropometric measurements of the truck driving population. Schmitt (1987) has worked with computer-aided design applications to determine the truck driver's field of view. Seat-back angle and longitudinal seat travel can be varied after a seating reference point has been established. As depicted in Figure 1, even the most aerodynamically efficient cab-over trucks offer a forward ground visibility of only about 15 feet, leaving much of the immediate roadway scene out of the driver's view (Schmitt, 1987).

Driver acceptance. Another area of research in CVO involves guidelines for assessment of user acceptance of IVHS components. Kantowitz and Barlow (1993) addressed concerns related to Advanced Traveler Information Systems (ATIS) and CVO implementation. It was suggested that an estimation of perceived utility be obtained to determine if the technology would be sufficient to evoke consumer interest. Also of interest in the study was the determination of components which had a low probability of acceptance, and to consequently direct resources to more useful areas of research.

Results from Ervin (1992) indicate truck manufacturers are generally uncommitted to producing navigational or routing devices as standard equipment due to lack of market interest. This is thought to be due in part to truck drivers' lack of knowledge concerning general IVHS goals related to the trucking industry; however, most original equipment manufacturers anticipate that a need for such equipment will develop at some point in the future. This shift in the market's perception will likely change a great deal when integration of IVHS components is more prevalent in passenger cars. Truck owner/operators represent the largest contingent of potential buyers of IVHS technology because these drivers tend to keep their vehicles longer than the typical three or four year time-period associated with vehicles in fleet companies. Some devices which may appeal to this segment of the market are safety-related items and those which favorably affect the drivers' status (Ervin, 1992).

The reluctance by truck drivers and fleet managers to purchase additional IVHS-related technologies is also due to the increase in the cost of equipment. In an attempt to

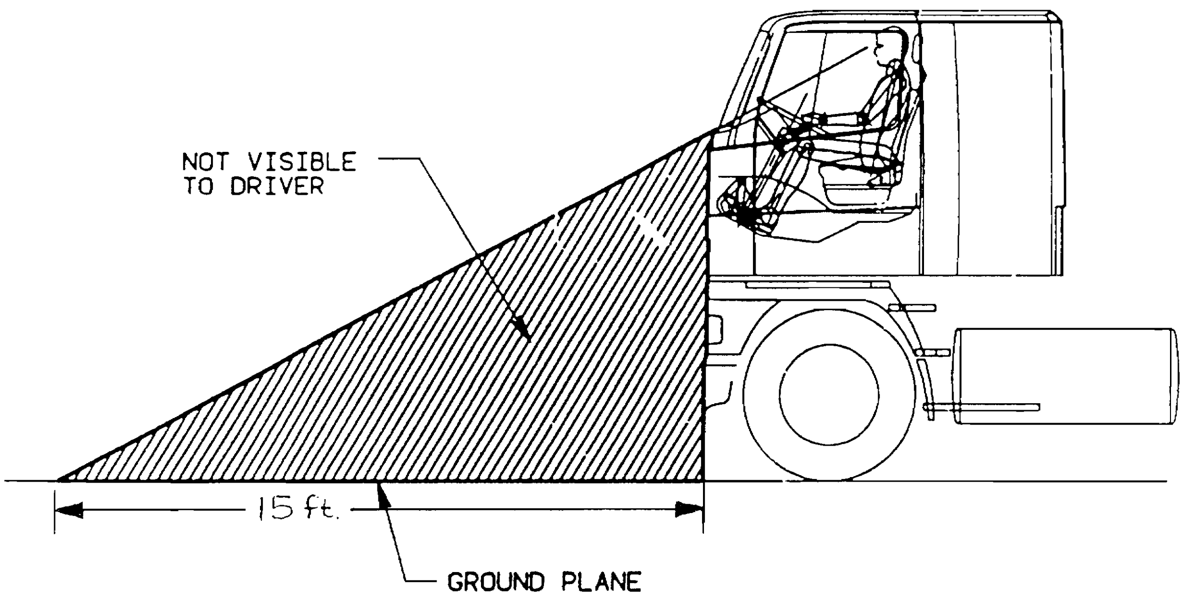

Figure 1. *Limited forward ground visibility (from Schmitt 1987).*

address these concerns, Hallowell and Morlok (1992) estimated the cost savings of a fleet of heavy trucks which utilized an advanced vehicle monitoring and telecommunication system. Their report indicated that annual costs of one major carrier decreased by more than 1.7 million dollars. The reduction was due primarily to increased utility of existing vehicles and personnel, and reduction in communications costs (Hallowell and Morlok, 1992).

DRIVER WORKLOAD

One of the most important issues facing human factors researchers and the most obvious difference between commercial and noncommercial drivers is driver workload. Commercial truck drivers encounter significantly more mental demand during the course of their interaction with the vehicle compared to typical passenger vehicle drivers. In addition to the normal complement of displays and controls found in most non-commercial vehicles, the commercial truck driver must also attend to many indicators including the air pressure status (primary and secondary supply of air in tanks for use in braking), pyrometer (temperature of air in engine turbocharger, if equipped), transmission temperature, and axle temperature (front and rear). Additional controls within the cab include a trailer hand valve brake (also called Johnson Bar or trolley valve), differential interlock, sliding 5th wheel (adjustment of axle weight according to different state requirements), trailer air supply evacuator, engine brake, stop light switch (activates brake lights when air brakes are applied), and suspension controls which lower or increase ride height (Alliance, 1981; Bishel, 1987; Carico, 1994; Federal Highway Administration, 1993; Kyropoulos, 1972). It is worth noting that this inherently more demanding list of additional tasks does not include the integration of *any* IVHS components.

Many studies have been conducted dealing with the driver workload of passenger vehicles, but few have focused specifically on the drivers of heavy commercial trucks. As discussed previously, the truck driver faces different demands than those of the passenger car driver. Thus, it will be necessary to review some of the salient research that has been conducted in the area of human information-processing and automobile driver workload.

Human Information-Processing

In order to assess the amount of informational overload experienced by a driver and to which modality the overload is occurring in a given situation, it is necessary to briefly examine how human operators process information. Information accessed by a driver reduces the uncertainty associated with the driving task and environment. A general human information-processing model is presented by Wickens (1992) which provides a conceptualization to locate human performance limitations. Figure 2 depicts the model which considers the processing of incoming stimuli, a division of attentional resources including perception, decision and response selection, response execution, and feedback.

The sensory processing areas of interest include characteristics of auditory and visual receptors and short-term sensory store (STSS). Although the decay time associated with STSS for auditory and visual stimuli is short (on the order of one to two seconds), it does allow information to be held temporarily, for later use and without attention. Perception and categorization of the stimulus then take place with assistance from long-term and working memory. Subsequently, the information may yield a decision, storage, or rehearsal. Finally, the response may be initiated, executed, and evaluated (Wickens, 1992).

Attention. The limited amount of attention available to the operator must be apportioned among the different sources selected to be processed. Consequently, a performance decrement will occur if too much attention is required of the operator to complete the task. In relation to driving, some tasks which occur more frequently than others may be learned and performed automatically with little attentional demand, e.g., shifting a manual transmission. Other tasks, such as receiving auditory and visual

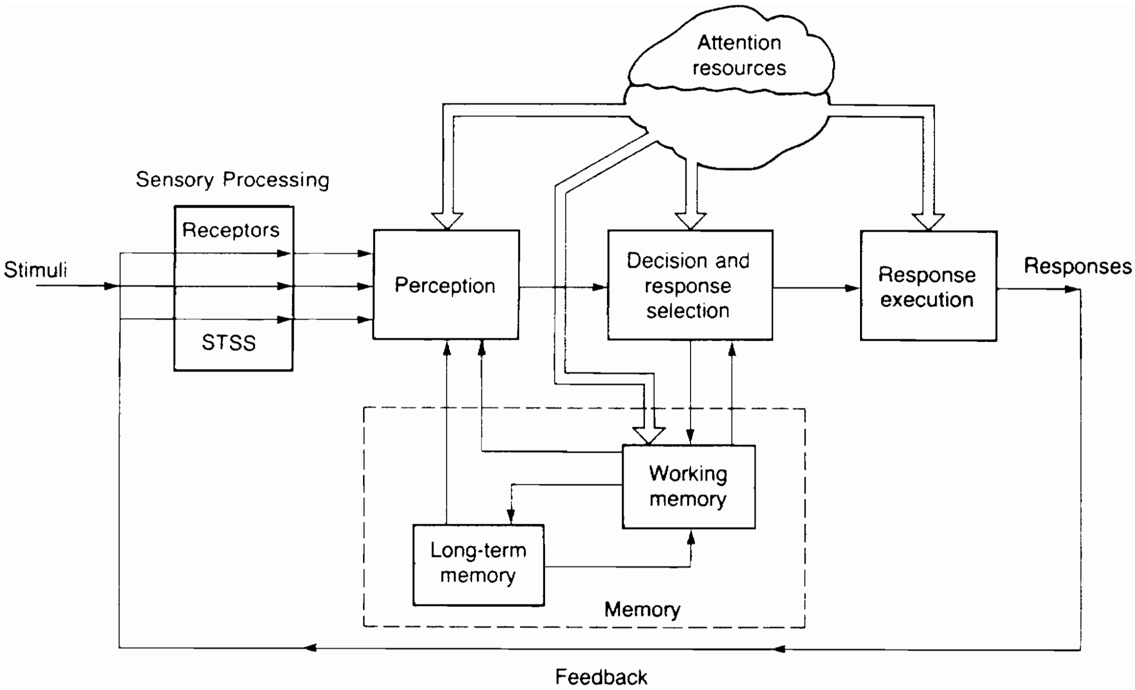

Figure 2. *A model of human information processing (from Wickens, 1992).*

navigational information in heavy traffic, may overextend the available attentional resources of the driver and lead to an unsafe situation. Devices which utilize cross-modality attentional resources are generally more effective than those which present all the information within one modality. An operator monitoring a system which transmits similar information simultaneously to visual and auditory domains will experience visual dominance, i.e., visual information is perceived more readily than auditory information (Köhler, 1971; Wickens, 1992).

Perception. The interpretation of the auditory and visual information is then necessary in order to make appropriate decisions and responses. Auditory perception of a stimulus differs from visual perception due to its transient nature, i.e., a visual informational display can be referred to repeatedly, while the same information transmitted in the form of a recorded or synthesized voice cannot. The auditory modality does offer a longer short-term sensory store which allows unfocused stimuli to remain at the preattentive level for three to six seconds. Also, since the ear is not capable of filtering out unwanted information as is possible in the visual domain, warning messages can be more effectively presented through the auditory domain , i.e., it is possible to ignore or intentionally disregard visual information by looking away from a particular object in the field of view, but assuming an adequate signal-to-noise ratio, information presented auditorially cannot be attended to selectively because of the inherent omnidirectional nature of the auditory sense (Wickens, 1992).

Competition for resources. There are several methods by which to present the required information to make it more perceptible. The information can be presented to either or both the visual or auditory domains. Cross-modal time-sharing is generally more efficient than time-sharing between two auditory or two visual channels. Intramodal time-sharing may cause confusion or masking of one message over the other. When this occurs, by "off-loading" one of the messages by presenting it in the other domain, the recipient is more likely to perceive and act according to the information in the message. Efficient time-sharing can also occur when appropriately determined spatial or verbal codes are utilized in the presentation of information. Generally, if verbal codes are used, the information is represented in linguistic form, and if spatial codes are used, the information is usually represented by a visual image. Different configurations are possible according to the desired compatibility of stimulus, working memory codes (verbal or spatial), and response modality (manual or speech). Figure 3 depicts the preferred configurations of the relationship between display format and working memory. Tasks which demand verbal working memory are best accomplished by utilizing speech in the auditory domain and print in the visual domain. Wickens (1992) also suggests that because echoic memory decays at a slower rate (the characteristic which allows auditory processors to retain the stimulus), speech messages are more conducive to successful rehearsal and retention, and should generally be used to convey verbal information. Furthermore, Wickens, Sandry, and Vidulich (1983) found that under high workload conditions, pilots experienced higher retention of auditory versus visual navigational information. However, if the message contained more than four or five unrelated words, both channels would exhibit a performance decrement. The optimal format as described by Wickens (1992) would be one in which a redundant visual display follows the delivery of a speech message. One inherent disadvantage of this format is increased display clutter.

Increasing retention. Because of the limited capacity associated with working memory, several methods of increasing retention of in-vehicle information are possible. Specifically, these methods are employed to minimize the message decay and working memory capacity. Chunking is one such method. Miller (1956) defined the maximum working memory capacity as seven plus or minus two chunks of information. By incorporating techniques which facilitate storage of the information, more complex

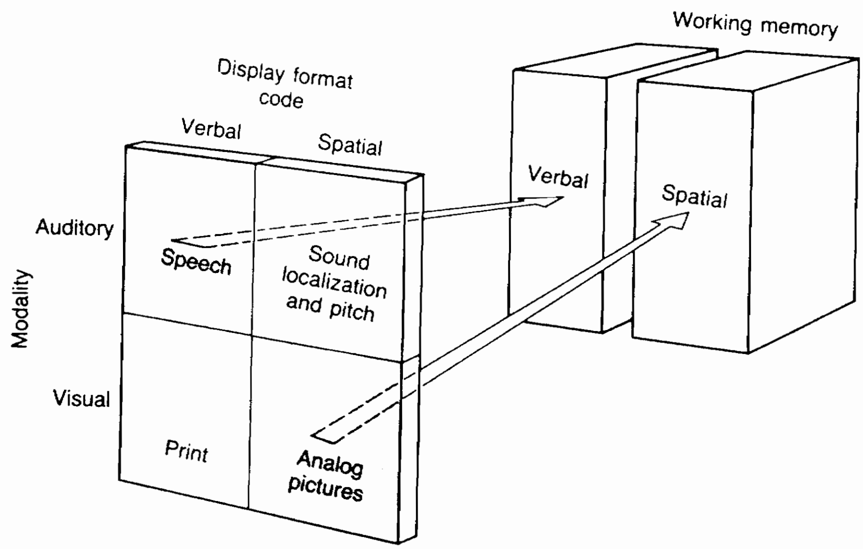

Figure 3. *Optimum assignment of display format to working memory code (from Wickens, 1992).*

messages can be presented to the driver. Parsing is a form of chunking which breaks up a message into an appropriate, meaningful sequence. For example, instead of presenting information such as "GMCV OIV HS", fragmenting the message differently ("GM CVO IVHS") can add meaning, and thereby increase retention, reduce capacity, and allow the operator to assimilate the information more quickly for decision making (Wickens, 1992).

Decisions. After the stimulus has been attended to and perceived, an appropriate course of action may be examined by the operator. During driving, usually the action will be taken in order to minimize the danger to the driver, passengers, other road users, or the environment. The problem exists in estimating the probability of a dangerous outcome based on the available information. Human operators can reasonably estimate mean values, but when estimating a proportion, variability, or the future position of an increasing function, biases can occur. These biases depend upon the operator's perception of the world at the time the decision is being made. In some cases, displaying additional information may assist the operator in overcoming the tendency toward bias. However, under time constraints, the operator will be generally unable to assimilate the additional information, searching for only the most salient cues (Wickens, 1992). According to Stene (1991), longer decision times generally correspond to a greater likelihood of accident involvement.

Choice reaction time. When a particular stimulus elicits a specific known response, the length of time associated with the onset of the stimulus and the response can be measured as a simple reaction time task. While there are few examples of this in the automobile driving environment (drag racing), the more likely scenario will involve a choice reaction time task. That is, the uncertainty regarding the stimulus onset as well as the response choice will be greater than in simple reaction time tasks.

According to the Hick-Hyman law, several factors determine information conveyed by a particular stimulus: the number of alternative stimuli, the probability of stimulus occurrence, and context in which it is presented. Thus, the more complex the situation, the longer the time necessary for correct stimulus identification. Specifically, the reaction time associated with a particular set of stimuli will increase a constant amount each time the number of alternatives doubles, i.e., increases by one bit of information. A more relevant approach to this study would be to examine the reduction in reaction time when the information is decreased by one bit, as in the case of the auditory-directional prompt type, discussed in a later section.

Other factors to be considered, which limit the generalizability of the Hick-Hyman law include stimulus discriminability, practice, stimulus-response compatibility, and the repetition effect, e.g., the same letter button prompted in two consecutive trials yields a quicker response (Wickens, 1992). Combinations of these factors determine the placement of the response function according to a speed or accuracy bias. The speed-accuracy trade-off curve depicted in Figure 4 shows how different instructions given to participants can alter the resultant performance. Each of the dots represent a particular speed-accuracy set, e.g., emphasizing high levels of accuracy to participants will lead to longer reaction times shown on the top right of the graph. Thus, the most efficient performance will result from instructions which emphasize intermediate levels of speed and accuracy (Wickens, 1992).

Defining Workload

A concise, widely accepted definition of driver workload is currently nonexistent. The importance in measuring the degree to which a driver is loaded can be of benefit in predicting human performance in a newly developed system, to determine if alterations

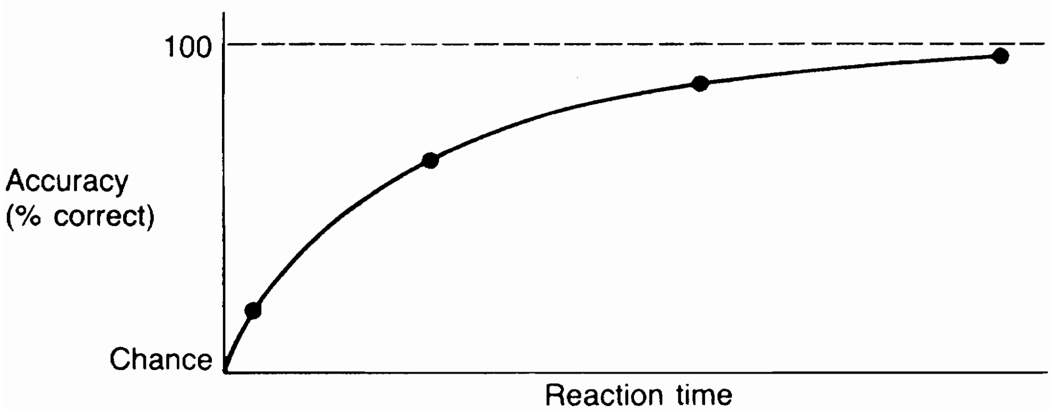

Figure 4. *The speed-accuracy trade-off (from Wickens, 1992).*

are required of the task, and to assess individual differences in task performance (Wickens, 1992). Many other researchers have also offered definitions of workload: "...the rate at which information is processed by the human operator, and basically the rate at which decisions are made and the difficulty of making the decisions" (Moray, 1979); "...the integrated effects on the human operator of task-related, situation-related, and operator-related factors that occur during the performance of a task" (Hart, 1986); "Mental workload is an intervening variable, similar to attention, that modulates or indexes the tuning between the demands of the environment and the capacity of the organism." (Kantowitz, 1988); "mental workload is the integrated mental effort required to perform the primary task. It includes such factors as level of attention, depth of thinking, and level of concentration required by the primary task" Casali (1982).

It is also generally agreed upon that mental workload is not synonymous with driver workload. One definition of driver workload as offered by Hancock and Parasuraman (1992) states that workload is perceived as a continuous variable which changes with different phases of driving, e.g., vehicle control, navigation, and collision avoidance. Verwey (1993) has also attempted to bridge the gap by incorporating the driver into the workload definition from Wickens (1984): "...the load on perceptual (visual, auditory, and tactile), central (cognitive) and output (hand, foot, and vocal) resources." (Verwey, 1993).

In the context of CVO, determination of the extent to which the driver is overloaded or underloaded is necessary to assess the riskiness of the driving task and ultimately to reduce accident propensity; however, it may also be useful in the evaluation of emerging IVHS technologies into the truck cab (Kantowitz, 1992). The workload associated with the integration of the aforementioned IVHS components may lead some drivers to experience informational overload. Conversely, technology such as Automated Vehicle Control Systems which will be designed to absorb much of the system monitoring and activation functions, i.e., drive the vehicle, may underload the driver (Kantowitz, 1992). Underload refers to a lack of sufficient workload as experienced by the driver in order to safely attend to the primary driving task.

Kantowitz (1992) also offered some information gathered by researchers in aviation which may be useful in defining heavy vehicle driver workload. Specifically, four issues are discussed as relevant: performance, methodology, measurement, and conceptual problems. Ultimately, a need was established for the formation of a cognitive task analysis and a model which relates cognitive components to the heavy vehicle driving task so that practical decisions about workload could be made. Since there is no universally adequate secondary task, the model and task analysis would serve to identify appropriate secondary tasks by which the specific mental operations may be measured (Kantowitz, 1992).

A study conducted by Harms (1991) which compared drivers' cognitive load under different road environments revealed an inverse relationship between driving speed and cognitive load. The dual-task study utilized mental subtraction as the secondary task. In the first portion of the experiment, 19 professional drivers were asked to drive on highway and rural routes where average speed and calculation times were measured. Not surprisingly, mean driving speed was lower in the village areas; however, calculation times were higher. Conversely, on the highway, speed was higher and calculation times were lower (Harms, 1991). If these results can be generalized to the commercial vehicle environment, it seems necessary to focus efforts on the transitional areas of the roadway, i.e., preceding a rural or village area where legal speeds are reduced and driver workload appears to increase.

Other methods by which the degree of truck driver workload have been assessed include a desktop simulator study conducted by MacAdam (1992) in which side-task activities were used in a attempt to assess primary task driving performance. Measures of driving performance, lateral vehicle position and heading angle degraded while side-task activities were performed on a supplemental display; however, the results were insufficient in determining whether or not the degree of degradation was such that safety would have been compromised in a real-world environment (MacAdam, 1992).

A study completed by Fuller (1988) used time headway (following distance) as a measure of driver performance. Driver's tended to adopt longer headway's (greater following distance) at the beginning and at the end of their shift. Fuller (1988) attributes the long headway at the beginning to a "lack-of-practice" effect, i.e., difficulties in the driving task tend to occur more frequently at the onset of the shift. At the end of the shift, exhaustion and drowsiness appear to be factors influencing greater headway. An alternative method of explanation may be that the driver experiences a higher degree of workload at the beginning, e.g., seat adjustments, radio manipulation, and at the end of the shift, e.g., approaching a delivery location in an urban area, higher probability that the vehicle in front will slow down or stop.

Visual and Auditory Workload

In the determination of driver workload in a particular vehicular environment the need exists to establish appropriate thresholds of safety. That is, the prediction of accident rates based on the level of workload experienced by a driver as a result of adding a new piece of equipment to the truck cab. One approach is to investigate the extent to which visual resources are utilized. The difficulty in doing so results from a lack of agreement on corresponding safe threshold values associated with glance duration and glance frequency. A study conducted by Antin, Dingus, Hulse, and Wierwille (1986) found a strong relationship between glance frequency to the in-vehicle display and percent trials where lane crossings occurred, but found no reliable relationship between glance duration and percent trials where lane crossings occurred. This suggests that if the driver is consistently glancing quickly at the navigational device while approaching an intersection, he/she may be looking to see if a navigational change, e.g., turning left or right, is required at an upcoming intersection. If this is the case, to avoid further reduction of visual resources, there may be a need to inform the driver that he/she is getting close to the desired intersection through auditory means. Furthermore, in recommending design improvements of the navigational display used in his study, Dingus (1987) suggested the use of an auditory warning device to alert the driver of an upcoming turn at an intersection.

In-vehicle display devices are of particular interest in human factors studies. The dilemma which exists deals with the appropriateness of the sensory modality chosen to transmit the required information to the driver. Labiale (1989) examined the influence of the presentation of navigational information to different modalities in the determination of the frequency of visual explorations. Frequent visual explorations for the purposes of gathering information can be considered partially indicative of the degree to which the driver is visually loaded. Thus, some conclusions from Labiale (1989) suggest that presentation of auditory navigational information versus visual presentation reduces visual exploration and consequently, some degree of workload. The disadvantage of presenting such information in the auditory domain is that the driver cannot refer to the information repeatedly, and must retain it after only one presentation. The timing of the auditory presentation must also be appropriate to allow the driver sufficient reaction time without becoming annoying, i.e., presented too frequently. To overcome these limitations, Labiale (1989) suggested incorporating written guidance when the vehicle is stationary, concise text and auditory guidance when moving, and an auditory message just before a change in direction is to take place.

An on-the-road driver workload assessment was conducted by Verwey (1991) which examined visual and cognitive workload through steering wheel actuation rate and mirror glance frequency. A visual display mounted on the dashboard was constructed to supply both experienced and inexperienced drivers with one of three secondary tasks. The particular driving situation was found to be important in the determination of visual load for experienced subjects. For inexperienced subjects, visual and cognitive load were determined by the driving situation, e.g., heavy traffic. This suggested that additional visual information should not be presented to the driver in complex driving situations, and that the tasks which consumed cognitive resources could not be successfully completed by inexperienced drivers. There was also a significant effect found due to experience associated with the secondary cognitive task in which information was presented auditorially to the subjects and repeated back to the experimenter (Verwey 1991). This implied that as the subjects become increasingly familiar with the information, it could be more efficiently presented through the auditory domain when the experienced driver could not sufficiently allocate resources from the visual domain (assuming that the auditory capacity was otherwise unencumbered). Although steering wheel action rate (SAR) was found to be a good indicator of high visual and/or cognitive workload, for commercial truck drivers, mirror glance frequency is significantly more prevalent than for automobile drivers, and may not be a reliable measure, due to differences in training.

Other studies have attempted to reduce visual load, i.e., glance time, by increasing display visibility, incorporating the navigational information into a heads-up display and utilizing voice guidance to convey information (Kishi, Asami, Ishikawa, and Itoh, 1990; Walker, Alicandri, Sedney, and Roberts, 1991). Kishi and Sugiura (1993) provide a summary of human factors considerations for voice route guidance in navigational displays. Tradeoffs between auditory and visual display of information within the navigational system are discussed and the benefits of their interaction are addressed.

In general, the appropriate use of auditory or visual means of information display is best addressed by Deatherage (1972). Table 1 lists the recommendations for the appropriate situations in which auditory or visual resources should be used in the acquisition of information by a human operator.

More specific to their study, Kishi and Sugiura (1993) suggested that auditory displays are best used when the timing or criticality of the information to be conveyed to the driver is important, e.g., upcoming intersection, and, if the message can be readily put into words, such as direction or heading. Information which is considered useful regardless of timing, e.g., comprehensive maps and graphics, are best conveyed visually (Kishi and Sugiura, 1993).

Kishi and Sugiura (1993) determined that in order to avoid information overload, the duration of the one sentence voice messages of the guidance system was limited to about six seconds. On a highway or in a rural area, each change of heading was accompanied by voice instructions which included turning direction, distance to turn, and a landmark to ensure the change in direction was completed successfully; however, on highways the turning point information was given long before the driver was able to make a visual confirmation. In addition, the driver could visually confirm the auditory instructions just received. The navigational system was evaluated using voice and visual outputs versus visual output only. The average glance duration per minute was shorter and heart rate was lower for the voice guided trials, thus implying some reduction in workload (Kishi and Sugiura, 1993).

In a driving simulator study which evaluated seven different navigational devices, Walker, Alicandri, Sedney, and Roberts (1991) also found that subjects who used one of the three auditory devices made fewer navigational errors and did not reduce their speed

TABLE 1

Appropriateness of Visual or Auditory Presentation of Information (from Deatherage, 1972)

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 deals with events in time.	The message deals with location in space.
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.

under high load conditions as compared to those who used visual devices or those in a paper strip map control group. Each of the three auditory and visual devices varied in complexity. For the auditory devices, complexity increased from a message of predetermined directional change, to a message describing each intersection regardless of whether or not it was part of the predetermined route. Visual complexity increased from a directional arrow displayed a block before the next directional change, to a detailed map, scaled in one-quarter mile increments, of the area surrounding the driver. In general, performance was best for the medium complexity devices. The complex visual device was the most difficult, and consequently, the least safe in terms of driving performance. Older subjects tended to perform the driving task less safely than either the middle-aged or younger subjects. The final recommendation was that future evaluations should consider the use of medium complexity devices which incorporate both auditory and visual components (Walker, Alicandri, Sedney, and Roberts, 1991).

Auditory localization. Synthesized auditory localization involves the perception of three-dimensional (3D) auditory stimuli (outside the head) independent of the orientation of the participant's head, whereas lateralization can be accomplished by modifying the system so that the listener perceives the sound as located near either ear or between the ears (inside the head).

This technique has been employed to increase the situational awareness of aircraft crews. Instead of looking at a display screen and then out the window to acquire the target, a navigator will soon be able to safely guide the aircraft through a high-traffic area by listening for potential obstacles (Nixon, 1994).

A study conducted by Begault (1993) evaluated commercial aircraft crews' acquisition time of visual targets using a head-up auditory display. The targets were simulated aircraft which activated the traffic collision avoidance system (TCAS) when in the vicinity of the crews' aircraft. The 3D presentation of the impending collision information allowed the crew to initiate the visual search for the target in the perceived direction of the verbal message and react accordingly.

This approach may also be useful with navigational and collision-avoidance displays in commercial trucks. However, any ground vehicle would require only two-dimensional presentation of the information, i.e., rarely would there be a collision threat from above or beneath the vehicle. Since the 3D auditory display directed the aircraft crew to focus their visual search in the area of the perceived message, the same exploration may be made regarding drivers. It would appear that directing the drivers' attention to the visual display by incorporating a directional auditory prompt (lateralization) also may be of benefit in isolating the driver's visual search for information. A study conducted by Gardner (1973) suggested that participants located sounds more accurately in the median plane (azimuth) when they were presented in the anterior rather than the posterior sector. The reason for the increased accuracy is partially attributable to the capturing of and frequency-specific influence on the sound by contours of the pinna; however, despite this inherent advantage, the anterior presentation method would not be possible in a commercial truck cab without occluding the visual field. Therefore, the apparatus in this study was constructed in a manner which utilized a posterior presentation method.

Issues in the Study

Much of the research regarding in-vehicle display devices suggests that auditory displays, when used properly, would be beneficial in the reduction of driver workload. To avoid overload of the commercial truck driver, several issues must be considered. If auditory messages are to be used, the messages must be presented in a fashion such that they are sufficiently audible, relatively short (approximately six seconds or less than four to five unrelated words), and used primarily in situations in which the visual domain is overloaded (Kishi and Sugiura, 1993; Labiale, 1989; Walker, Alicandri, Sedney, and Roberts, 1991; Wickens, 1992).

The evidence for using auditory displays with existing visually-oriented navigational devices to reduce workload is substantial, although few studies have addressed the problems associated with the integration of such devices into the heavy truck cab. The problems of ambient noise, age-related effects, and the extent of increased workload are barriers with which researchers must contend.

The findings of Shaw and Sanders (1985) estimate the mean age of the male truck driving population to be 44.1 years, which suggests that many drivers have already experienced some degree of presbycusis (age-induced hearing loss). Because of the significantly larger cab volume and louder ambient noise level found in heavy trucks, in-vehicle display devices which utilize the auditory domain may not be audible to the driver if the information is presented through the factory-installed cab loudspeakers from which other audio sources, such as the radio may be heard (Morrison, 1993; Pachiaudi and Blanchet, 1990). Also, since the visual domain is usually heavily loaded with the driving task, one approach to this problem is to present auditory information to drivers through headrest loudspeakers (Pachiaudi and Blanchet, 1990).

When applied for this purpose, the headrest loudspeakers carry only voice messages from the navigational device, i.e., not from radio, CD, or tape, etc.. One advantage of presenting information through the headrest loudspeakers (instead of the existing audio system in the truck) concerns the signal-to-noise ratio in the cab. As Morrison (1993) discovered, in the presence of typical truck cab noise, the speech intelligibility of synthesized messages presented through loudspeakers was poor even for normal hearing subjects. With the headrest loudspeakers, even in a noisy truck cab, it is claimed that the sound intensity of the message can remain low because it is presented more closely to the ear, and, consequently is more likely to be clearly heard and understood (Pachiaudi and Blanchet, 1990).

Results from the study indicate that the preferred signal sound level of 65 dBA was determined by 16 drivers' preferences while driving a test vehicle around a circular track. The distribution was bimodal; while younger subjects (average age 23 years) preferred 59 dBA, older subjects (average age 40 years) preferred 64 dBA. In the presence of music from the factory-installed loudspeakers (noise condition), the level of the messages was increased to 69 dBA to be sufficiently heard by all subjects. Questionnaires completed by passengers sitting next to the subjects revealed that the messages were found by 11 of 13 subjects to be barely audible but not understandable from the passenger seat. Half of the subjects suggested that the passenger should also be able understand the message, perhaps by including a headrest loudspeaker system in the passenger seat as well (Pachiaudi and Blanchet, 1990).

In order to assess the truck driver workload sufficiently, and thus, "spare capacity", a need exists to evaluate and update previous heavy truck task analyses sufficient to address emerging integration of IVHS technology into the driver workspace (Kantowitz, 1992). Many of the findings of the previously-mentioned studies indicate that the primary task of driving had been adversely affected by the integration of a new component and, that the "spare capacity" associated with the visual domain had been reduced. Most of the currently used display systems intended for information acquisition by the driver primarily utilize the visual domain.

A review and update of the task analytic literature, which appears in the next section, has been conducted in order to identify areas of potential visual overload in the commercial truck cab. Priority will be given to those tasks which contribute to the forward movement of the truck. A subjective judgment will also be included to indicate areas in which the driver may experience excessive consumption of visual or auditory resources.

Ultimately, the goal of this and subsequent studies will be the determination of the appropriate sensory modality for the safe and efficient use of salient information displayed in the heavy truck cab. Furthermore, an attempt will be made to divide sensory workload between the two modalities. To that end, the efforts of this study will experimentally examine the use of two different types of auditory prompts to guide the driver to the area of the display in which the desired information exists, before any visual resources have been consumed. By providing a directional component to the auditory domain, it may be possible for drivers to conduct a more efficient visual search for the desired information.

TASK ANALYSIS

In evaluating and updating a task analysis for the commercial truck, one goal of this study will be to isolate areas of driver activity in which the visual system may be overloaded, and to determine whether presentation of additional information to the auditory modality could be beneficial. As mentioned previously, the increase in overall driver workload is of particular concern. Driving functions examined in the task analysis review will include five principal activities: vehicle control, collision avoidance, vehicle systems monitoring, navigation, and scheduling and timing. The extent of detail will be focused primarily on those tasks which offer insight into the appropriateness of the auditory or visual modality for the display of information inside the truck cab.

Review of the Task-Analytic Literature

Several criteria for determining representative tasks were established by Moe, Kelley, and Farlow (1973) in a truck and bus driver task analysis study. To be considered valuable to the study, the task must have had to be important and unique to truck or bus operations. Secondly, the task must have required "some overt behavior on the part of the driver." Finally, the task to be considered was to have been "related to safe and efficient vehicle operation."

After the criteria had been established, the task descriptions were developed. An outline was prepared and examined by subject matter experts (SME's) who agreed on six main topics: preoperative procedures, routine driving tasks, special driving tasks, driving emergencies, hooking-up doubles (connecting tandem trailers), and carrying passengers; the latter category was generally reserved for bus drivers. Emphasis was placed on avoiding jargon in the descriptions, rather, terminology was developed based on accepted usage among drivers. The intent of the study was to measure task criticality (high, medium, and low) through the use of SME evaluation. High criticality was defined in terms of something that "every driver must do to ensure the safety and efficiency of operations." Medium or moderate criticality was defined as something that "every driver ought to do to improve the safety and efficiency of operations." Finally, low criticality was defined as something that "a driver may omit without seriously endangering the safety or efficiency of operations".

After a criticality assessment, the experts then ranked each individual category, e.g., highest medium criticality would be less critical than lowest high criticality. Each of the 61 experts completed three sets of 25 randomly selected task statements. The results of the evaluations yielded a "summary criticality index" based on the distribution of mean item ranks from both truck and bus experts, ranging in increasing criticality from one to five X's. Estimation of judgment reliability was based on the comparison of between and within variances of the items. Although reliability of individual items was not impressive (highest: $r = 0.46$), the estimates of reliability for truck expert evaluations ($r = 0.74$), bus expert evaluations ($r = 0.68$), and the combined coefficient ($r = 0.80$) were sufficiently higher (Moe, Kelley, and Farlow, 1973).

Table 2 provides those items in Moe, Kelley, and Farlow (1973) which are viewed as important in identifying the appropriateness of auditory or visual modality for the display of information inside the truck cab. The convention used by Young and Rabideau (1974) was to limit the task analysis to tasks which were necessarily performed during forward movement of the truck, i.e., it was not considered essential to analyze the driving task by incorporating preoperative procedures such as vehicle inspections. One reason for this approach was based on accident statistics which indicated most occurrences took place during the "route driving section". Because this assumption was made 20 years ago, further investigation into more recent accident statistics will be reviewed later. In addition, an event-based approach was chosen over time or distance-based methods because of the increased accuracy of prediction in a given driving environment (Young and Rabideau, 1974). In this analysis, truck and trailer backing events are considered important as the only exception to the "forward movement" convention.

The table of tasks and their accompanying subjective criticality rating from Moe, Kelley, and Farlow (1973) has been modified to include the affected modality of the task. By identifying the tasks according to criticality and an estimate of importance based on the affected modality, it will be possible to more clearly isolate congested areas where a high degree of workload may exist. Further, it may be possible to reallocate tasks to a different modality in these areas.

In Moe, Kelley, and Farlow (1973), the criticality of each task was represented by a previously determined number of X's. For the purposes of this study, the increasing task criticality will be represented by the numbers one through five, corresponding to the number of X's in the original study. As an addition to the task description and criticality, a subjective judgment of the modality utilized or affected in the task will be added, and represented by the letters A (auditory), V (visual), and AV (both). Also, gender-specific language was eliminated. Task descriptions which are unaccompanied by criticality or modality information are subject headings unless otherwise noted.

TABLE 2

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Task Description	Criticality	Modality
Engine and Power train Performance		
Checks for proper engine and vehicle acceleration	1	AV
Steering Mechanism		
Checks for excessive play in steering wheel	4	V
Check for castering	1	V
Checks for excessive steering resistance in both left and right turns	4	V
Checks front wheel alignment by removing hands from steering wheel momentarily to determine if truck veers to right or left	2	V
Brakes		
Checks service braking system for normal operation	4	AV
Checks emergency braking system for normal operation	3	AV
Checks to ensure that all brakes release properly	4	AV
Checks to determine if brakes pull to left or right	4	V
Checks for proper engine braking	3	AV
Vehicle Tracking		
Checks to ensure that trailer(s) are properly aligned behind the tractor when the vehicle is traveling in a straight line	4	V
Checks to ensure that trailers do not sway back and forth excessively after a turn	4	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Checks to ensure that individual units are not canted in either direction	3	V
Checks to ensure that trailers stay nearly vertical (perpendicular to roadway) during and just after turns	3	V
Accelerating to roadway speed		
Accelerates to maximum speed in each gear	1	AV
Accelerates engine to near maximum speed in each gear before shifting to next higher gear	N/A	AV
Observes color-coded speed ranges on speedometer and shifts to next higher gear when vehicle speed reaches upper limit of each colored area	N/A	V
Steering - General		
Checks trailer alignment using rearview mirrors to determine if trailer is tracking properly	3	V
Prevents weaving (fishtailing) by avoiding jerky steering corrections	4	V
Uses cues from distant field of vision to anticipate required steering responses and to avoid fishtailing	3	V
Turning		
Right turns		
Approaches intersection in right-hand lane	4	V
Signals a right turn	4	V
Reduces speed to about five miles-per-hour	3	V
Veers slightly to the *left*-- keeps approach lane guarded or blocked to prevent following traffic from entering blind spot	5	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Checks traffic approaching from left on cross street	4	AV
Drives into intersection until front end of vehicle reaches the driving lane for oncoming traffic approaching from right on the cross street	3	V
Checks oncoming traffic	N/A	AV
Continues in original direction until vehicle's turning point reaches intersection	3	V
Checks clearances in right and left rearview mirrors	4	V
Turns steering wheel smartly to the right	N/A	V
Enters driving lane for oncoming cross street traffic	2	V
Continues turn until entry of driving lane of cross street is complete	N/A	V
Curves		
Setting up the curve		
Slows to the speed limit posted for the curve	5	AV
Judges radius of curve	4	V
Selects a turning radius appropriate for the curve	3	V
Steers to the outside portion of lane	4	V
Checks the rearview mirror to ensure rear end of vehicle has not drifted into adjacent lane on outboard side of curve.	3	V
Judges correctness of speed and steering control and makes adjustments as necessary	4	AV
Upgrades		
Slows down to let other vehicles pass before reaching bottom of the grade	1	AV

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Keeps well to the right (or in the right-hand lane of-lane highway)	4	V
Pulls off to the side of the road to let traffic pass on long or steep hills if shoulder is satisfactory	2	AV
Does not pull off if shoulder is soft, if it is covered with loose dirt which could cause a dust cloud, or if driving conditions are bad	4	V
Uses special truck (slow) lanes when available	2	V
Downgrades		
Approaches top of grade at slow speed	5	AV
Keeps the rig strung out while going downhill (by depressing the accelerator and brake at the same time, jackknifing can be prevented; also referred to as power braking)	4	V
Applies light (five pounds) brake pressure while going downhill	2	AV
Selects a gear that will permit keeping the engine speed at about half power	4	AV
Passing		
Determines whether sufficient speed and distance to pass can be achieved in relation to type of vehicle to be passed	5	V
Makes smooth transition when changing lanes to avoid whipping the trailer	4	V
Returning to driving lane	5	V
Judges distance, as seen through side-view mirror, to determine when to return to driving lane	N/A	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Surveillance and situation awareness		
Roadway obstructions		
Posted obstructions		
Bridges and tunnels	3	V
Checks posted load limit	N/A	V
Checks posted overhead and side clearances	N/A	V
Checks for bridge ramp or bump	2	V
Slows if ramp incline is significant	4	AV
Drives as close as possible to center of roadway	2	V
Drawbridge		
Stops before going onto bridge	N/A	AV
Toll plazas		
Checks for special truck/bus toll gate	N/A	V
Moves to truck/bus lane as soon as possible	2	V
Checks overhead and side clearances	2	V
Weigh station		
Determines whether weigh station is open or closed; that is, determines whether he is required to stop	1	V
Reduces speed to 3 miles-per-hour or less before arriving at scale	1	AV
Avoids using brakes on scale	1	AV
Parks on exit side of scale if it is desirable to make a convenience stop	1	V
Unposted obstructions		
Bridges and tunnels	N/A	V
Checks bridge deck for recent repair work	3	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Checks for built-up snow or ice	3	V
Checks bridge for gussets (strengthened corners)	3	V
Checks curvature of tunnel ceiling (or bridge cover)	3	V
Trees		
Checks for overhanging branches	3	V
Roadway and roadside obstructions		
Stalled vehicles on roadway		
Removes foot from accelerator	N/A	AV
Turns on emergency flashers or pumps brakes to provide warning to following traffic	3	AV
Makes decision to stop or pass	N/A	V
Passes cautiously if there is room to do so on roadway	4	V
Stops if there is not enough room on the roadway	5	V
Animals in roadway		
Daytime		
Stops or slows to permit animal to cross roadway	2	AV
Sounds horn to warn animal	1	AV
Nighttime		
Stops or slows to permit animal to cross roadway	3	AV
Switches headlights from high to low beams or turns them off momentarily if animal seems to be fixating on lights	2	V
Sounds horn to warn animal	1	AV
Vehicles parked on roadside		
Slows and moves to outer lane	2	AV

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Pedestrians standing on roadside		
Slows and moves to outer lane	3	AV
Roadway characteristics		
Shoulders		
Determines shoulder characteristics	4	V
Tracks clear of shoulder hazards	3	V
Weather		
Hot Weather		
Reduces driving speed	1	AV
Cold Weather		
Detects and compensates for black ice (usually undetectable patches of ice)	5	V
Monitors rear tires to see if snow is sticking	1	V
Reduced visibility		
Turns on headlights	4	V
Drives at a speed that will permit vehicle to be stopped within the prevailing visibility range	5	AV
Turns on windshield wipers before entering water or snow spray created by another vehicle	4	AV
Wind		
Reduces speed	5	AV
Monitors trailer for excessive tilt angle	4	V
Observes roadside vegetation to determine direction and velocity of wind	2	V
Prepares to steer into wind when leaving the lee of a building, hill, or another vehicle	3	AV

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Avoids following campers or house trailers (any vehicle with large sail area and small mass)	2	V
Skid control		
Drives at reduced speed on slippery roads	5	AV
Makes small, smooth steering corrections rather than large, jerky ones when attempting to control skid	5	AV
Keeps rig strung out (by depressing the accelerator and brake at the same time, jackknifing can be prevented; also referred to as power braking)	3	AV
Steers in intended direction of travel	4	V
Maintains maximum directional control	5	V
Traffic		
Reads-the-road-high to detect potentially hazardous situations well in advance (taking advantage of inherently higher road view)	5	V
Pays attention to the movements of all vehicles ahead, not just the one immediately ahead	5	V
Slows immediately when farm equipment or other slow moving vehicles are sighted on roadway	5	V
Watches for vehicles entering lane anywhere ahead	5	V
Avoids tailgaters	2	V
Pacing traffic lights		
Times approach to traffic light to avoid stopping, if possible	2	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Braking and stopping		
Ensures that all wheels are on the same type or condition of road surface before braking	1	V
Avoids sharp braking on turns or curves	5	V
Applies steady pressure on foot brake when initiating stop	3	AV
Avoids locking wheels (keeps wheels turning) to maintain directional control of vehicle	5	AV
Turnabouts		
Avoids making U-turns or Y-turns	4	V
Reverses direction by driving around the block (makes three right turns followed by a left turn)	1	V
Parking		
Parking on roadway		
Parks past driveways	2	V
Checks surface condition of parking space	2	V
Checks to ensure parking space is clear of overhead obstructions	2	V
Ensures there is adequate clearance for tractor as well as trailer	4	V
Turns front wheels into curb	3	V
Turns off engine	1	A
Parallel parking	3	V
Drives forward into parking space	N/A	V
Selecting a parking place		
Parks inside terminal in cold weather if possible to prevent brakes from freezing	1	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Parks well clear of vehicles bearing hazardous materials placards	2	V
Does not block the exit of other vehicles	2	V
Ensures that exit is not or will not be blocked when leaving	2	V
Driving in off-street areas (parking lots, loading, delivery areas, etc.)		
Uses driveway, when available	2	V
Crosses inclined driveway slowly and at an angle to avoid striking undercarriage	3	V
Drives over curbs slowly	1	AV
Scans for posted and unposted obstructions	3	V
Brake system failures		
Loss of air pressure		
Detects sound of escaping air from brake system, decelerating of vehicle, or activation of emergency braking warning system	N/A	AV
Grasps steering wheel firmly	5	V
Presses brake pedal to activates brake lights	4	AV
Turns on four-way flashers or sounds horn to attract attention of other drivers	5	AV
Overpowers emergency braking system (accelerates) to avoid sudden stop in path of following traffic	4	AV
Stops vehicle as soon as possible off roadway if possible	5	V

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Uses parking brake to stop (in the event that all other braking systems fail		
Removes foot from accelerator	3	AV
Downshifts if possible	5	AV
Sets parking brake firmly while maintaining firm grip on steering wheel with other hand	5	AV
Releases parking brake momentarily if the vehicle begins to bounce or to veer in either direction	5	AV
Downshifts if possible	N/A	AV
Resets parking brake	N/A	AV
Stops vehicle as soon as possible off roadway	5	AV
Emergency quick stop		
Uses full pressure on brake pedal	4	AV
Uses power braking if time permits	3	AV
Engine failures		
Activation of Motorguard Device (designed to stop an engine if oil pressure drops below five pounds or if engine temperature exceeds 212°)		
Stops vehicle as soon as possible, off roadway if possible	3	AV
Activates overrule device to restart engine only if it is necessary to move vehicle from a hazardous location	3	AV

TABLE 2, continued

Tasks Which Consume Auditory and/or Visual Resources During Forward Movement of a Heavy Truck (adapted and modified from Moe, Kelley, and Farlow, 1973; Modality: Auditory (A), Visual (V), Auditory and Visual (AV))

Fires		
Cargo fire		
Scans cargo area periodically for smoke; informs fire department officials of the type of cargo loaded on the truck noting especially any hazardous materials as soon as the fire fighting assistance arrives	2	V
Drives truck to uninhabited area if possible	5	AV
Blowouts		
Grasps steering wheel tightly and attempts to keep vehicle straight	5	AV
Lifts foot off accelerator and allows engine to decelerate the vehicle (does not apply brakes)	5	AV
Looks for suitable place to park	3	V
Pulls off to side of road	4	V

Using this cursory glance at the primary driving task, it is possible to indicate several areas in which the task demands represent potential for concern. Specifically, traffic negotiation tasks such as steering, turning, passing, and parking rely largely on the visual domain for information. Because of the high criticality of these tasks, integration of a collision avoidance system utilizing an auditory warning may diminish the visual workload on the driver. The criticality and visual burden associated with unposted obstructions and inclement weather is such that drivers confronted with these situations may also benefit from auditory advisory devices.

Rabideau and Young (1973) and Young and Rabideau (1974) provided a methodology which focused on tasks which offered insight into display and control design in the truck cab. In defining the human's perfect behavior in a system, the concept of "safety-critical behaviors" (SCB) was adopted in the completion of a task analysis. A "safety critical behavior" was defined as a behavior "capable in a given situation of rendering future system behavior either more safe or less safe from the standpoint of physical damage to system components." Furthermore, a list of behaviors consistent with safe driving include adequate observation, processing of inputs, and skillful, appropriate, and time-shared reaction to inputs. To identify the SCB, Rabideau and Young (1973) suggest that unsafe driving may differ from safe driving in two ways: the "omission of SCB actions" or "deliberate choice and use of non-SCB actions over SCB actions".

The need for safety-related criteria can be supported by the work of Boyar, Couts, Joshi, and Klein (1985). In their analysis of the causes of nearly 32,000 preventable accidents in which truck drivers were involved, some relevant statistics may be cited in support of assumptions made by Young and Rabideau (1974). Table 3 provides a summary of observations from the study.

TABLE 3

A Summary of Significant Observations from Preventable Accidents in which Truck Drivers were Involved (from Boyar, Couts, Joshi, and Klein, 1985)

• Sixty-eight percent of all accidents reported were preventable using accepted industry standards for determining preventability of accidents.
• Over 50 percent of all preventable accidents could be attributed to five prime cause categories: Failure to Allow for Adverse Environmental Conditions, Following Too Closely, Failure to Maintain Control, Careless/Reckless, and Improper/Erratic Lane Changes.
• Forty percent of all preventable accidents were attributed to prime cause categories that clearly represent a lack of responsibility on the part of the professional driver toward other highway users.
• Professional driver failures were the prime cause in 94.5 percent of all preventable accidents.
• For every 100 professional drivers killed in preventable accidents, 145 other drivers were killed
• There is a substantially greater chance of a commercial vehicle driver fatality being related to the prime cause category of Failure to Maintain Control than to the other top categories.
• Of all the primary cause categories the highest ratio of collision accidents to non-collision accidents occurred in the primary cause category Following Too Closely.
• The majority of driver at fault accidents occur where the weather or the roadway were not contributing factors.
• Seventy percent of all preventable accidents related to mechanical defects involved brake or tire failures.
• The Improper/Erratic Lane Changes primary cause category accounted for only 4.6 percent of all preventable accidents, but had the highest percentage of preventable accidents involving collisions with moving objects (94.5 percent) and had the highest percentage of collisions with passenger vehicles (67.3 percent).

From all the observations, it was concluded that three important areas be addressed toward the goal of increasing driver skills: driver/environment interaction, driver/vehicle interaction and driver/highway user interactions. Additionally, it was recommended that vehicle modifications may be one method by which to reduce preventable accidents (Boyar, Couts, Joshi, and Klein, 1985).

The observation that professional truck driver failures were the prime cause in 94.5 percent of all preventable accidents is particularly alarming. Approximately 88.4 percent of all preventable accidents occurred during the "route driving section," supporting the assumptions of Young and Rabideau (1974). Further investigation into the nature of the operational definitions provides some insight into this disturbing finding.

The convention used to determine Failure to Maintain Control of the Vehicle included situations in which the visibility was good and the pavement was dry, whereas, if the visibility was poor, and the road conditions were icy or wet, the accident was judged to be caused by Failure to Allow for Environmental Conditions; in either instance, the driver was judged to be "at fault". It is worth noting that 75.7 percent of the accidents in the latter category occurred in the presence of snow, sleet, or rain. Whether the accidents can be attributed to delivery time pressures under such conditions is not known, but it would be reasonable to assume that driver workload under these conditions is high (Boyar, Couts, Joshi, and Klein, 1985). Human information-processing capabilities and appropriate system design concepts must also be taken into account when placing such blame on drivers (Wickens, 1992).

Table 4 provides an example of the categories considered by Rabideau and Young (1973) and Young and Rabideau (1974) in completing their truck driving behavioral task analysis based on "safety critical behavior".

TABLE 4

Information Categories Used in the Driving Behavior Task Analysis (from Rabideau and Young, 1973 and Young and Rabideau, 1974)

Category	Example
Task Identification	Maintain required forward motion and path within posted speed limit
Display problem	Drive truck at speed limit on straight road; assume no curves or traffic; assume level, positive, and negative roadway grades
Critical stimulus variables	Speed limit; grade of road (present and approaching); engine speed and characteristics; loading of vehicle; position of accelerator pedal; the gear-in-use and its characteristics; camber in road surface; obstacles on roadway
Time values	Steering correction before truck leaves lane (dependent on speed and yaw angle); other times, for example, optimum shift points and optimum braking times when over speed limit (not safety-critical)
Display noise	Poor visibility (includes sun-induced glare); unknown speed limit; "deadband" in steering mechanism
Required decisions	Speed up or slow down now; speed up or slow down soon; move steering wheel
Controls	Accelerator pedal; brake pedal; clutch pedal; gear selector; steering wheel

TABLE 4, continued

Information Categories Used in the Driving Behavior Task Analysis (from Rabideau and Young, 1973 and Young and Rabideau, 1974)

Control activation	Move up or slow down to position yielding desired speed/acceleration; push down to produce desired deceleration; described in shifting procedure; turn in direction to be taken, then straighten out
Control action	Determined by acceleration/ deceleration properties of truck for particular gear, grade, and loading; rate of deceleration dependent upon grade, speed, vehicle weight, and force on pedal; amount of rotation depends upon steering ratio of vehicle; force depends on ratio, loading, amount of power assist, road surface, speed, and tire pressure
Feedback	
Cues	Visual and auditory sensations of speed change; speedometer reading changes
Time delay	Virtually no time delay to onsets of change; completion time varies with conditions
Criteria of response adequacy	Adequacy indicated by speedometer reading same as posted limit; vehicle perceived as centered in own lane
Critical values:	Corrective actions:
Stalled engine	Restart (procedure)
Locked brakes	Release pedal pressure
Missed shift	Repeat (shifting procedure)
Wheels out of lane	Turn steering wheel in smooth motion as required to correct lateral position

TABLE 4, continued

Information Categories Used in the Driving Behavior Task Analysis (from Rabideau and Young, 1973 and Young and Rabideau, 1974)

Characteristic errors	"Hunting" around speed limit due to accelerator overcorrection; weaving down road due to steering overcorrection; excessive frequencies of change in acceleration (increases fuel consumption) and braking (increases brake wear)

Validation of the task analysis performed by Rabideau and Young (1973) and Young and Rabideau (1974) was completed with on-the-road activity sampling and structured interviews of professional truck drivers. Interviews yielded such information as personal driving habits (techniques) and frequency and probable causes of near accidents. During the interviews, drivers were also asked to rank order a set of driving preferences to determine common control activation methods. After an examination and categorization of the comments, the task analysis was altered to reflect the new information (Young and Rabideau, 1974) .

The activity sampling involved the random monitoring of a driver on a normally scheduled route. Emphasis was placed on control activation methods. Estimation based on observations produced gross time allocations, time-shared activities, and frequency of task repetition which were compared to the task analysis predictions. In addition, graphic behavior theories were developed and tested to better understand the influence of subcomponent design on the safe behavior of the driver. The graphic behavior theories were constructed based on the task analysis data to represent interactions between the vehicle, system components, environment, and the driver (Young and Rabideau, 1974).

Voids in the Literature

Several areas of CVO have been targeted for future research. IVHS America (1992a) suggests human factors efforts should be expended in five particular areas: 1) detailed specification of what information the driver needs to make each IVHS function effective, 2) determination of what sensory display modes and what associated information format and density are most appropriate for each IVHS function, 3) determination of what associated data entry and function selection encoding and formats would best support the aforementioned areas, 4) task analysis and taxonomy for IVHS interactions, and 5) development of design-oriented human factors guidelines for displays and controls for the multiple IVHS functions and for their integration. For this study, the goals related to in-vehicle display modality allocation and the development of human factors guidelines were pursued.

The above task descriptions and accident data provide a sufficient framework by which to include the incorporation of tasks common in the truck cab of today, i.e., it is necessary to modify the analysis to reflect those tasks which were not common to the truck driver 20 years ago. Also, tasks such as eating, drinking, smoking, or other comfort-related tasks have not been given much attention, but will undoubtedly affect the driver workload and, consequently, must be considered in future studies. Table 5, which lists additional tasks common in current heavy truck configurations, was compiled based on an informal survey conducted to assess component availability from a Volvo-GM heavy truck manufacturing facility. As with the previous task descriptions, a subjective judgment of the modality utilized or affected in the task was added to identify potential areas of driver overload.

Based upon the literature review, there appears to be a strong need for further pursuit of automotive research conducted with in-vehicle display devices and display modality allocation. Future display devices which may be used for navigation, collision-avoidance, diagnostic evaluation, automatic vehicle identification, weigh-in-motion, automated toll collection, maintenance scheduling, and vehicle positioning may all benefit from research in this area. Specifically, because of the nature of the commercial truck environment, factors such as ambient noise, age-related effects, and inherently greater workload must be considered in the display of auditory or visual information.

In many studies, the use of auditory and visual information has been promoted as more beneficial to the driver than the use of either modality exclusively; however, few guidelines exist regarding which types of systems benefit most from the use of a

TABLE 5

Updated Task Listing and Utilized or Affected Modality: Auditory (A), Visual (V), Auditory and Visual (AV)

Category	Task Description	Modality
Primary task	Maintain required forward motion and path within posted speed limit (Young and Rabideau, 1974)	AV
Display Monitoring	Oil pressure (A: low level)	AV
	Oil temperature (A: high level)	AV
	Tachometer (A: high level)	AV
	Speedometer	V
	Air pressure (supply of air in tanks for use in braking)	V
	Primary: cab air pressure	V
	Secondary: trailer air pressure	V
	Water temperature	V
	Ammeter (alternator)	V
	Voltmeter	V
	Application pressure (amount of air pressure applied to brakes)	V
	Pyrometer (temperature of air in engine turbocharger, if equipped)	V
	Fuel (A: low level)	AV
	Transmission temperature	V
	Axle temperature (front and rear)	V
	Odometer	V
	Trip odometer	V
	Cellular phone	AV
	Clock (A: alarm)	AV

TABLE 5, continued

Updated Task Listing and Utilized or Affected Modality: Auditory (A), Visual (V), Auditory and Visual (AV)

Control Activation	Differential interlock	AV
	Sliding 5th wheel (adjustment of axle weight according to different state requirements)	AV
	Low beam headlights	V
	High beam headlights	V
	Driving lights	V
	Marker or clearance lights	V
	Interior cab lights	V
	Back of cab lights	V
	Turn signal switch	AV
	Hazard flasher	AV
	CB Radio	AV
	Cellular phone	AV
	Windshield wipers	V
	Windshield washer fluid	V
	Wind deflector	AV
	Horn	AV
	Seat belts	V
	Door latch (inside cab)	V
	Cruise control	AV
	Power windows	AV
	Power door locks	AV
	Hood release	V
	Electric mirrors	V
	Heated mirrors	AV
	Climate controls/Defroster	V
	Vent adjustment	V

TABLE 5, continued

Updated Task Listing and Utilized or Affected Modality: Auditory (A), Visual (V), Auditory and Visual (AV)

	Clock adjustment	V
	Trip odometer reset	V
	Suspension seat control	V
	Vertically adjustable seat	V
	Suspension control (lowering or increasing ride height)	AV
	Radar/Laser detector	AV
Shifting, double-clutching	Gearshift	AV
	High/low actuator	V
	Accelerator pedal	AV
	Clutch pedal	AV
Steering	Tilt steering wheel (Steering wheel angle adjustment)	V
	Telescopic control of steering wheel	V
Braking	Brake pedal	AV
	Trailer hand valve (brake; also called Johnson Bar or trolley valve)	AV
	Engine brake	AV
	Trailer air supply evacuator	AV
	Parking brake	AV
	Stop light switch (activates brake lights when air brakes are applied)	V
Comfort-Related Tasks	Smoking	V
	Eating	V
	Drinking	V

particular configuration. This research effort focused on methods used to alert the driver (defined here as prompts) to visual information on an in-vehicle display by using either an auditory or visual prompt.

RESEARCH OBJECTIVES

In the present study, a method was proposed which utilized an auditory prompt for the purposes of directing the research participants' attention to a side-task display. Furthermore, a lateralization procedure was used in an attempt to direct the participants' attention to a particular portion of the display (right or left), and consequently, focus the area of the initial visual search for the desired information so that overall task time was reduced. In addition, a headrest loudspeaker apparatus was utilized to increase the likelihood of auditory message acquisition in the presence of representative, modern truck cab noise. A prototype of this device was previously used in a passenger car study in which the benefit was transmission of the auditory information at a lower sound level, i.e., establishing a lower signal-to-noise ratio (Pachiaudi and Blanchet, 1990); however, there was no investigation of this concept with respect to performance-related measures, such as reaction time or search accuracy.

As discussed previously, the successful implementation of the auditory localization concepts within the commercial aircraft environment has led to the design of a unique presentation medium for ground-based vehicles. The populations which control these vehicles differ greatly in a number of important areas. Given the characteristics of the commercial aircraft pilot population, such as intensive training, it is not surprising that the pilots' use of the three-dimensional auditory information was beneficial in increasing primary task safety and performance; however, the commercial truck population is not as extensively trained and the criticality of primary task success is quite different, e.g., commercial pilots are usually responsible for the safe delivery of passengers as opposed to cargo. Thus, it was not clear whether the use of the adapted auditory prompt would provide any benefit over traditional methods.

Based on the literature review, it was hypothesized that the effect of increasing the amount of navigational information available to the participant would produce a performance decrement for each of the dependent variables. Additionally, it was hypothesized that auditory presentation of information would be more effective than visually-presented information, when the driver experienced a high degree of visual workload.

General hypothesis. The goal of this study was to determine whether presentation of information to the visual or auditory sensory modality would result in better search performance for a visually-loaded driver. Toward that end, this experiment examined the use of two different types of auditory prompts to guide the driver to an area of the simulated navigational display in which the desired information existed, before any visual resources had been consumed. Because the technique of using a directional component in the auditory domain had not been previously attempted in this fashion, the researchers were unsure of the extent to which drivers would be able to utilize this technology. It was assumed that if drivers performed according to the experimenter's instruction, the directional component would allow participants to conduct a more efficient visual search for the desired information as compared with the diotic auditory prompt. The primary hypothesis of this study was that the presentation of the auditory message would reduce secondary task performance time (acquisition time) and increase the accuracy in the acquisition of the desired navigational information targets. Additionally, it was expected that the participants would subjectively rate the visual prompt as more demanding than either auditory prompt.

EXPERIMENTAL METHODOLOGY

Experimental Design.

The experimental design was a three-factor, within-subjects design. A complete factorial design was utilized in order to resolve all main effect and interactions in an analysis of variance (ANOVA). Participants were treated as random-effects variables and the independent variables as fixed-effects variables. The structural model for the experimental design is represented by the equation:

$$Y_{ijklm} = \mu + \alpha_i + \beta_j + \phi_k + \gamma_l + \alpha\beta_{ij} + \alpha\phi_{ik} + \alpha\gamma_{il} + \beta\phi_{jk} + \beta\gamma_{jl} + \phi\gamma_{kl}$$
$$+ \alpha\beta\phi_{ijk} + \alpha\beta\gamma_{ijl} + \beta\phi\gamma_{jkl} + \alpha\beta\phi\gamma_{ijkl} + \varepsilon_{m(ijkl)}$$

in which Y (observations) are specified by the linear combination of the population mean (μ), the factors prompt type (α_i), information density (β_j), and noise type (ϕ_k). Participants are represented as γ_l, and random error is represented by $\varepsilon_{m(ijkl)}$. Since all independent variables are within-subjects factors, only random error is nested in all other effects.

The three independent variables which were manipulated were Information Density (D), Noise Type (N), and the type of Prompt (P). Figure 5 depicts the experimental design graphically.

Task types The two types of tasks were defined as dual (combination of the primary and secondary tasks) and secondary only (which was compared to the dual-task scenario to ensure that the primary task offered sufficient workload). Because of

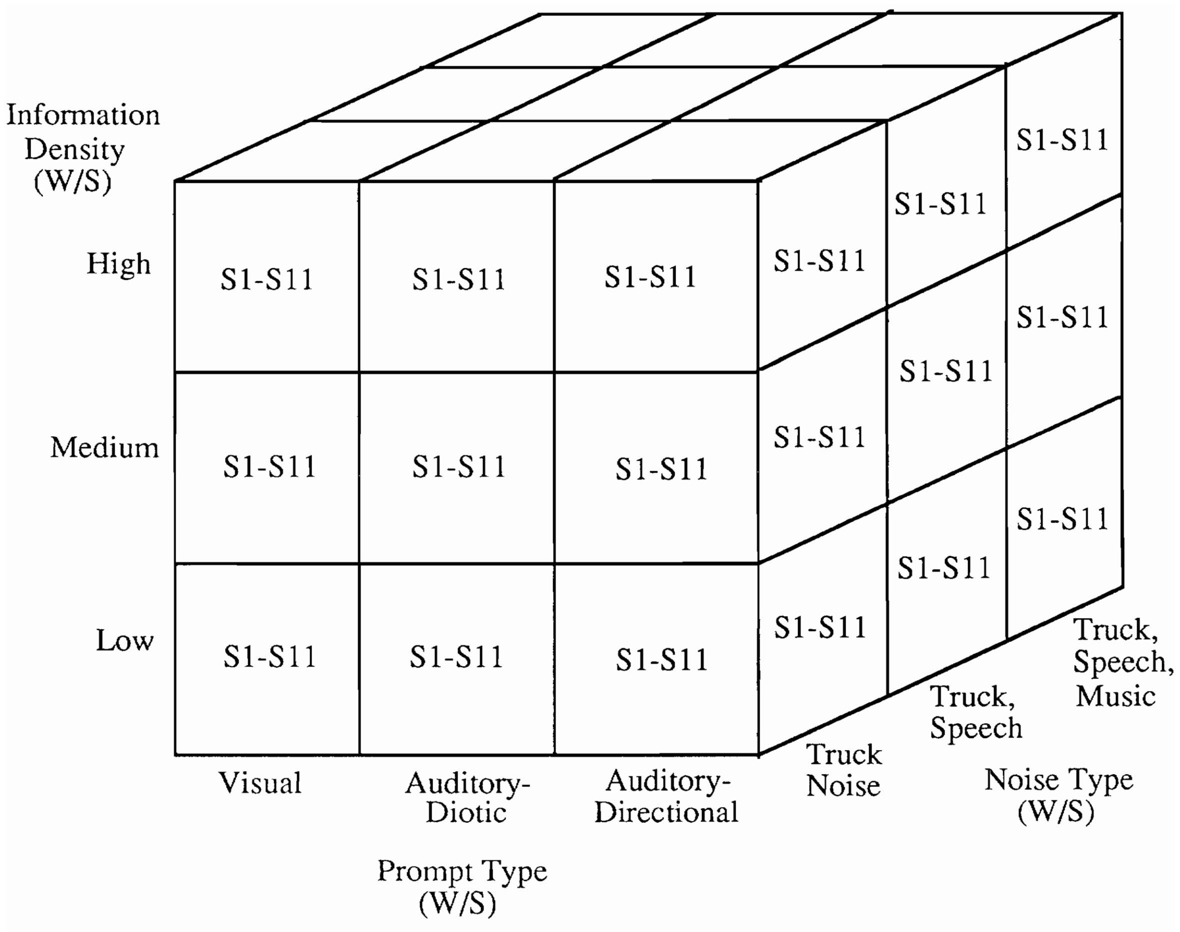

Figure 5. *Experimental design matrix. (Explanation in the text).*

differences in the presentation interval, these two tasks could not be combined as an additional factor in the experiment.

Information density independent variable. Information density was presented to the participant as high (12 items), medium (8 items), or low (4 items). The levels of task difficulty were constructed based on a study of driver selective attention using auxiliary automobile displays by Noy (1990). Each of the letter buttons were approximately 2.5 cm-by-2.5 cm in dimension across all levels. Given the seated position of the participants, this corresponded to 118.9 minutes of arc. The presentation of the letter buttons was randomized; thus the placement of the buttons and the actual letter to be identified was different across participants. These levels were examined in the pilot study and adjusted to ensure minimum and adequately different levels of workload.

Noise type independent variable. The three levels of noise used were truck cab noise, truck cab noise and background speech, and truck cab noise, background speech, and music. For the latter condition, compact discs were added to previously recorded truck cab noise and background speech from Morrison (1993) by using a Fostex model 260 mixing board. The content of the background speech was an audio cassette abridgment of the novel, *The Firm.* Similarly to Morrison (1993), this selection was used to approximate the effect of in-cab CB-radio chatter and because of the relatively constant sound pressure levels, i.e., a portion of the tape was extracted which did not vary greatly in dynamic range. The compact discs used in the third level of noise type were also prescreened to ensure relatively equal sound pressure levels. Selections which deviated significantly in sound pressure level were not programmed into the CD player memory during the experiment.

Prompt type independent variable. The type of prompt presented to participants consisted of three levels: visual-only, auditory-diotic, and auditory-directional. The directional component was added to the auditory message by recording to only the right or left channel. The auditory prompts were not accompanied by visual prompts in order to compare the unique effect of each prompt type.

Treatment condition presentation. Although a balanced Latin square design would have been beneficial for balancing each of the 27 treatment conditions, it would have required a minimum of 54 participants, which was viewed as economically infeasible. Another potential problem existed because of the limited availability of the population of interest to participate in the study (licensed male commercial truck drivers). Given the demanding schedules of most commercial truck drivers, it was expected that attrition would have been unavoidable if the data could not have been collected during one experimental session.

Differential transfer, a carryover effect which occurs disproportionately across all sequence orders of treatments, was also a consideration during the determination of the treatment order; the effect is usually more pronounced with motor skills tasks. Therefore, the presentation of all the treatment conditions was accomplished using randomization without replacement to minimize this effect.

Dependent measures. Percent accuracy over trials and acquisition time of the participant's responses to the prompted navigational information was obtained from a HyperCard program running on an Apple Macintosh PowerBook 140. Response time was calculated from the time the simulated navigational information appeared on the side-task display until a response was made by the participant. The value recorded by the program was the time in milliseconds (ms) or TO (timed-out) for no response. The participant responded by touching a specific letter button on the touchscreen, as indicated by the preceding auditory or visual prompt. Accuracy was determined by whether or not the participant selected the correct letter button. The value recorded by the program was either a 1 (correct), 0 (incorrect). The latter condition was also recorded if no selection was made by the participant. All of these values were visible to the experimenter as the recording was made into the data output field by the HyperCard program. A sample output of the experimenter's PowerBook screen appears in Figure 6.

Because of the nature of the study and the available driving game simulator apparatus, it was not possible to obtain driving performance measures from the primary task, such as lane deviation, steering reversals, and headway. These measures would have been useful in order to make a correlation between driver's performance on identical portions of the driving route and specific treatment conditions, e.g., lane deviations and steering reversals with auditory-directional, high information density, truck noise, and dual-task, versus lane deviations and steering reversals with visual, high information density, truck noise, and dual-task. These measures would have allowed an assessment of instantaneous workload levels for each participant on any portion of the route and with any combination of treatment conditions. Since these measures could not be taken, an attempt was made to maintain a stable, minimum amount of workload associated with the primary task. In accordance with this criterion, frequency data were collected based on the number of times a participant crashed or received a ticket during the operation of the primary task; the data were associated with the particular condition in which the crash or ticket occurred.

A rating scale was also used to assess the subjective workload of the participants. At the end of the presentation of each of the 27 treatment conditions during the dual-task configuration, participants estimated the workload on the most recently completed condition by verbally rating the difficulty on a graphic Likert scale from one to seven, with one anchored by "extremely easy" and seven by "extremely difficult". Appendix I provides a depiction of the rating scale. The crash/ticket and subjective workload rating data were not taken during the secondary task trials. Instead, these data were only collected during the second portion of the experiment in which the dual-task scenario was

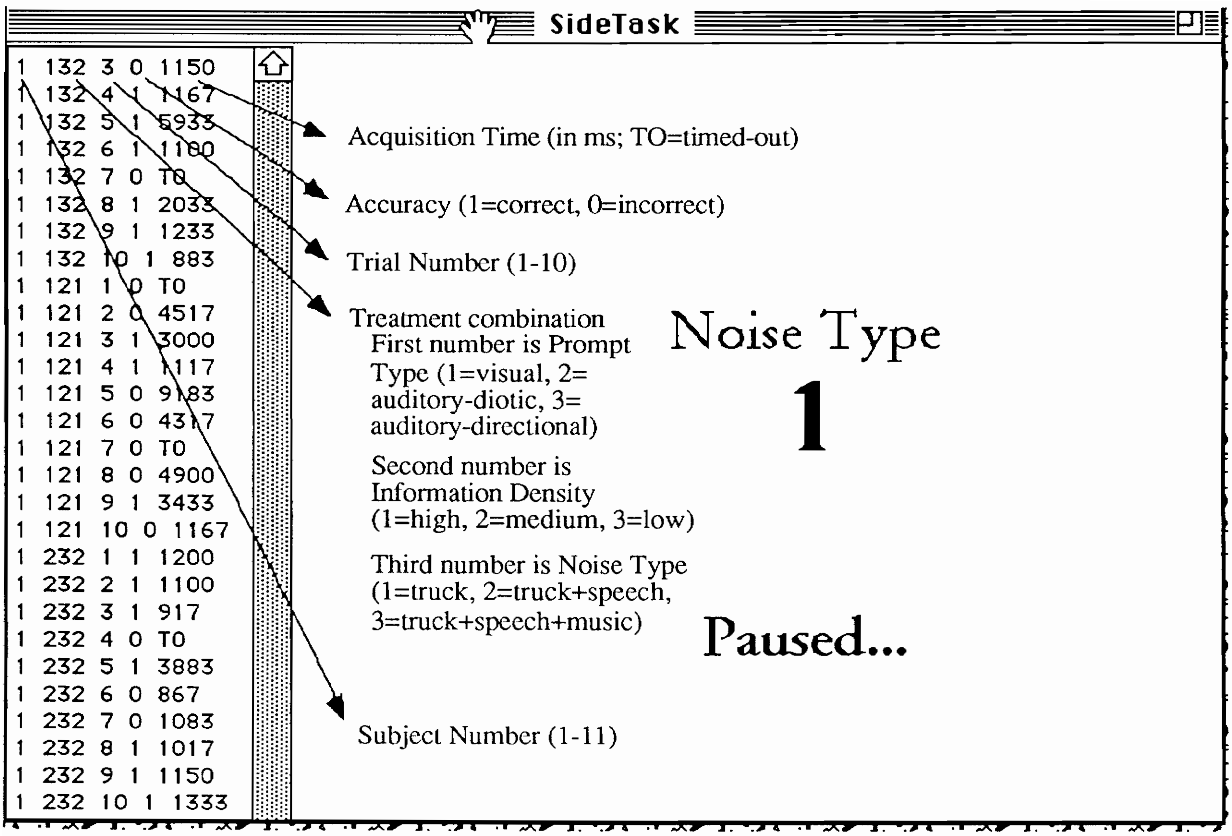

Figure 6. *A sample output of the data field and experimenter prompt as displayed on the PowerBook.*

presented.

Participants. Eleven licensed male commercial truck drivers participated in the study. The mean age of the participants was 34 (range: 22 to 43 years of age). Participants' commercial truck driving experience ranged from four to 28 years, with a mean of 12 years. Participants averaged 307 miles per week on the job and drove various types of heavy trucks including 18-wheel tractor-trailers.

Experimental Apparatus, Tasks, and Stimuli

Experimental facility. The experiment was conducted in a specially-prepared room of the Auditory Systems Laboratory located in the Human Factors Engineering Center at Virginia Polytechnic Institute and State University.

A lining of two-inch thick Sonex sound-absorbing foam was used to reduce barrier (wall) reflections in the testing facility, to simulate the effects of upholstery in the actual truck cab. The emission axes of both noise-presenting Infinity® RS 9b loudspeakers were located in the back of the room, directed toward the head of the participant. This arrangement approximated a uniform, diffuse sound field around the head of the participant in which there was no perceptible directional component attributable to the *noise*. Figure 7 depicts the facility.

Support instrumentation. A Beltone Model 114 clinical pure-tone audiometer was used with a set of Telephonics TDH 50 earphones to determine the participants' pure-tone hearing threshold level during the screening process using a Hughson-Westlake manual audiometry procedure (Carhart and Jerger, 1959). The criteria for rejection, similar to Morrison (1993), involved dismissal of a participant whose pure-tone average (PTA) hearing level at 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz or 6000 Hz exceeded 50

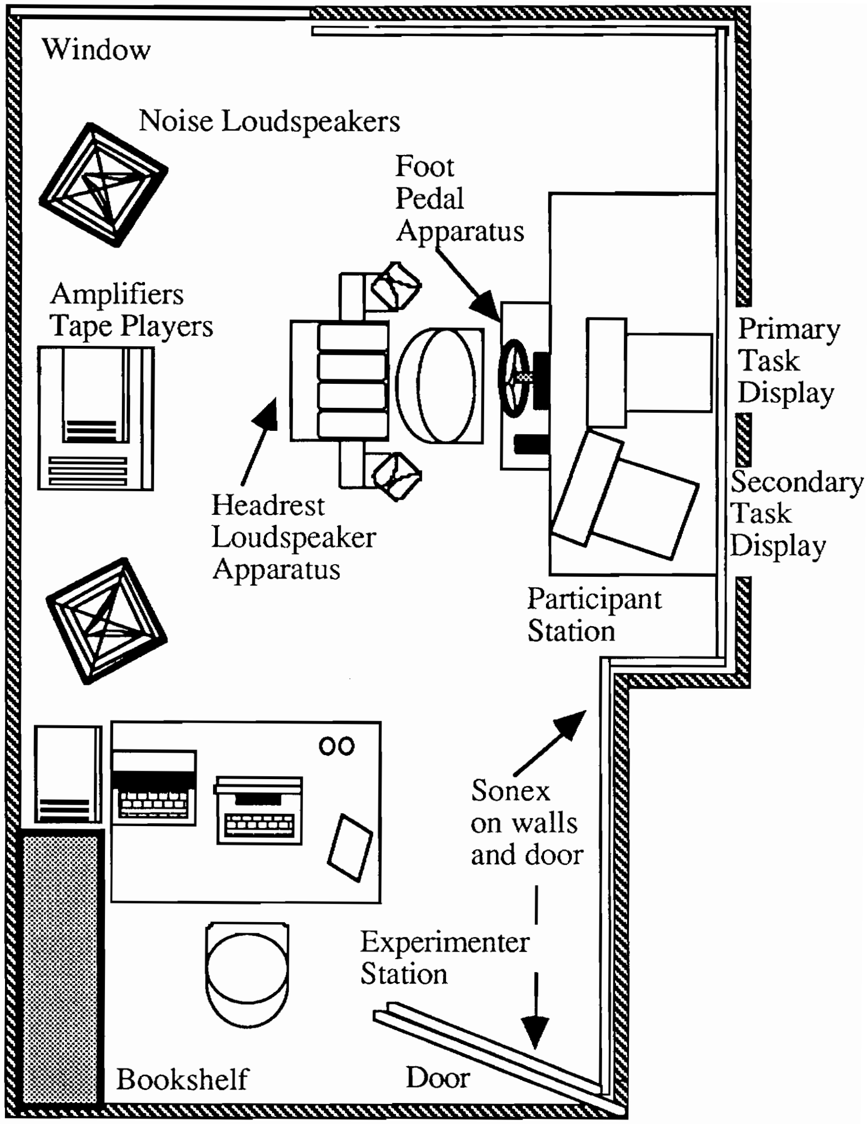

Figure 7. *The experimental room.*

dBHL. Determination of threshold values at these frequencies is primarily important because it is an indication of the participant's ability to understand human speech. Using the dBHL criterion, it was assumed that all participants could reliably hear the auditory prompts.

Primary task. An Apple Macintosh IIci was used with an Apple 14" high-resolution monitor to present the primary task. A driving game (VETTE!©) produced by Spectrum HoloByte™ was used as the primary driving task while the participant drivers also monitored and responded to the secondary navigational/search task. This game had an added advantage in that its manual control involvement, combined with the brake and accelerator pedal assembly and steering wheel, posed considerable face validity to actual driving. The game could be modified to produce a number of vehicle and road configurations of varying difficulty. The configurations were modified according to the following characteristics: vehicle type, difficulty level, and vehicle and environmental preferences. Table 6 includes the options which can be manipulated to increase or decrease difficulty. The specific settings for the experimental procedures were determined through pilot testing to avoid a ceiling or floor effect of workload on the primary task.

Several issues related to the primary task require discussion. During the pilot testing procedures it was discovered that manipulation of the primary task driving game parameters was necessary to ensure that the workload level experienced by the participants was sufficiently engaging during performance of the dual-task scenario. If the primary task was too easy, the participant had no motivation to attend to it while performing the secondary task; thus the workload experienced during the dual-task would not be significantly different than the secondary task configuration. Sufficient motivation on the part of the participant was paramount to avoid duplication of the secondary task configuration data. A partial solution was to employ the medium difficulty level

TABLE 6

VETTE!© Options Which Affect Primary Task Difficulty (adapted from Sphere, Inc., 1991)

Vehicle type	Difficulty level	Preferences (available with all vehicle types and difficulty levels)
Stock 1989 Corvette	Trainee	*Brake rate*: affects how quickly braking occurs after pedal actuation.
1989 ZR1 "King of the Hill" Corvette	Rookie	*Minimum turn*: determines minimum amount of steering input to turn the wheel.
Callaway "Twin Turbo" Corvette	Pro	*Maximum turn*: affects how far steering wheel can turn.
Callaway "Sledgehammer" Corvette		*Turn correction*: adjusts the speed with which the player may correct the car's path while in a skid.
		Skid traction: determines point at which car begins sliding and to what extent.
		Skid rate: affects the extent to which the car spins once spin has been initiated.
		Skid scrub rate: determines how much speed is subtracted from the car when it skids.
		Traffic density: dictates the amount of traffic on the roads.
		Gravity: affects how well the car adheres to the roadway when approaching a hill at high speed.

(Rookie) of the game. At this level, errors on the part of the participant (speeding tickets and/or collision damage) would necessitate pausing the secondary task until the participant regained control of the simulated vehicle at the posted speed. Depending on the road upon which the driver was traveling, the speed limit was updated and posted on the dashboard of the simulated vehicle. Originally, it was proposed that if a virtual police officer issued a ticket to the driver for speeding or "hit-and-run" (collision), the experimental condition in which the error occurred was to be repeated. Similarly, if a crash occurred, noticeable changes in the vehicle's handling prevented continuation of the primary task, while the secondary task was being presented. It was discovered during pilot testing that the secondary task presentation could not be repeated because of the omission of a pausing mechanism in the programming. Subsequently, a pause button was added so that the secondary task could be continued after control of the vehicle was regained without losing any of the completed trials within the experimental condition.

It was assumed that if the participant did not crash or receive a ticket, sufficient attention was being committed to the primary task. The appropriateness of the particular difficulty level of the primary task was ascertained during pilot testing.

Control of the primary task was achieved through the use of a mouse-wheel (a steering wheel apparatus to which a mouse is attached), a spring-loaded accelerator and brake pedals, which, when depressed, actuated a floor-mounted keyboard. A wooden platform was constructed which approximated the angle of incidence and placement of the accelerator, brake pedal, and floor pan of a commercial truck. The pedal apparatus was used in order to add additional face validity. The keyboard under the platform was linked to another keyboard, used for experimenter intervention during participant errors, and the Apple Macintosh IIci. The additional experimenter keyboard was used in order to expedite recovery during error conditions experienced by the participant, i.e., so that the experimenter would not have to restart the primary task by using the keyboard under the participant's feet. Participants practiced the primary task while following a route specified by the experimenter, before beginning the dual-task configuration. In addition to becoming familiar with the display/control environment, it was necessary for participants to complete the predetermined route once during practice, so that each could continue to the dual-task scenario without the need to respond to route directions. The route which included four right turns, was traveled by participants in an average of 15 minutes. A captured screen from the simulated environment appears in Figure 8.

Secondary task. A HyperCard 2.1 application for the Apple Macintosh was used to develop a program for the presentation and acquisition of data associated with the secondary task. An Apple Macintosh PowerBook 140 was used in conjunction with a Radius PowerView and a 14" Apple high-resolution touchscreen monitor (modified by MicroTouch) to present the HyperCard program, including the auditory navigational prompts digitized in SoundEdit™ Pro. The PowerBook was used with the Radius PowerView to enable the experimenter to view the real-time data collection process through the use of an additional monitor. In addition, a prompt could be viewed by the experimenter when a change in noise types was required. Since the presentation order was completely randomized for each participant, advanced automated preparation of the noise types was not possible. Therefore, the noise types were adjusted manually using the Fostex model 260 mixing board and marked so that daily calibration could be initiated at each level. Following calibration, the experimenter marked the location on the mixing board for the experimental sessions, indicating the appropriate level of the noise type to be presented. This required that the experimenter be notified in advance of the particular experimental condition chosen at random by the HyperCard program, so that changes in noise type could be made quickly and the flow of the experiment was not interrupted. Subsequently, a method of notification was developed and integrated into the program. In addition to prompting the experimenter, the augmented program was

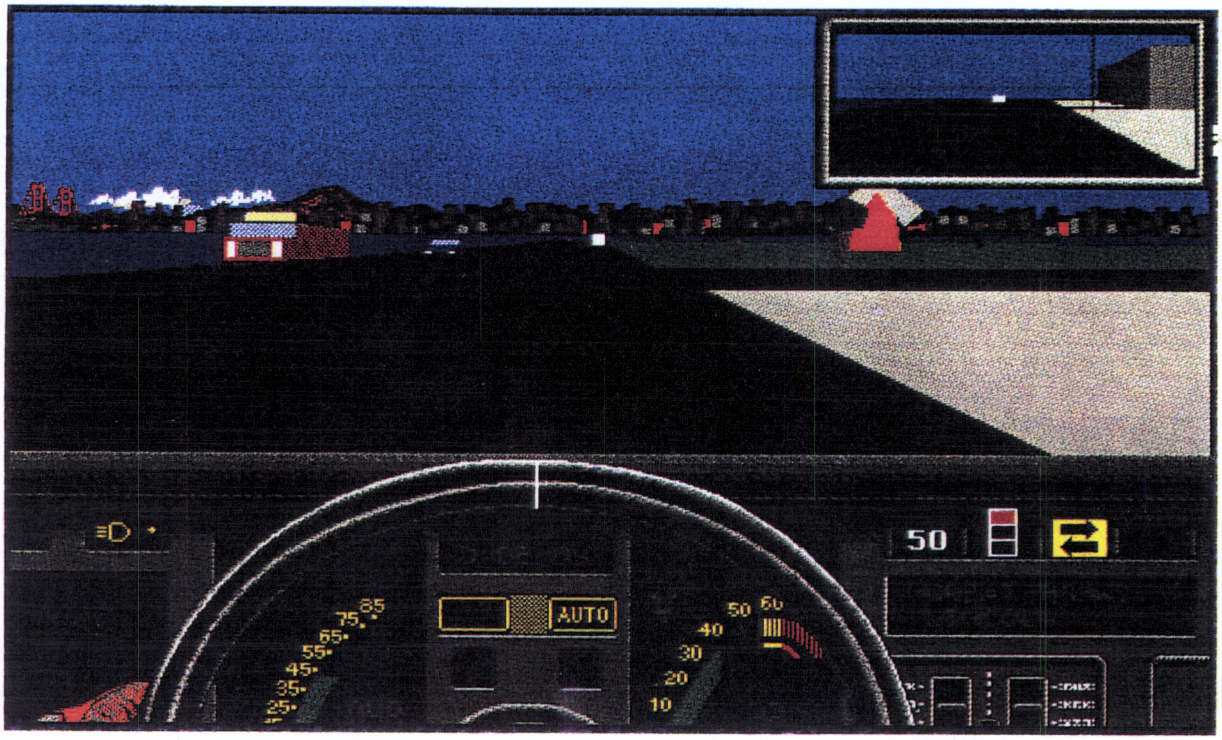

Figure 8. *A captured screen from the simulated driving environment (taken from the driving game VETTE!©, produced by Spectrum HoloByte™).*

able to automatically pause the secondary task until a change in noise types was completed. A photograph of the experimenter's station is provided in Figure 9.

The left one-third portion of the PowerBook screen was dedicated to the display of real-time data collection. This information included items such as the level of each of the independent variables, the acquisition time, and accuracy. These data were duplicated on paper as they occurred during the experiment to prevent the loss of valuable information. The crash and ticket frequency and the values associated with the subjective workload rating also were cataloged on paper during the experiment.

The right two-thirds of the PowerBook screen was used to prompt the experimenter as to which of the three noise types should be activated for the subsequent experimental conditions. In addition, the script allowed the placement of data onto one field as a series of rows and columns which was easily exported into a Microsoft Excel file for organization, and subsequently exported and analyzed in a statistical software package, SuperANOVA, for the Apple Macintosh.

The location of the participant's side-task display was to the right of the primary task display, and at a downward visual angle (with respect to the participant) of about 20 degrees. This configuration approximated the anticipated placement of the display on the actual cab dashboard of the heavy commercial truck. The distance from the participant was based on thumb-tip reach for a 5th percentile male, 74.3 cm (NASA, 1978). The shadowed letter buttons on the white display screen represented navigational information to be acquired by the participant after a visual or auditory prompt. The buttons were designed such that they were randomly-spaced relative to one side of the display or the other. For instance, the 12 letter buttons on the screen in the high density condition were divided such that six were located on the left and six on the right side of the display. This placement ensured that the participant was not further loaded in the directional prompt condition by placing buttons in the middle, since the directional prompt only indicated a

Figure 9. *A photograph of the experimenter's station.*

right or left orientation of the buttons. The activation of these on-screen buttons was accomplished by simply touching the display screen where the letter button appeared. As a confirmation to the participant, when the button area was touched, a beep was heard and the letter button inverted in polarity, i.e., the button changed to black and the letter changed to white. A closed-response format was utilized for the information presented on the side-task display, i.e., the prompted information actually occurred on the screen. An example of the high information density condition is depicted in Figure 10.

It was originally proposed that the secondary task be designed such that Modified Cooper-Harper (MCH) rating scales be presented to the participant following each experimental condition (Wierwille and Casali, 1983). Participants were to have responded by using the touchscreen, which would have allowed for automated data collection. During pilot testing the MCH became too time-consuming between experimental conditions, which minimized its usefulness. Instead, a more simplified seven-point, anchored Likert scale with equal interval scale steps was used to assess the subjective workload of participants. The scale was anchored at each of the seven levels from decreasing to increasing subjective workload: Extremely Easy, Very Easy, Moderately Easy, Neutral, Moderately Hard, Very Hard, and Extremely Hard. Participants responded verbally while continuing to control the vehicle in the primary task following each experimental condition, i.e., when no other data were being collected from the primary or secondary task. It was decided that this method enabled participants to experience continuity throughout the dual-task scenario. They could continue driving while responding to the question "OK, on a scale from one to seven, how would you rate the workload experienced from the last configuration?". The alternative would have been to restart the primary task after the completion of each condition. This was viewed as infeasible because it would have added significantly to the time required in the experiment, leading to additional concerns regarding fatigue effects. A paper scale was

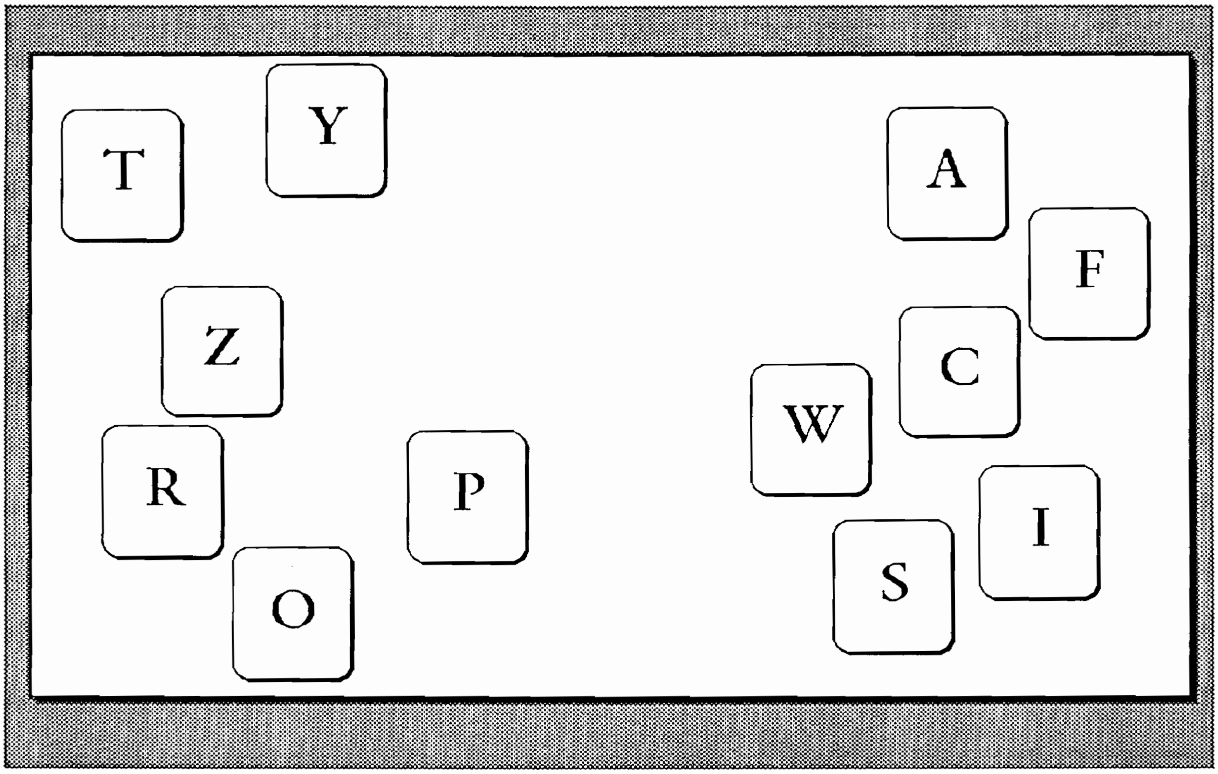

Figure 10. *A sample high density informational display.*

placed under the monitor on which the primary task was presented, so that participants could refer to the anchors while making a subjective workload rating.

Auditory prompt. While performing the primary task, the prompts given to the participants consisted of either a visual message, or one of two auditory messages indicating the information to be acquired on the subsequent display screen. For example, the visual condition presented the phrase "Touch the letter" followed by the letter button to be visually acquired on the following screen. The phrase remained on the screen for two seconds, the approximate length of each auditory prompt.

The auditory prompts used in the secondary task program were recorded in the anechoic chamber of the Auditory Systems Lab using the PowerBook 140, an AKG C 535 EB omnidirectional microphone, and SoundEdit™ Pro, a commercially available software application. Each letter and phrase required for the secondary task was recorded at 22 KHz and digitized using this application, e.g., "Touch the letter", "A", "B", "C". Each of the captured sounds were then edited so that three versions were produced: diotic (the original stereo recording), a left channel-only recording, and a right channel-only recording. The latter two recordings represented the auditory-directional prompts for each letter or phrase. Subsequently, all three versions were assimilated into the HyperCard secondary task program for presentation.

The sound level of the auditory prompts was determined during pilot testing. The method by which the sound level was determined was similar to that used in a study conducted by Pachiaudi and Blanchet (1990). While performing the primary task, normal-hearing pilot participants were asked to adjust the level of the signal (auditory prompt) in the presence of all three noise types, such that it could be clearly understood. The mean preferred level for each noise type was then calculated. The appropriate components, i.e., previously-recorded truck cab noise, background speech, and compact discs, were combined at the respective average value using a Fostex model 260 mixing board (Morrison, 1993). An NAD model 1020B stereo preamplifier, NAD model 2200 stereo power amplifier, Optimus® CD-1650 compact disc player, TEAC model 124 cassette deck and a Sony TC-W7R stereo dual-cassette deck in conjunction with two Infinity® RS 9b loudspeakers were used to present the noise types. A RION NA-29E octave-band analyzer and RION NH-17 half-inch microphone were used for daily calibration of ambient noise conditions, all noise types, and the auditory prompt. The analyzer was also used to monitor participants' noise exposure levels. The actual levels experienced during participation in the experiment did not exceed 80 dBA time-weighted average (TWA) for approximately three and one-half hours, and OSHA (1989) allows up to an 85 dBA TWA for an eight-hour day before a hearing conservation program is required

Daily calibration. The daily calibration values of the ambient level, noise types, prompt types, and the RION octave-band analyzer are arranged in Table 7. A sample form used prior to each participant is presented in Appendix H. All measures taken were A-weighted Leq (Fast) using the RION octave-band analyzer, with the prompt loudspeaker height fixed at 44" and the microphone at the participant's head center, but with no participant present. After the octave-band analyzer had been internally calibrated, calibration of the other equipment began approximately one hour before the arrival of the participant. Calibration of the octave-band analyzer was also completed following each participant.

The conditions under which the ambient readings were obtained include setting the room's air conditioning system to "low" and turning on all the stereo and computer equipment. The ambient noise level ranged from 50 dB and 60 dB, well below the 72 dB to 76 dB truck noise present during the experimental trials.

The truck noise, previously recorded by Morrison (1993) was re-recorded onto a three-minute continuous tape. The same representative 30 second portion of tape was used for calibration. The acceptable range was between 72 dB and 76 dB, A-weighted L_{eq}. Similarly, the truck and background speech noise type, also recorded by Morrison (1993) was re-recorded onto two 90-minute tapes. The same representative 30 second portion of tape was used for daily calibration. The acceptable range also was between 72 dB and 76 dB, A-weighted L_{eq}. The presentation of this noise type was based on a 10-minute portion of the tape which was recorded nine times on the 90-minute tape. A backup tape was then recorded and the two tapes played continuously in the Sony TC-W7R stereo dual-cassette deck. A problem discovered in pilot testing necessitated the use of two continuously-playing 90-minute tapes. Since the level of the noise types was controlled by a stereo mixer, allowing the experimenter to fade-in the noise, occasionally, the tape would be switching sides during the presentation. Consequently, no noise type would be heard by the participant. The two 90-minute tapes were then synchronized such that one began in the middle of the tape and the other began at the end, i.e., if one tape were switching sides, the other tape would begin presenting the noise. This method was used so that the noise type would still be heard by the participant during the five- to seven second pause in the tape while switching sides.

For the truck, speech, and music noise type condition the compact discs (CDs) used to present music were mixed into the truck and speech noise type. Mixing the CDs at the appropriate level was largely determined by the acceptable range of the other noise types. The truck and speech noise level was held constant as the music level was increased to a point approaching the upper bound of the acceptable range. The result was that the truck, speech, and music noise type was generally louder than the truck and speech noise type by approximately 1.2 dBA, as shown in Table 7. The music was chosen by the participant from one of eight CDs, prescreened to ensure relatively constant sound pressure levels. Selections which deviated significantly, i.e., out of the acceptable

TABLE 7

Daily Calibration Data (all data are A-weighted L_{eq} measurements, unless otherwise stated)

Participant	RION octave-band analyzer before and after session (94.0 is reference level for calibration)	Room Ambient Noise Level	Truck Noise	Truck, Speech	Truck, Speech, Music	Auditory Prompt*
1	94.0/94.0	54.4	73.3	72.6	74.3	79.6
2	94.0/94.0	53.6	72.8	73.5	74.2	79.6
3	94.0/94.0	53.6	72.8	73.5	74.2	79.6
4	94.0/94.0	53.0	73.2	72.7	74.2	79.7
5	94.0/94.0	52.9	72.9	72.6	74.3	80.5
6	94.0/94.0	53.5	72.9	72.5	74.0	79.4
7	94.0/94.0	53.5	72.9	72.5	74.0	79.4
8	94.0/94.0	53.7	73.0	73.1	74.6	80.6
9	94.0/94.0	53.8	73.4	73.9	75.2	79.9
10	94.0/94.0	54.1	73.8	75.5	76.0	80.1
11	94.0/94.0	53.7	73.3	74.9	75.8	80.6
Mean	**94.0/94.0**	**53.6**	**73.1**	**73.4**	**74.6**	**79.9**

* Auditory Prompt was calibrated using a peak measurement due to the transient nature of the stimulus.

range, were programmed out during the experiment. As with the previous noise types, the same 30 second portion of a representative song was used for daily calibration.

The auditory prompt was calibrated using the phrase "Touch the letter", recorded at 22 KHz in an anechoic chamber and digitized in SoundEdit™ Pro. The acceptable range for the prompt was between 76 dB and 80 dB, peak measurement.

Another part of the daily procedures involved calibration of the touchscreen using a special control panel for the Apple Macintosh. Adjustments included the amount of cursor offset and the touchscreen boundaries. It was necessary to conduct the procedure prior to the arrival of each participant, to control for errors in data collection resulting from equipment drifts. In addition, the touchscreen monitor was cleaned before each participant arrived, in order to reduce the effects of glare on smudged portions of the display.

Supporting apparatus. The headrest loudspeaker apparatus was constructed in a similar fashion to that used in Pachiaudi and Blanchet (1990). Two directional loudspeakers (Optimus® XTS 3) were fitted onto an adjustable, reinforced loudspeaker stand to accommodate the varying stature of participants. The loudspeakers were driven by the PowerBook 140 and amplified by a Realistic SCR-3010 stereo receiver. Each loudspeaker was mounted such that it was angled approximately 45 degrees toward, and three- to four-inches away from the ear canal entrance of the participant. In addition, a foam headrest ensured greater channel separation by keeping the participant's head in a relatively stable position (the back of the headrest was approximately one inch from the back of the participants' head). This adjustable apparatus ensured that the auditory prompt loudspeakers were located in the same relative position for all participants. Figure 11 depicts a front view of the headrest loudspeaker apparatus.

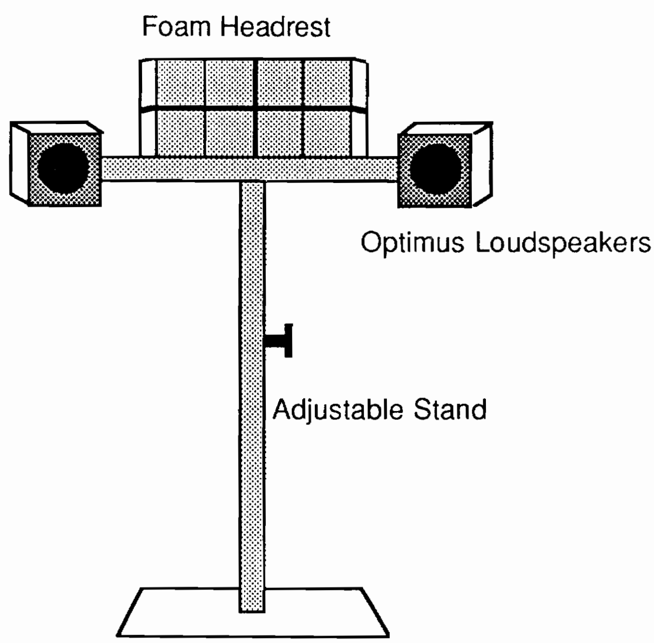

Figure 11. *Front view of headrest loudspeaker apparatus.*

Preexperimental Procedures

Pilot testing. The goal of pilot testing was to determine an appropriate level of workload on the primary and secondary task, the mean interval between stimuli presentation, the level of the signal (auditory prompt) in the presence of all three noise types, such that it could be clearly understood, and the proper number of stimuli per condition.

To achieve primary task stability, participants in the pilot study were asked to familiarize themselves with the driving game. The participants were asked to follow instructions from the experimenter regarding changes in direction. After 15 minutes of practice controlling the driving game, the secondary task was added (MacAdam, 1992).

To approximate the appropriate mean interval between stimuli presentation it was necessary to estimate secondary task completion time and the time required for the entire trial. The sequence of individual events required to complete the secondary task (attention, sensation, perception, searching, deciding, and responding) required approximately five seconds with the medium information density display.

Previous driving simulator studies (MacAdam, 1992; Noy, 1990) indicate that between 20 to 33 percent of total time was spent on the secondary task activities and that individual trials lasted between two and six minutes. Using these figures, and the 5 s subjectively estimated for secondary task completion, the presentation frequency should range from 15 s to 25 s. To assess the validity of these figures with regard to the present study, it was originally proposed that the secondary task stimuli be presented every 20 s (plus or minus 5 s to combat errors of anticipation). During pilot testing, this technique proved infeasible because of the amount of time required to complete all the experimental conditions, e.g., one participant required over five hours to complete the entire experiment. One reason for the discrepancy between the proposed figures relates to the addition of another proposed independent variable to the experimental design (Task Type). Initially, participants were to have completed only a dual-task configuration, whereby no comparison data would have been possible. It was also decided to present all 27 conditions to participants while they were *not* engaged in primary task activity. Given the above figures, this decision effectively doubled the experimental completion time. Subsequently, a reduction in the secondary task presentation interval was required to comply with the previously stated fatigue-related concerns. In fact, this proved to be more effective from the point of view of the participants. Since the secondary task condition involved no driving, the participants were literally staring at a non-moving primary task display while responding to the secondary task about every 15 s. After the reduction in the task presentation interval, participants responded to the secondary task prompts every five seconds, which shortened the required time considerably, and provided each with a more engaging experience. In an effort to further reduce the experimental completion time, the dual-task presentation interval was reduced from 15 s to 10 s; however, due to the decreased presentation interval associated with the secondary task-only conditions, the task type variable was removed from the experimental design.

The proper number of secondary task stimuli per experimental condition was obtained after the workload level and the mean interval between stimulus presentation had been established. It was originally proposed that the participant would begin with 20 stimulus presentations. Response time was monitored through the use of the PowerBook, which displayed the real-time data acquisition from the HyperCard program. As the response data became asymptotic for a given trial, this would have been an indication of the acclimation of the participant, and consequently, be the point at which further stimuli would yield little additional information. Therefore, a mean was to have been taken at this relative point across participants to determine the point at which data collection would begin in the experimental conditions. For instance, if pilot participants became acclimated after eight presentations of the stimulus, then data collection was to have begun on presentation nine. But this procedure was also not possible due to the time constraints in the study. Instead, the secondary task presentation, which preceded the dual-task configuration, served to acclimate participants. It was decided, based on these discoveries made during pilot testing, to present 10 trials for each of the 27 conditions during each of the two task scenarios (secondary task and dual-task). The figures described in the pilot testing sessions also conform to the *apriori* time limit of two and one-half hours for the experimental conditions to minimize effects due to fatigue and inattention. The 150 minutes was divided by the time possible to complete each of the 54 conditions, and further divided by the number of anticipated stimuli to be presented (10), to give a value of approximately 10 s between stimulus presentations, not including the average response time of the participant. After completing the pilot testing procedures, a set of experimental procedures was developed which is provided in Appendix B.

Screening procedures. Participants were initially screened during a telephone questionnaire, provided in Appendix A, which yielded information including age, height, weight, native language, and any known hearing or vision problems. Those respondents who were licensed male commercial truck drivers were then asked about accident frequency, years of experience, and approximate number of miles driven per week.

The participants were informed that they would be required to spend approximately 45 minutes to complete the necessary screening and training procedures (including the audiogram), and at most, two and one-half hours to complete the 54 experimental conditions (27 with the secondary task alone and 27 with the dual-task scenario). As mentioned previously, one reason for establishing this limitation was because after approximately three hours, problems with fatigue due to repetition may have begun to confound data collection. Each participant was paid fifty dollars for his participation. The reason for a flat compensation rate instead of hourly compensation was to ensure that participants were not motivated to malinger or disregard driving instructions during the experimental conditions, e.g., participants would have had the opportunity to crash the simulated vehicle repeatedly, extending the time of the study, and, consequently, enabled them to receive more compensation but reduce the validity of their responses.

One advantage of utilizing a within-subjects design was that fewer participants were required, due to repeated observations. Since the truck driver population had been estimated as ranging from 76 percent to 95 percent male, this study was conducted with only male participants.

Experimental Procedures

Upon arriving at the Auditory Systems Laboratory, the participant was welcomed and asked to read the experimental description, provided in Appendix C. After any questions had been answered by the experimenter, the participant was asked whether or not he would like to take part in the study. If his answer was affirmative, then the participant was asked to complete the informed consent form, provided in Appendix D.

Otological examination and audiogram. All participants were then screened to ensure adequate hearing. The experimenter performed an otological inspection of the pinna, ear canal, and eardrum using a Welch-Allen 21700 otoscope. Upon successful completion of the inspection, i.e., no discovery of impacted earwax or lesions, the participant was directed to the test booth where the pure-tone hearing threshold was determined at 500, 1000, 2000, 3000, and 4000 Hz (Morrison, 1993). A modified Hughson-Westlake procedure, which is a variant of the method of limits, was used for threshold determination (Carhart and Jerger, 1959). Participants were seated in the test chamber and instructed to respond by pressing and holding down a silent, hand-held push-button when they heard the pure-tones, and releasing the button only when they could no longer hear the tones. The experimenter controlled the signal presentations and recorded the responses. A sample participant evaluation form is provided in Appendix E.

The experimenter presented a pure-tone signal at a particular frequency for five pulses. If the participant did not respond, the level was increased by 10 dB. If the participant did respond, the level was reduced by 10 dB at which point the pulses were presented again. Subsequent ascending presentations were increased by five dB until the participant responded. This value was recorded and the procedure continued. Threshold recordings were made only on ascending presentations. As mentioned earlier, criteria for acceptance were taken from Morrison (1993): a pure-tone average of no more than 50 dBHL for any frequency. According to Miller and Wilber (1991), this hearing level is indicative of a slight to mild impairment in which the participant may experience some difficulty in hearing normal speech. If the participant did not complete the audiogram successfully, he was to be debriefed, compensated, and dismissed from the study; however, all candidate participants met the established audiometric criteria.

After completing the audiogram, the participant was directed to the specially-prepared experimental room where the apparatus and procedures were explained and demonstrated. The experimenter responded to any questions to the extent possible. The participant was instructed to sit in the chair facing the two monitors and assume a posture that would be comfortable for about two hours. The legs of the chair were then marked with tape so that the position could be reproduced after rest breaks. In addition, the headrest loudspeaker apparatus was adjusted so that the prompt loudspeaker height and distance from head was such that the participant's ear canal was approximately at the midpoint of the loudspeaker and the participant's head was approximately one inch from the foam headrest. After choosing one of the eight prescreened compact discs to be listened to during the truck, speech, and music noise type condition, the three noise types were presented to the participant for 20 s each (Morrison, 1993). Secondly, the two types of auditory prompts were presented for familiarity. At this point, the experimenter read from a script to yield consistency, which emphasized the intent of the auditory-directional condition. The script is presented in Appendix F. For example, the participant was instructed that the auditory information ("Touch the letter D") would appear to be coming from the right loudspeaker in the headrest apparatus. This would then be followed by navigational information presented on the right region of the side-task display. It was originally proposed that three such practice exercises were to have been performed, one for each of the levels of information density (high, medium, and low). Due to the complete randomization of the presentation, difficulty was experienced in manipulating the HyperCard script after the parameters for the actual experimental sessions had been set. Therefore, not all participants received the same configuration during the three practice trials. This point will be addressed in more detail in the Discussion section.

Experimental session procedure. For the secondary task configuration, the participants were instructed (via the script) to use the primary task display as a visual reference point and to place their hands at the 10 o'clock and 2 o'clock position on the steering wheel. They were also instructed to keep their head as close to the foam headrest as possible. The reason for these references was so that the data would be accurately obtained without having to account for additional posture variations among participants. This was especially important for the trials during which the auditory-directional prompt was displayed, since it was not known *apriori* the nature of the effect under different posture configurations.

For the visually-oriented trials, the HyperCard program generated a visual prompt approximately every five seconds, indicating to the participant to look for a particular letter, e.g., "Touch the letter D on the next screen". The subsequent screen contained various letters in the form of buttons. Density of the display, i.e., how many letters on a particular screen, was randomly determined, presented, and accounted for by the HyperCard program from low (4 items), medium (8 items), or high (12 items), the levels of task difficulty used by Noy (1990) in a study of driver selective attention using auxiliary automobile displays. For both the auditory-diotic and auditory-directional conditions, the digitized prompt imported into the program from SoundEdit™ Pro "Touch the letter A on the next screen" was presented through the headrest loudspeaker apparatus. The previously blank (white) screen on the 14" touchscreen then displayed the simulated navigational information in the form of letter buttons randomly spaced and equally sized. Participants responded by touching the appropriate letter button on the screen, as indicated by the previous auditory or visual prompt.

Primary task training session. Following the secondary task configuration, participants were required to complete 20 minutes of training on the primary task (driving game) without the intrusive effects of the secondary navigational task (MacAdam, 1992). The participants were instructed to adhere to the route directions from the experimenter. The desired effect of the training was to eliminate unnecessary workload which may have been incurred as a result of learning the primary task during the course of responding to the secondary task demands in the experiment. Upon completion of the prescribed route, the parameters of the HyperCard program were changed to reflect the dual-task configuration. The presentation interval was changed so that the secondary task was presented every 10 s rather than every 5 s as in the secondary task scenario.

For the dual-task scenario the participants also were instructed (via the script) regarding the salient displays and the operation of the controls. They were shown the primary task display screen which depicted an inside-looking-out view of the simulated vehicle. Other items within the field of view include the rearview mirror, steering wheel, headlight indicator, street name, and the elapsed time since the last restart of the game (this value was not used for data collection purposes).

The aforementioned controls included the mouse wheel and an accelerator and brake pedal apparatus, the functionality of which were described to each participant according to the script. Since the accelerator and brake pedals were keyboard-actuated, their feedback was less than optimal, i.e., it was somewhat difficult for participants to maintain a given speed due to the "on" or "off" state of the pedal controls. The steering (mouse) wheel was also difficult to control initially. During pilot testing the speed of the mouse was manipulated from slow to fast on the Macintosh control panel in an effort to increase realism. The mouse wheel apparatus was also altered to increase the resistance. In addition, the parameters which control the steering response of the simulated vehicle were altered. Although many such attempts were made to increase the realism of the steering controls, all participants in the pilot study expressed that steering the vehicle was the most difficult portion of the experiment. The difficulty of these tasks was reduced somewhat during the practice session in which the participants learned the prescribed route; however, if the tasks were too easy, it would call into question the degree of workload experienced by the participants. As the data indicate in a following section, the workload experienced under the dual-task configuration, wherein driving was a major component, was significantly greater than in the secondary task configuration.

Displays of importance in the driving game include a speedometer, tachometer, and an updated window showing the posted speed limit of the road on which they were traveling. It was necessary to point these out to the participant because the simulated dashboard utilized digital display technology, which confused some pilot participants because the tachometer and speedometer readouts look very similar and appear next to each other. It was also discovered during pilot testing that auditory feedback of the vehicle's acceleration and deceleration were helpful in maintaining speed control of the vehicle, crucial for consistent performance. This level was then tested and permanently set on the Macintosh sound control panel for the duration of the experiment to ensure minimal interference with the noise types and auditory prompts, i.e., the sound of the vehicle's engine was barely audible but beneficial to participants' control of the simulated vehicle. As in the secondary task scenario, participants were asked to place their hands at the 10 o'clock and 2 o'clock position on the steering wheel and keep their head close to the foam headrest.

As the practice session began, the experimenter dictated route changes to be made in the simulated roadway environment. The route consisted of four right turns and involved speed changes (from 30 miles-per-hour (48 km/h) to 55 miles-per-hour (89 km/h)) as dictated by the updated window on the vehicle's dashboard. Each participant was instructed according to the script to maintain the speed of the vehicle as close to the speed limit as possible. After about 15 minutes, most of the participants had completed the route and were asked to take a brief break while the experimenter set up the dual-task scenario.

After the participant returned, additional instructions were provided including information about responding to the subjective workload rating and emphasizing that a quick response was desirable while interacting with the secondary task touchscreen. The experimenter then set the appropriate noise type and restarted the primary task and instructed the participant to drive the simulated vehicle. The experimenter then began the secondary task only after control of the vehicle had stabilized. Figure 12 depicts a mock participant responding to a prompt during the dual-task scenario. Response time and accuracy (whether or not the participant selected the correct button on the screen) was recorded by the HyperCard program script and the presentation order, crash and ticket frequency and subjective workload rating were recorded by the experimenter for each of the 27 experimental conditions associated with the dual-task configuration. After each condition had been completed, the experimenter asked the participant to give a subjective rating from one to seven, describing the workload experienced with that condition.

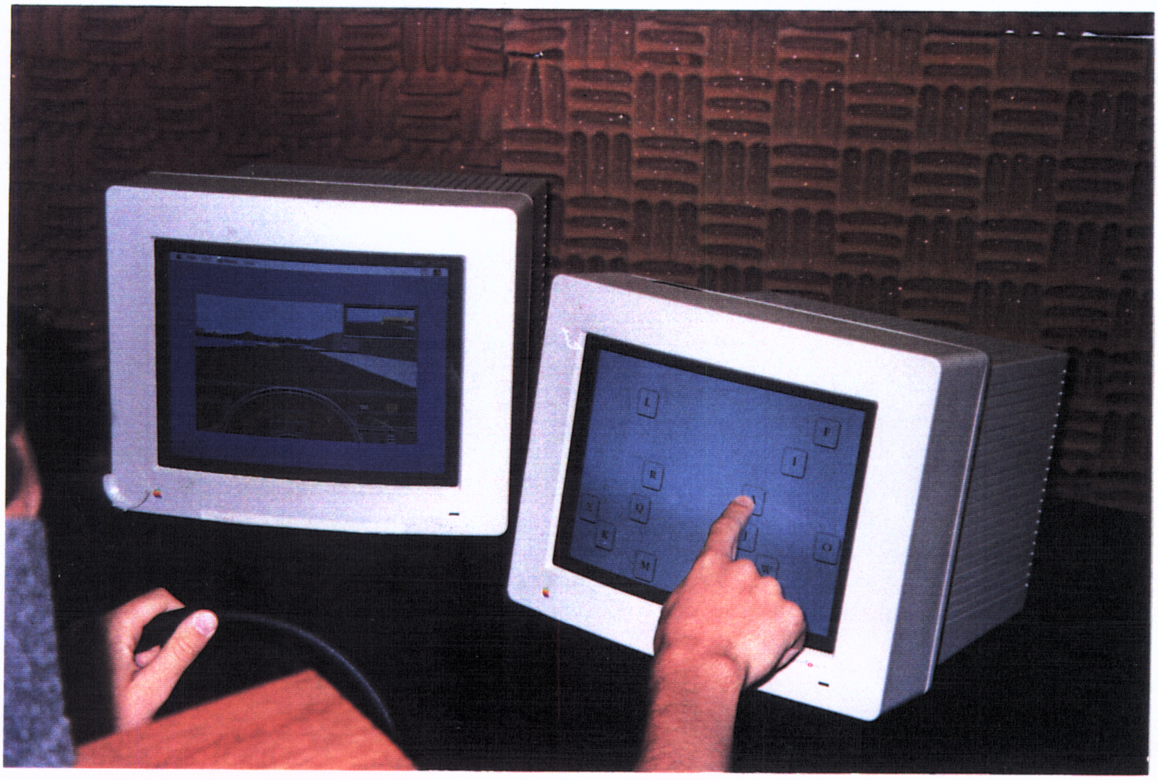

Figure 12. *A photograph of a mock participant responding to a prompt by selecting a letter button on the touchscreen during the dual-task scenario.*

Upon successful completion of all the experimental procedures, the participant was paid, debriefed, and dismissed. After the participant left, data were backed up, exported to Microsoft Excel for reduction, and an internal calibration measurement from the RION octave-band analyzer was taken.

EMPIRICAL RESULTS

Data Reduction

Dependent measures. For the secondary task conditions, the dependent measures used were acquisition time and accuracy. For the dual-task conditions, crashes/tickets on the primary task and a subjective workload rating were examined in addition to acquisition time and accuracy.

Acquisition time was defined as the length of time from presentation of the letter buttons to the selection by the participant, as captured by the HyperCard program. Accuracy was defined as whether the prompted letter button was selected by the participant, as recorded by the HyperCard program.

During the dual-task conditions, the experimenter recorded a crash when the simulated vehicle was involved in a collision which caused sufficient damage as to result in uncontrollable handling characteristics, i.e., it was possible for the participant to crash the simulated vehicle and continue, assuming that the damage incurred was not severe; however, if the participant received a speeding ticket, the primary task was necessarily restarted. These two measures were combined to assess the frequency of primary task difficulty across all treatment conditions under the dual-task scenario.

The subjective workload rating was comprised of a seven-point interval Likert scale given verbally by participants, following each dual-task treatment condition. The anchors were one: extremely easy; seven: extremely hard. Both the crash/ticket data and subjective workload rating values were recorded by the experimenter and later entered into the existing database.

Data reduction was simplified through the use of Microsoft Excel, a commercially-available spreadsheet application. Each of the tab-delimited data fields from the HyperCard program (Figure 6) were copied into a formatted spreadsheet, arranged as a database, and averaged across each group of 10 trials. At this point in the reduction process, the accuracy data yielded a proportional value for each of the 54 experimental conditions. Subsequently, each of the mean values for a given treatment condition were ranked according to the corresponding factor level, e.g., 111 designated level one for all factors. Since the presentation of the treatment conditions was randomized, the ranking was necessary in order to place the data in the proper location for a comparison without regard to order. The data were then transposed and further reduced to a tabular format consisting of the unique treatment combination, and the mean values for accuracy and acquisition time; for the dual-task data, the frequency of crashes and tickets and the mean subjective workload rating for each condition were also included. These data were then subdivided into groups of means according to the different dependent measures, which allowed an easy transition to a format compatible with SuperANOVA, a statistical software application used for the subsequent analysis.

Statistical Analysis

Analysis of variance (ANOVA) techniques were used to test the significance of main effects and interactions of all factors from the complete factorial design. According to the experimental hypotheses, of interest was whether the auditorially-presented prompts allowed participants to complete the secondary task more quickly and accurately than when the visual prompt was used to convey the information. Additionally, it was hypothesized that decreased performance would result from the high information density level, and that the dual-task scenario would result in poorer performance than the secondary task conditions.

Assumptions of the ANOVA. Because the experimental design contained only within-subjects variables, more stringent Geisser-Greenhouse corrections (Vasey and Thayer, 1987) were used to protect against potential effects due to violations of the homogeneity of covariance, or sphericity assumption, i.e., positive bias in the ANOVA resulting in inflated p-values of within-subjects sources of variance. Both the Geisser-Greenhouse epsilon (ε) correction values and p-values are shown in the ANOVA tables. Where p-values appear in the text to follow, these indicate the Geisser-Greenhouse corrected values.

Overall analysis. Originally, it was proposed to combine the secondary and dual-task data into a separate factor in the experimental design; however, due to time constraints during data collection, the task presentation interval for the secondary task conditions was reduced. Therefore, since the task presentation interval was not identical for the two task types, the analysis was conducted separately.

Each of the dependent measures (accuracy, acquisition time, crashes/tickets, and subjective workload rating) were subjected to a three-way, within-subjects factor ANOVA. All main effects and interactions of prompt type, information density, and noise type were included as sources of variance for both the secondary and dual-task conditions. Analyses were completed using SuperANOVA for the Apple Macintosh, a commercially available statistical software application. Where appropriate, post-hoc Newman-Keuls and simple-effects F-tests were administered to determine the locus and nature of the effect(s). The Newman-Keuls test was chosen primarily out of convention; however, this test utilizes progressive critical values according to the number of compared means, which makes it more powerful than some other post-hoc analyses (Glass and Hopkins, 1984).

Secondary task accuracy. No statistically-significant ($p < 0.05$) main effects or interactions were observed for accuracy during the secondary task configuration. The complete ANOVA summary table for accuracy is provided in Table 8. Table 9 provides mean values and standard deviations for all possible treatment conditions for secondary task accuracy. Since a ceiling effect was expected because the participants were not driving in the simulated environment, this result was anticipated.

Dual-task accuracy. Although not statistically-significant ($p < 0.05$) after the Geisser-Greenhouse correction factor was applied, a depiction of the Prompt Type-by-Information Density (PxD) interaction $\{F(4,40) = 2.92, p = 0.0584\}$ in Figure 13 appears to support the assumption that auditory prompts may lead to more accurate performance than visually-presented prompts under high visual load scenarios; however, only a statistically-significant ($p < 0.05$) main effect for Prompt Type (P) means $\{F(2,20) = 13.52, p = 0.0023\}$ was observed. Table 10 shows the complete ANOVA summary table and Table 11 provides mean values and standard deviations for all possible treatment conditions for dual-task accuracy.

Newman-Keuls post-hoc analyses were conducted to fully explore the significant Prompt Type main effect found for the dual-task accuracy measure. The Newman-Keuls results appear in Table 12. The data suggest that more difficulty was experienced during the visually-prompted trials under the dual-task configuration, as evidenced by the poorer accuracy. Figure 14 depicts the prompt type main effect for dual-task accuracy.

Secondary task acquisition time. Statistically-significant ($p < 0.05$) main effects of Prompt Type (P) means $\{F(2,20) = 42.41, p < 0.0001\}$, Information Density (D) means $\{F(2,20) = 54.16, p < 0.0001\}$, and the interaction of Prompt Type-by-Information Density (PxD) $\{F(4,40) = 3.72, p = 0.0380\}$ were observed. The complete ANOVA summary table for acquisition time is provided in Table 13. Table 14 provides

TABLE 8

ANOVA Summary Table for Secondary Task Accuracy Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	0.207	0.021				
Within-Subjects							
Prompt Type (P)	2	0.004	0.002	0.822	0.4538	0.9773	0.4516
P x S	20	0.050	0.003				
Information Density (D)	2	0.021	0.010	2.417	0.1148	0.6867	0.1372
D x S	20	0.085	0.004				
Noise Type (N)	2	0.005	0.003	1.717	0.2050	0.8688	0.2100
N x S	20	0.031	0.002				
P x D	4	0.007	0.002	0.629	0.6442	0.4329	0.5225
P x D x S	40	0.108	0.003				
P x N	4	0.001	0.0003	0.132	0.9699	0.6908	0.9298
P x N x S	40	0.102	0.003				
D x N	4	0.010	0.003	1.753	0.1575	0.4796	0.2006
D x N x S	40	0.056	0.001				
P x D x N	8	0.016	0.002	0.614	0.7640	0.2760	0.5659
P x D x N x S	80	0.265	0.003				
Total	296						

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 9

Mean Proportional Values (Standard Deviation) of Main Effects for the Secondary Task Accuracy Dependent Measure (Proportions are dimensionless and range from 0 to 1.)

	Secondary		
	Visual	Auditory-diotic	Auditory-directional
Truck			
High	0.9818 (0.0405)	0.9545 (0.0934)	0.9636 (0.0924)
Medium	1.0000 (0.0000)	1.0000 (0.0000)	0.9909 (0.0302)
Low	0.9545 (0.0820)	0.9818 (0.0405)	0.9636 (0.0674)
Truck+Speech			
High	0.9818 (0.0405)	0.9636 (0.0809)	0.9727 (0.0647)
Medium	1.0000 (0.0000)	0.9909 (0.0302)	0.9909 (0.0302)
Low	0.9818 (0.0405)	1.0000 (0.0000)	0.9727 (0.0647)
Truck+Speech+Music			
High	0.9636 (0.1206)	0.9636 (0.0809)	0.9727 (0.0467)
Medium	0.9909 (0.0302)	0.9818 (0.0405)	0.9545 (0.0688)
Low	0.9909 (0.0302)	0.9636 (0.0505)	0.9818 (0.0603)

TABLE 10

ANOVA Summary Table for Dual-Task Accuracy Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	0.519	0.052				
Within-Subjects							
Prompt Type (P)	2	0.546	0.273	13.520	0.0002	0.6003	0.0023*
P x S	20	0.403	0.020				
Information Density (D)	2	0.013	0.006	2.692	0.0922	0.9212	0.0977
D x S	20	0.047	0.002				
Noise Type (N)	2	0.006	0.003	1.165	0.3321	0.8037	0.3256
N x S	20	0.054	0.003				
P x D	4	0.041	0.010	2.922	0.0327	0.6590	0.0584
P x D x S	40	0.141	0.004				
P x N	4	0.047	0.012	2.412	0.0649	0.6801	0.0935
P x N x S	40	0.195	0.005				
D x N	4	0.011	0.003	0.667	0.6183	0.6901	0.5673
D x N x S	40	0.160	0.004				
P x D x N	8	0.021	0.003	0.9346	0.9346	0.5271	0.8395
P x D x N x S	80	0.566	0.007				
Total	296						

*Statistically-significant effect at *G-G p* $p < 0.05$.

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 11

Mean Proportional Values (Standard Deviation) of Main Effects for Dual-Task Accuracy Dependent Measure (Proportions are dimensionless and range from 0 to 1.)

	Dual		
	Visual	Auditory-diotic	Auditory-directional
Truck			
High	0.8727 (0.1272)	0.9364 (0.0809)	0.9636 (0.0674)
Medium	0.8909 (0.1375)	0.9545 (0.0522)	0.9636 (0.0674)
Low	0.8727 (0.1348)	0.9727 (0.0467)	0.9727 (0.0467)
Truck+Speech			
High	0.8818 (0.1168)	0.9364 (0.0924)	0.9545 (0.0688)
Medium	0.9273 (0.0905)	0.9727 (0.0467)	0.9364 (0.1027)
Low	0.8818 (0.0982)	0.9909 (0.0302)	0.9818 (0.0405)
Truck+Speech+Music			
High	0.8364 (0.1286)	0.9818 (0.0405)	0.9636 (0.0674)
Medium	0.8818 (0.1079)	0.9545 (0.0688)	0.9818 (0.0603)
Low	0.8182 (0.1601)	0.9818 (0.0405)	0.9636 (0.0505)

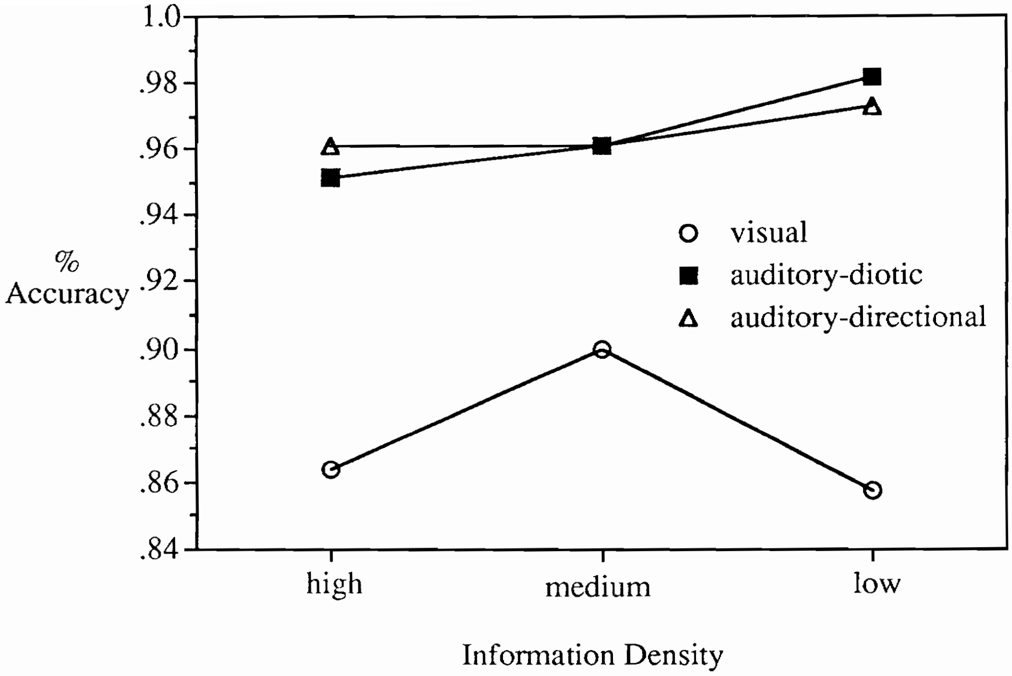

Figure 13. *Prompt Type-by-Information Density Interaction for Dual-Task Accuracy Dependent Measure (Means are* <u>*not*</u> *significantly different at* $p < 0.05$*).*

TABLE 12

Newman-Keuls Test Results for the Prompt Type Main Effect for Dual-Task Accuracy Dependent Measure (Mean values are in percent.)

Prompt Type	Means	0.864	0.965	0.965	C.D.**
visual	0.864		0.101*	0.101*	0.04
auditory-diotic	0.965			0.000	0.03
auditory-directional	0.965				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

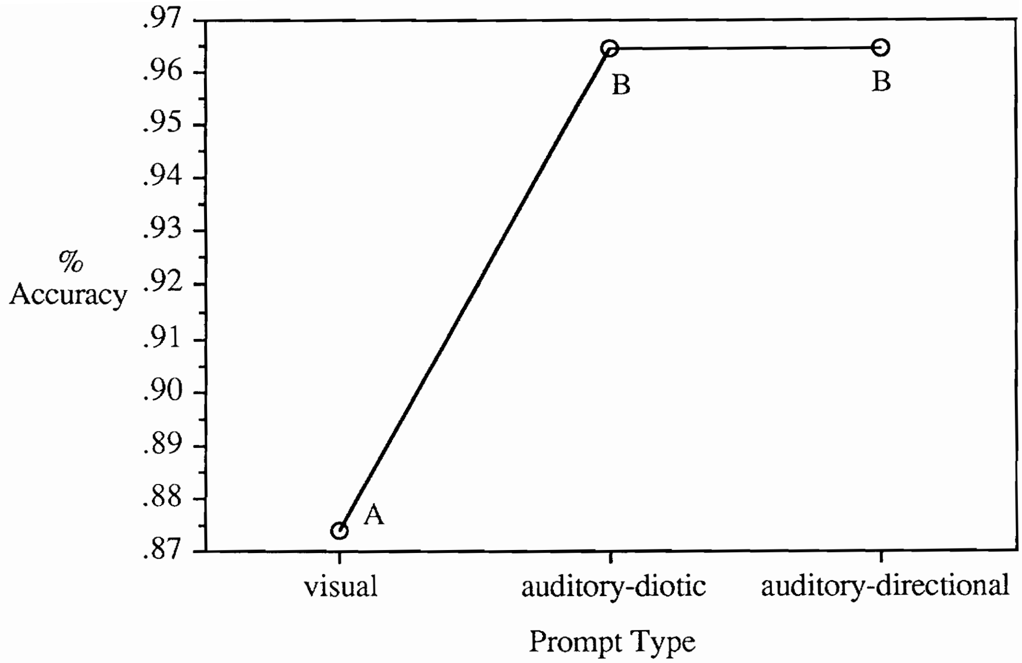

Figure 14. *Prompt Type Main Effect for Dual-Task Accuracy Dependent Measure (Means with different letters are significantly different at* $p < 0.05$*).*

TABLE 13

ANOVA Summary Table for Secondary Task Acquisition Time Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	20701792.5	2070179.25				
Within-Subjects							
Prompt Type (P)	2	7244558.32	3622279.16	42.414	0.0001	0.7695	0.0001*
P x S	20	1708039.83	85401.991				
Information Density (D)	2	8901697.84	4450848.92	54.157	0.0001	0.6835	0.0001*
D x S	20	1643686.98	82184.349				
Noise Type (N)	2	7148.02	3574.01	0.073	0.9298	0.9242	0.9180
N x S	20	979038.795	48951.94				
P x D	4	733873.535	183468.384	3.718	0.0115	0.5412	0.0380*
P x D x S	40	1973936.54	49348.413				
P x N	4	248538.02	62134.505	1.06	0.3886	0.6935	0.3779
P x N x S	40	2343654.05	58591.351				
D x N	4	73250.141	18312.535	0.461	0.7637	0.7501	0.7114
D x N x S	40	1587987.93	39699.698				
P x D x N	8	577751.273	72218.909	1.865	0.0772	0.5099	0.1340
P x D x N x S	80	3098152.43	38726.905				
Total	296						

*Statistically-significant effect at *G-G p* $p < 0.05$.

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 14

Mean Values (Standard Deviation) of Main Effects for the Secondary Task Acquisition Time Dependent Measure (Mean values are in ms.)

	Secondary: Visual	Secondary: Auditory-diotic	Secondary: Auditory-directional
Truck			
High	1624 (482)	1706 (516)	1102 (318)
Medium	1386 (408)	1340 (352)	1061 (353)
Low	1252 (344)	1091 (284)	930 (225)
Truck+Speech			
High	1764 (343)	1605 (459)	1238 (286)
Medium	1443 (270)	1266 (281)	1096 (341)
Low	1171 (416)	1036 (241)	973 (349)
Truck+Speech+Music			
High	1577 (459)	1569 (457)	1322 (392)
Medium	1537 (300)	1263 (297)	990 (182)
Low	1256 (361)	1062 (365)	928 (241)

means and standard deviations for all possible treatment combinations for secondary task acquisition time.

Simple-effects F-tests were conducted on the PxD interaction for secondary task acquisition time to determine significant prompt type main effects according to different levels of information density. This post-hoc test was chosen because it partitions the data such that the alpha error is distributed across one level of the factor of interest, while evaluating the other factor at that level.

Statistically-significant main effects for prompt type occurred for all levels of information density: high $\{F(2,40) = 39.45, p < 0.0001\}$, medium $\{F(2,40) = 27.94, p < 0.0001\}$, and low $\{F(2,40) = 13.45, p < 0.0001\}$. Similarly, statistically-significant main effects for information density occurred for all levels of prompt type: visual $\{F(2,40) = 30.79, p < 0.0001\}$, auditory-diotic $\{F(2,40) = 53.76, p < 0.0001\}$, and auditory-directional $\{F(2,40) = 13.09, p < 0.0001\}$. These analyses were conducted by using the error term from the overall two-way interaction (PxDxS). Subsequently, Newman-Keuls tests were conducted to quantify the differences between prompt types at each level of information density, e.g. each prompt type compared at the high information density level. Table 15 provides the results of the Newman-Keuls tests. Figure 15 depicts the PxD interaction according to secondary task acquisition time.

Dual-task acquisition time. Statistically-significant ($p < 0.05$) main effects of Prompt Type (P) means $\{F(2,20) = 10.92, p = 0.0015\}$, Information Density (D) means $\{F(2,20) = 50.23, p < 0.0001\}$, and the interaction of Prompt Type-by-Noise Type (PxN) $\{F(4,40) = 3.21, p = 0.0358\}$ were observed. The complete ANOVA summary table for acquisition time is provided in Table 16. Table 17 provides means and standard deviations for all possible treatment combinations for secondary task acquisition time.

Simple-effects F-tests were conducted on the PxN interaction for dual-task acquisition time to determine significant prompt type main effects according to different

TABLE 15

Newman-Keuls Test Results for the Prompt Type-by-Information Density Interaction for Secondary Task Acquisition Time Dependent Measure (Mean values are in ms.)

High Density	Means	1221	1627	1655	C.D.**
auditory-directional	1221		406*	434*	133
auditory-diotic	1627			28	111
visual	1655				

Medium Density	Means	1049	1290	1455	C.D.**
auditory-directional	1049		241*	406*	133
auditory-diotic	1290			165*	111
visual	1455				

Low Density	Means	944	1063	1226	C.D.**
auditory-directional	944		119*	282*	133
auditory-diotic	1063			163*	111
visual	1226				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

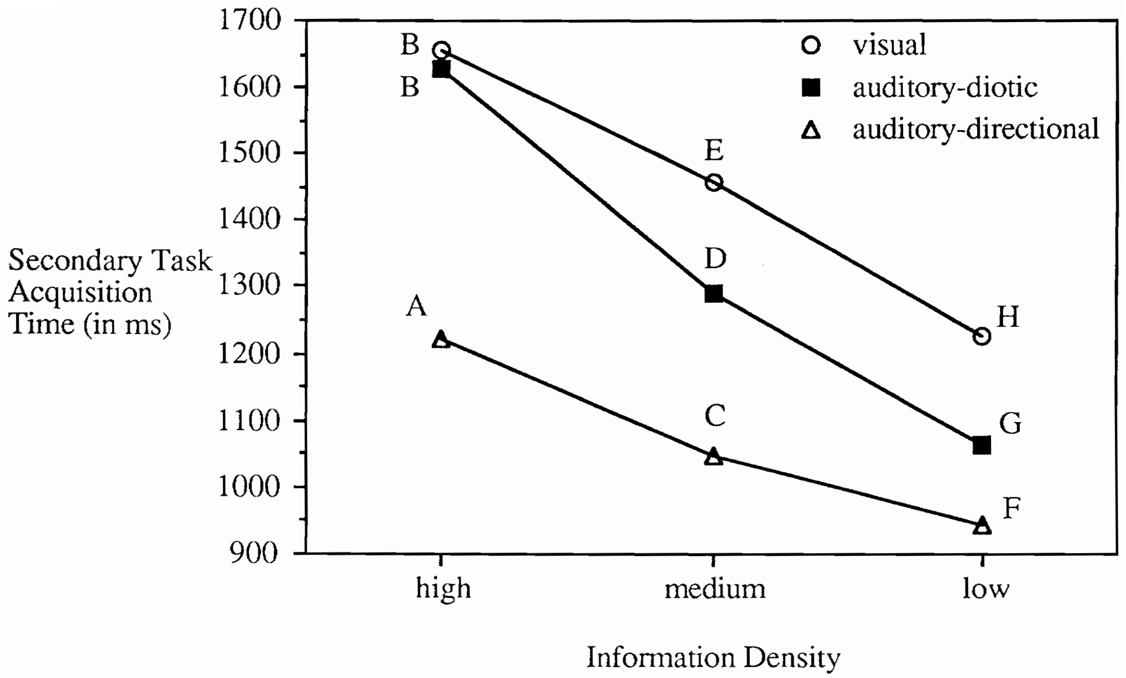

Figure 15. *Prompt Type-by-Information Density Interaction for Secondary Task Acquisition Time Dependent Measure (Means with different letters at each level of Information Density are significantly different at* $p < 0.05$*).*

TABLE 16

ANOVA Summary Table for Dual-Task Acquisition Time Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	72967085.4	7296708.54				
Within-Subjects							
Prompt Type (P)	2	10739155.7	5369577.84	10.918	0.0006	0.8311	0.0015*
P x S	20	9836434.98	491821.749				
Information Density (D)	2	23028656	11514328	50.226	0.0001	0.7852	0.0001*
D x S	20	4585025.95	229251.298				
Noise Type (N)	2	156956.451	78478.226	0.244	0.7856	0.7644	0.7275
N x S	20	6425137.55	321256.877				
P x D	4	1417442.07	354360.519	1.501	0.2201	0.6569	0.2394
P x D x S	40	9441205.7	236030.143				
P x N	4	2439266.4	609816.599	3.213	0.0223	0.7649	0.0358*
P x N x S	40	7592564.05	189814.101				
D x N	4	1570998.03	392749.508	1.442	0.238	0.6374	0.2551
D x N x S	40	10894193.7	272354.844				
P x D x N	8	1297729.79	162216.223	0.633	0.7481	0.4986	0.6417
P x D x N x S	80	20513218.7	256415.233				
Total	296						

*Statistically-significant effect at *G-G p* $p < 0.05$.

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 17

Mean Values (Standard Deviation) of Main Effects for the Dual-Task Acquisition Time Dependent Measure (Mean values are in ms.)

		Dual	
	Visual	Auditory-diotic	Auditory-directional
Truck			
High	2260 (739)	2633 (1082)	1996 (661)
Medium	1900 (478)	2013 (500)	1854 (752)
Low	1704 (698)	1894 (932)	1515 (591)
Truck+Speech			
High	1986 (506)	2800 (654)	2101 (634)
Medium	1810 (470)	2372 (931)	1897 (943)
Low	1424 (341)	1762 (712)	1230 (382)
Truck+Speech+Music			
High	2437 (901)	2632 (985)	1983 (651)
Medium	1965 (622)	2136 (935)	1539 (429)
Low	1857 (785)	1668 (778)	1644 (782)

levels of noise type. Since the effect of the noise type variable was present only in this interaction, and nowhere else in the ANOVA, it was decided to examine the interaction according to each noise type. Statistically-significant main effects for prompt type occurred for all levels of noise type: truck noise $\{F(2,40) = 20.01, p < 0.0001\}$, truck noise with background speech $\{F(2,40) = 7.68, p = 0.0015\}$, and truck noise with background speech and music $\{F(2,40) = 4.33, p = 0.0198\}$; however, only the visual prompt type was found to be statistically-significant for the noise type variable: visual $\{F(2,40) = 5.31, p = 0.0090\}$. These analyses were conducted by using the error term from the two-way interaction in the overall ANOVA (PxDxS). Newman-Keuls tests were then conducted to examine the differences in prompt type at each level of noise type. Table 18 provides the results of the Newman-Keuls tests. Figure 16 depicts the PxN interaction for dual-task acquisition time.

Although not statistically-significant, a depiction of the Prompt Type-by-Information Density (PxD) interaction $\{F(4,40) = 1.50, p = 0.2394\}$ appears in Figure 17. The trends of the data are similar to the statistically-significant PxD interaction for the secondary task conditions. It is likely that additional manipulation of the levels of the variables examined in this study would result in significant findings for the dual-task scenarios. The statistically-significant main effect of information density was subjected to a Newman-Keuls test, shown in Table 19 and depicted in Figure 18. This result serves to validate the levels of information density adapted from Noy (1990).

Crashes and tickets. No statistically-significant ($p < 0.05$) main effects or interactions were observed for the crash/ticket dependent measure. The complete ANOVA summary table for crashes and tickets is provided in Table 20, and a complete means table can be found in Table 21.

TABLE 18

Newman-Keuls Test Results for the Prompt Type-by-Noise Type Interaction for Dual-Task Acquisition Time Dependent Measure (Mean values are in ms.)

Truck	Means	1788	1954	2180	C.D.**
auditory directional	1788		166*	392*	133
visual	1954			226*	111
auditory binaural	2180				

Truck+Speech	Means	1740	1743	2312	C.D.**
visual	1740		3	572*	133
auditory directional	1743			569*	111
auditory binaural	2312				

Truck+Speech+Music	Means	1722	2086	2146	C.D.**
auditory directional	1722		364*	424*	133
visual	2086			60	111
auditory binaural	2146				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

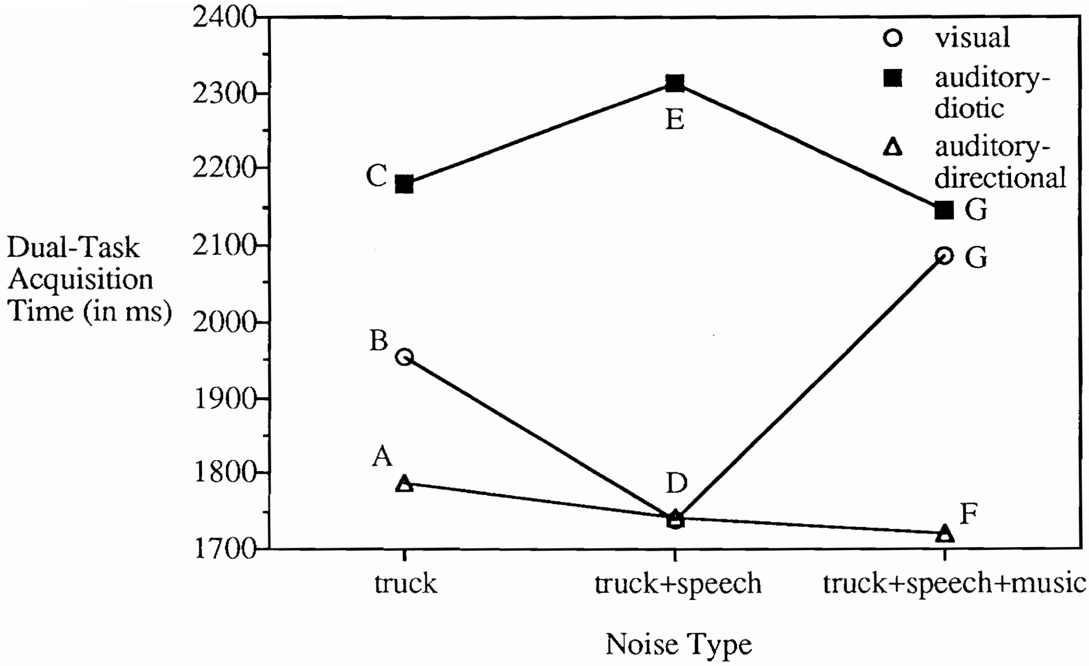

Figure 16. *Prompt Type-by-Noise Type Interaction for Dual-Task Acquisition Time Dependent Measure (Means with different letters within each Noise Type are significantly different at* $p < 0.05$*).*

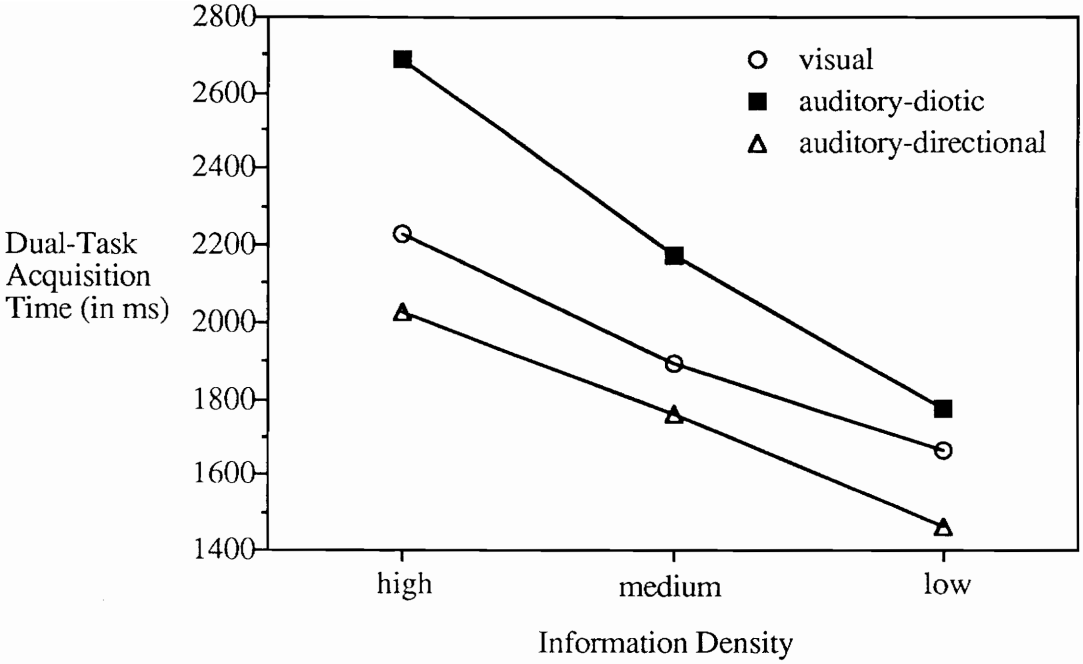

Figure 17. *Prompt Type-by-Information Density Interaction for Dual-Task Acquisition Time Dependent Measure (Means are* *<u>not</u>* *significantly different at* $p < 0.05$*).*

TABLE 19

Newman-Keuls Test Results for the Information Density Main Effect for Dual-Task Acquisition Time Dependent Measure (Mean values are in ms.)

Information Density	Means	1633	1943	2314	C.D.**
low	1633		310*	681*	172
medium	1943			371*	142
high	2314				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

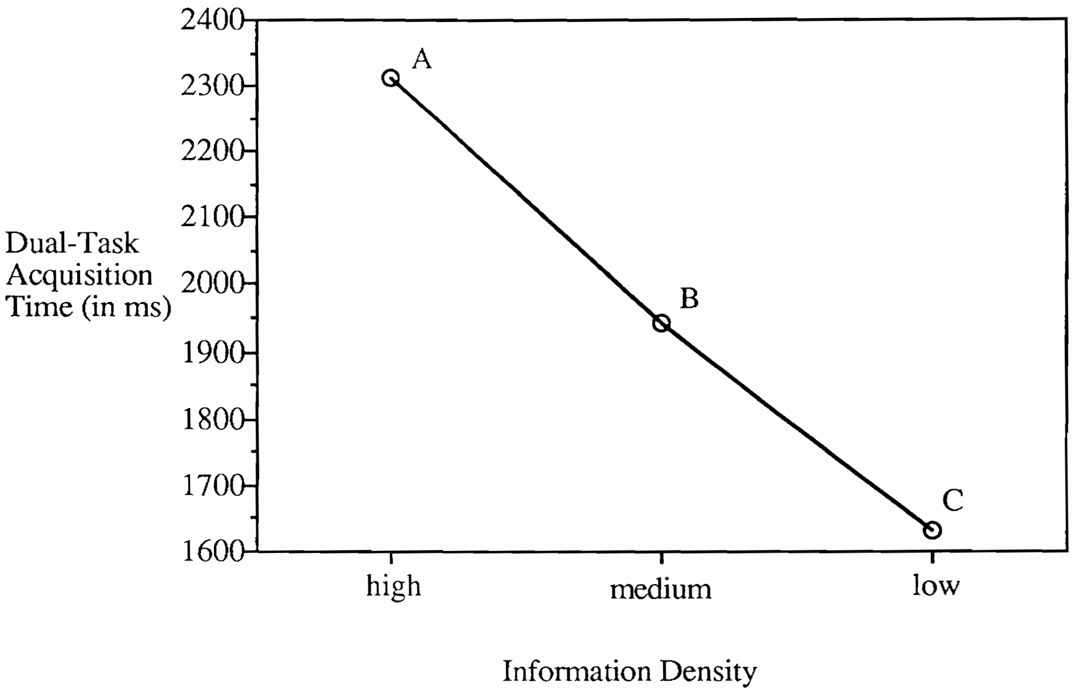

Figure 18. *Information Density Main Effect for Dual-Task Acquisition Time Dependent Measure (Means with different letters are significantly different at $p < 0.05$).*

TABLE 20

ANOVA Summary Table for Crashes/Tickets Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	1.921	0.192				
Within-Subjects							
Prompt Type (P)	2	0.109	0.055	0.766	0.4781	0.8105	0.4552
P x S	20	1.423	0.071				
Information Density (D)	2	0.177	0.089	2.072	0.1521	0.7237	0.1686
D x S	20	0.855	0.043				
Noise Type (N)	2	0.028	0.014	0.404	0.6732	0.9879	0.6709
N x S	20	0.699	0.035				
P x D	4	0.017	0.004	0.141	0.9661	0.7388	0.9330
P x D x S	40	1.228	0.031				
P x N	4	0.113	0.028	0.625	0.6477	0.7588	0.6064
P x N x S	40	1.813	0.045				
D x N	4	0.125	0.031	0.620	0.6509	0.7823	0.6139
D x N x S	40	2.010	0.050				
P x D x N	8	0.503	0.063	1.774	0.0945	0.4236	0.1652
P x D x N x S	80	2.835	0.035				
Total	296						

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 21

Mean Proportional Values (Standard Deviation) of Main Effects for the Crashes/Tickets Dependent Measure (Proportions are dimensionless and range from 0 to 1.)

	Dual		
	Visual	Auditory-diotic	Auditory-directional
Truck			
High	0.1818 (0.2523)	0.2045 (0.2185)	0.1136 (0.1719)
Medium	0.1136 (0.2589)	0.2045 (0.2919)	0.1136 (0.2335)
Low	0.1136 (0.1719)	0.0909 (0.1685)	0.1136 (0.2050)
Truck+Speech			
High	0.0909 (0.1685)	0.2955 (0.3503)	0.2273 (0.2078)
Medium	0.1818 (0.2261)	0.1591 (0.2311)	0.1818 (0.2261)
Low	0.0909 (0.1261)	0.0909 (0.2311)	0.1364 (0.2335)
Truck+Speech+Music			
High	0.1136 (0.1306)	0.0227 (0.0754)	0.2273 (0.2611)
Medium	0.1364 (0.2335)	0.2045 (0.2454)	0.2045 (0.1877)
Low	0.0682 (0.1168)	0.2045 (0.2697)	0.1136 (0.1719)

Subjective workload rating. Statistically-significant ($p < 0.05$) main effects for Prompt Type (P) {$F(2,20) = 8.03$, $p = 0.0050$} and Information Density (D) {$F(2,20) = 21.46$, $p < 0.0001$} were observed. The complete ANOVA summary table for subjective workload rating is provided in Table 22, and a means table in Table 23. A Newman-Keuls analysis was used to determine the nature of the prompt type main effect, which is provided in Table 24. Figure 19 illustrates the rating at each level of prompt type. Table 25 and Figure 20 depict the results of the Newman-Keuls test for the information density main effect for dual-task acquisition time.

Data from the Crashes/Tickets and Subjective Workload Rating dependent measures were only taken during the dual-task scenario. Since the secondary task conditions did not involve driving, Crashes/Tickets data were unobtainable. Due to the aforementioned time constraints of the study and an anticipated floor effect with regard to workload, Subjective Workload Rating data were viewed as unnecessary, and therefore, not obtained during the secondary task conditions.

TABLE 22

ANOVA Summary Table for Subjective Workload Rating Dependent Measure

Source	df	SS	MS	*F***	*p*	*G-G ε*	*G-G p*
Between-Subjects							
Subjects (S)	10	222.822	22.28				
Within-Subjects							
Prompt Type (P)	2	26.687	13.34	8.028	0.0028	0.8383	0.0050*
P x S	20	33.239	1.66				
Information Density (D)	2	22.081	11.04	21.459	<0.0001	0.7289	<0.0001*
D x S	20	10.290	0.51				
Noise Type (N)	2	0.384	0.19	0.216	0.8075	0.7281	0.7386
N x S	20	17.764	0.89				
P x D	4	6.323	1.58	1.573	0.2002	0.7524	0.2163
P x D x S	40	40.195	1.00				
P x N	4	4.505	1.13	1.427	0.2427	0.6020	0.2603
P x N x S	40	31.569	0.79				
D x N	4	0.929	0.23	0.225	0.9230	0.6579	0.8550
D x N x S	40	41.367	1.03				
P x D x N	8	5.152	0.64	0.647	0.7362	0.5273	0.6402
P x D x N x S	80	79.663	1.00				
Total	296						

*Statistically-significant effect at *G-G p* $p < 0.05$.

** For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

TABLE 23

Mean Values (Standard Deviation) of Main Effects for the Subjective Workload Rating Dependent Measure (Mean values are in Likert interval scale units, with a rating range from one to seven.)

		Dual		
		Visual	Auditory-diotic	Auditory-directional
Truck				
	High	4.9091 (1.1362)	4.6364 (1.2060)	4.7273 (1.5551)
	Medium	5.0000 (1.2649)	4.6364 (1.2863)	3.9091 (1.2210)
	Low	4.4545 (1.3685)	4.2727 (1.5551)	3.8182 (1.5374)
Truck+Speech				
	High	4.7273 (1.1037)	5.1818 (0.7508)	4.0909 (1.3003)
	Medium	4.7273 (1.7373)	5.0000 (0.6325)	4.0000 (1.0000)
	Low	4.4545 (1.4397)	4.0000 (1.4142)	3.4545 (1.2933)
Truck+Speech+Music				
	High	5.0000 (1.4142)	4.5455 (1.4397)	4.7273 (1.2721)
	Medium	4.6364 (1.2863)	4.7273 (1.3484)	3.9091 (1.4460)
	Low	4.8182 (1.5374)	3.7273 (1.5551)	3.6364 (1.2060)

TABLE 24

Newman-Keuls Test Results for the Prompt Type Main Effect for Subjective Workload Rating Dependent Measure (Mean values are in Likert interval scale units, with a rating range from one to seven.)

Prompt Type	Means	4.03	4.53	4.75	C.D.**
auditory-directional	4.03		0.50*	0.72*	0.46
auditory-diotic	4.53			0.22	0.38
visual	4.75				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

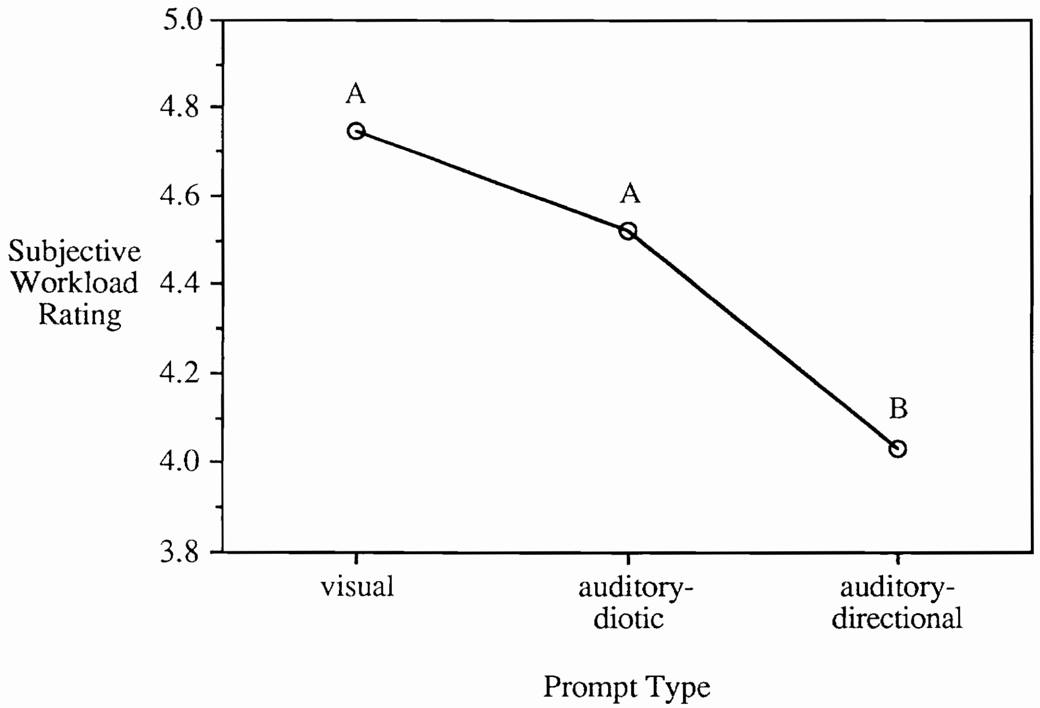

Figure 19. *Prompt Type Main Effect for Subjective Workload Rating Dependent Measure (Means with different letters are significantly different at p < 0.05).*

TABLE 25

Newman-Keuls Test Results for the Information Density Main Effect for Subjective Workload Rating Dependent Measure (Mean values are in Likert interval scale units, with a rating range from one to seven.)

Information Density	Mean	4.07	4.51	4.73	C.D.**
auditory-directional	4.07		0.44*	0.66*	0.26
auditory-diotic	4.51			0.22*	0.21
visual	4.73				

*Statistically-significant at $p < 0.05$.

**C.D. is the critical difference which must be exceeded by any two compared means, for the difference to be considered statistically-significant.

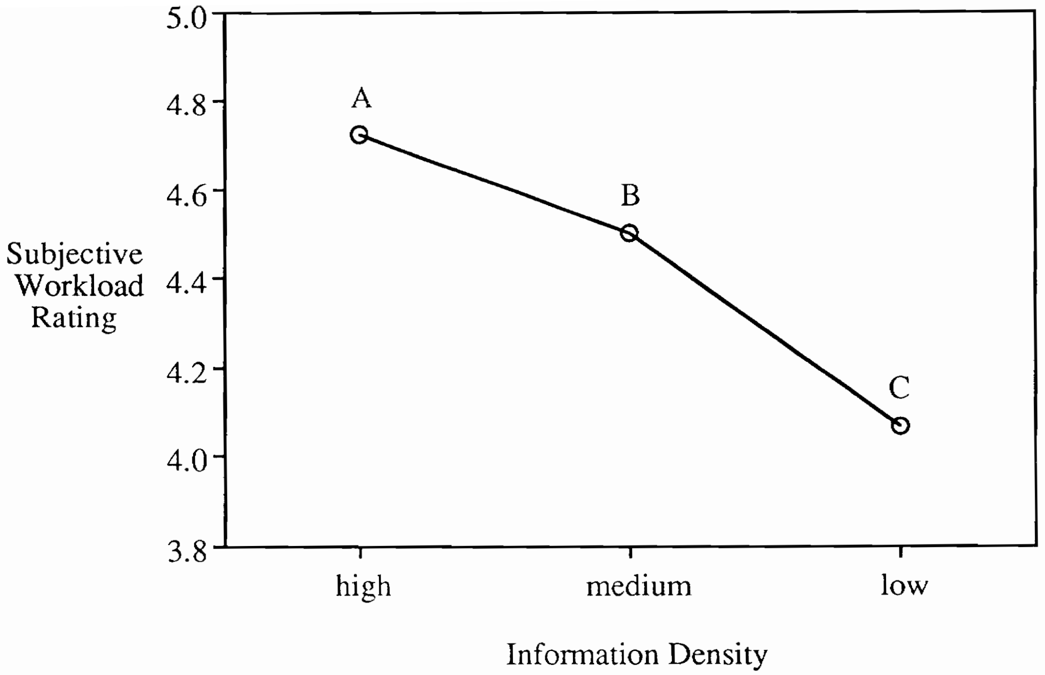

Figure 20. *Main effect of Information Density for Subjective Workload Rating (Means with different letters are significantly different at p < 0.05).*

DISCUSSION

Accuracy

Secondary task . No main effects or interactions were found statistically-significant for secondary task accuracy. As expected, a ceiling effect was noted for accuracy performance at 98%. Moreover, participants performed nearly equally with all prompt types under the secondary task scenario. Since no manual control involvement or high degree of visual attention was required during the secondary task experimental sessions, it was anticipated that participants would perform with high accuracy.

Dual-task . Participants performed more accurately than expected during the dual-task configuration (93%), suggesting that further loading in the form of a more demanding primary task may be desirable in future studies to more effectively measure the effectiveness of the auditory prompts. The significance of the prompt type main effect for information density (Figure 14) revealed that participants could more accurately respond to the auditory prompts than with the visual prompts under conditions of higher visual workload.

During the dual-task conditions it was observed that participants performed better during trials in which auditory instead of visual prompts were presented, with no statistically-significant degradation in accuracy compared to the secondary task conditions. The mean values for the visual prompt type taken from Tables 9 and 11 indicate a reduction in accuracy of as much as 18% from secondary to dual-task performance (difference value calculated for the low information density, and truck with background speech and music noise type conditions for secondary and dual-task scenarios). In the case of the auditory-diotic and auditory-directional prompts, the accuracy was reduced by 2% and 1% respectively when comparing performance under the two task types; as expected, in most cases the dual-task scenario resulted in lower accuracy. Moreover, participants' accuracy during the secondary task as well as dual-task configurations was statistically equivalent for both auditory prompts. It was observed that only with additional visual workload (the primary driving task) was a performance decrement experienced for the visual prompt. This suggests that as the visual task demands became greater, information was more effectively presented to the auditory domain. Implications for in-vehicle display devices include the advantage of being able to respond with greater accuracy to an auditory rather than visual prompt under driving conditions similar to that present in this study.

Acquisition Time

Secondary task . Significance was observed for prompt type, information density, and the PxD interaction. As shown in Figure 15, participants appear to have selected items on the touchscreen more quickly using the auditory-directional prompt type as compared to the other prompt types. There also appears to be a trend involving an increased benefit under increasing visual load, i.e., at low information densities the differences in performance between the auditory-directional versus the other prompt types was smaller than at higher information densities. Participant performance during auditory-diotic presentations was unexpectedly less than the high information density condition. Specifically, the auditory-diotic and visual prompt types resulted in statistically-equivalent data at the high information density level. Although the workload was minimal during the secondary task sessions, the data suggest that the auditory-directional prompt shows potential for further study.

Dual-task . Under the dual-task conditions, statistically-significant results were observed for the prompt type, information density, and the PxN interaction. Since the truck with speech noise type was approximately equal in terms of sound pressure level to each of the other two noise types, the reason for its unique demonstration of significance, i.e., resulting in faster acquisition times, is not clear (Figure 16). Initially, it was hypothesized that with the additional noise types, i.e., the addition of speech and music to the truck noise-only configuration, the performance during the auditory conditions would degrade somewhat, even considering that each of the noise types were presented at approximately the same sound pressure levels. One reason for including this variable was to add a certain degree of face validity to the experiment because the sound pressure levels approached those found in actual commercial truck cabs. Prior to the experimental sessions, it was decided to perform the study with the intention of testing the possible benefits of using the auditory prompts under conditions during which they could be understood, i.e., auditory prompts were sufficiently intelligible in the presence of all noise types. Therefore, there is no obvious explanation regarding the presence of the unexpectedly significant PxN interaction.

Acquisition time was significantly faster during trials in which the auditory-directional prompt was used as compared to the auditory-diotic prompt, suggesting that the aural lateralization procedure presented to participants may have been of benefit in acquiring information more quickly over traditional diotic auditory displays. From Table 18 and Figure 16 it can be stated that the auditory-directional benefit in terms of the actual time over the auditory-diotic prompt type was approximately 0.392 s under the truck noise type, 0.569 s under the truck noise with background speech noise type, and 0.424 s under the truck noise with background speech and music noise type. In addition, a statistically-significant advantage over the visual prompt was noted at the truck and truck with background speech and music level of noise type, 0.226 s and 0.364 s, respectively.

As in the secondary task conditions, slower acquisition times were associated with using the auditory-diotic prompts compared to the visual prompts under all noise type conditions (Figure 16). This is an important finding with implications for previous studies which have compared the benefits of using auditory versus visual presentation of information (e.g., Kishi and Sugiura, 1993; Labiale, 1989; Verwey, 1993; Verwey, 1991; Walker, Alicandri, Sedney, and Roberts, 1991). It is possible that such studies have not examined the full potential of the auditory domain.

As depicted in Figure 18, a near linear effect of acquisition time was observed for information density, suggesting that the levels of information density were sufficiently different from each other and, consequently, resulted in a measurable amount of additional workload during the dual-task conditions. The difference in acquisition time for the dual-task conditions between the high and medium levels of information density was 0.371 s and the difference between medium and low levels was 0.310 s. Because the levels of information density were adapted from a previous simulation study (Noy, 1990), this was an expected result. Moreover, the data from this study also serve to validate these levels. This information will also be important in establishing information density thresholds in future studies. That is, it would be beneficial to determine, to the extent possible, the maximum amount of information which can be presented to the driver before inducing an overload situation. These data could then provide system designers with the human-information processing requirements necessary for safe operation of an in-vehicle display; however, this study was not specifically designed to address these issues.

If these results can be generalized, the directional method of presentation would appear to be of some benefit in the development of collision-avoidance and navigational display systems employing the auditory domain to reduce driver workload.

Crashes/Tickets

As stated earlier, errors on the primary task driving game were classified as either a crash or ticket received due to inadequate attention or difficulty experienced in the dual-task scenario. These data were recorded by the experimenter. All conditions had crash/ticket totals which were statistically-insignificant from each other (Table 17), suggesting that the predetermined route the participants were instructed to follow provided a relatively constant level of workload throughout the dual-task scenario. This was an especially important finding because of an inability to record driving performance measures from the primary task to ensure equal workload across all treatment conditions. In addition, there were no conditions during which participants received significantly more tickets than in other conditions. This was an indication that participants generally adhered to the speed limit, again suggesting that all participants experienced approximately the same level of workload. The disadvantage of not recording more salient driving performance measures is that the *degree* of workload experienced by the participants could not be specifically determined.

Subjective Workload Rating

As shown in Figure 19, participants rated the level of workload experienced during trials in which an auditory-directional prompt was used as least difficult (4.03 rating out of 7.00), and the visual prompt as most difficult (4.75 rating out of 7.00).

These differences, though smaller than one scale unit on the seven-point scale, were statistically-significant. As expected, trials during which the participant had the least information from which to choose were also rated as least difficult (4.05 rating out of 7.00). Conversely, the trials during which the participant had the most information from which to choose were rated as most difficult (4.75 rating out of 7.00). Thus, Figure 20 would appear to confirm that the levels of information density were sufficiently different in terms of perceived difficulty, as the other performance measures had also indicated. Although the range of differences is small, the lack of a higher rating may reflect a tendency of participants not to assign extreme rating values, but to gravitate toward a central tendency.

Experimental Limitations

Although the results of the study seem to support the use of the auditory-directional prompt, the overall experiment was limited in a number of ways. Because there was no method by which to link the primary task driving game to the secondary task, which served as the data presentation and collection device, the exact amount of workload as experienced by the participants in the study cannot be fully estimated. Initially, off-road excursions were to have been included as a primary task dependent measure in addition to crashes and tickets, but data capture was not possible due to the other duties for which the experimenter was responsible during the experimental sessions.

Concerns stated by pilot as well as experimental participants involved the sturdiness of the steering wheel apparatus. One of the major problems relating to the feeling of instability was the small diameter of the steering wheel (20 cm). Although nothing could be done to correct this problem (other than developing a new steering wheel apparatus), attempts were made to correct other steering-related problems. After some pilot participants expressed difficulty in operating the "hypersensitive" steering wheel, efforts were made to enhance the rigidity and resistance of the steering wheel.

Participants also expressed the opinion that if an information-delivery device such as the one simulated in the study were available in a heavy commercial truck, they would have experienced no difficulty in performing the tasks adequately. This seems to indicate that the participants who maintained this view felt that driving the truck would be an easier task than driving the low-fidelity simulator used in this study.

CONCLUSIONS

IVHS Implications

The overall time-savings effect of the auditory-directional prompt at all information density levels under secondary task conditions (Figure 15) and the accuracy benefit during dual-task conditions (Figure 14) were perhaps the most salient results from this study. Despite the lower level of involvement during the secondary task conditions, this display technique has proven to be viable in terms of increasing accuracy in the dual-task conditions, where the manual control involvement approximated actual driving. Initially, it was not known how well participants would be able to utilize this added auditory display feature. Because the uncertainty associated with the selection of a letter button had been reduced by 50% through the use of the auditory-directional prompt type, i.e., by one bit of information, the results are supported by research conducted in areas of human information-processing (Wickens, 1992).

In the discussion of choice reaction time in a previous section (*Human Information-Processing*), it was mentioned that the instructions given to participants can be a factor in determining the speed-accuracy trade-off relationship. That is, performance can be different for the same set of experimental variables. Consequently, the importance of specifying instruction sets for participants may affect the way in which they perceive the particular tasks. The greatest performance efficiency can be attained when the instructions target a particular response at intermediate levels of the speed-accuracy trade-off curve (Figure 4). A set of instructions read to participants (Appendix F) clearly indicates that the primary focus of the dual-task conditions was to maintain control of the simulated vehicle. In addition, it was emphasized to participants to respond to the secondary stimuli as quickly as possible. According to Wickens (1992), too much emphasis on accuracy in instructions is associated with longer reaction times, and with emphasis placed on responding quicker, reduced accuracy will be the result; however, the results from this study clearly indicate the existence of an amicable speed-accuracy trade-off relationship, suggesting that the instructions read to participants unambiguously defined their duties.

From the results of this study, it appears that the auditory-directional method of information presentation may be beneficial not only in reducing the driver's perceived workload, but also reducing acquisition time and increasing accuracy during information acquisition. With a fully-developed, integrated display system and driver training, the technology may eventually prove to be an effective method by which to reallocate some of the inherent visual workload of driving to the auditory domain. Additionally, presenting the auditory messages through the headrest loudspeakers is a viable delivery apparatus to overcome the relatively high ambient noise levels in commercial truck cabs. Although further investigation in higher fidelity simulators and/or on-the-road vehicles which more closely resemble the heavy commercial truck driving environment is recommended in order to validate these advanced auditory display concepts, the potential implications for commercial truck cabs involve presenting additional information to the driver in a manner which may ultimately result in fewer vehicular accidents due to informational overload. It appears that a reduction in time demands associated with searching an in-vehicle visual display may be possible using a display apparatus similar to that used in this study.

Eventually, in the commercial truck cab of the future, the driver will undoubtedly have many sources of information from which to choose which will require additional attention. Among other areas of research, consideration must be given to the prioritization of information displayed. Given the limited amount of unoccupied panel display space in the cab, the information allocated to the auditory domain will most likely increase as in-vehicle information display devices become more prevalent. An attempt to increase the utility and salience of visual displays may lead to standardization of display location, e.g., the most critical information will always be in the same place on any given in-vehicle display. If results prove useful to system designers, consideration must also be given to driver usability and operating costs to commercial fleet and individual owners. Allocation of in-vehicle information to either the visual or auditory modality is the first crucial step toward the development of these safe, efficient, and usable IVHS systems.

SUGGESTIONS FOR FUTURE RESEARCH

The efforts of this study were to determine the benefit of presenting auditory prompts consisting of digitized human speech versus visual prompts in a simulated driving environment. Another method of presenting the auditory prompts involves rule-generated synthesized speech. Some advantages of using synthesized speech as characterized by Merva (1987) include increased system flexibility, i.e., all possible messages could be presented with minimal storage capacity problems, and reduced maintenance requirements.

An examination of the quality and intelligibility of synthesized speech in an environment similar to that used in the present study can be found in Morrison (1993). Results indicated that the low level of intelligibility experienced by participants limited the usefulness of this presentation technology and could not be used reliably in its current state, i.e., contemporary synthetic speech is not reliably intelligible in the noise environment of heavy commercial truck cab. Therefore, it was decided to perform the experiment in a favorable noise environment which approximated the actual sound levels in a commercial truck cab, i.e., one in which the auditory prompt could always be heard.

Since no hypothesis was made regarding the signal-to-noise ratio of the auditory prompts, future studies should investigate this issue further with data obtained from on-the-road truck noise measurement studies. Similarly, in order to specify the temporal and spectral content of the auditory signal, a more accurate in-cab sound profile could be constructed based reverberation time (T_{60}), acceleration, and constant-speed measurements within the truck cab. This accumulation of data will make possible masked threshold evaluations of potential auditory stimuli as well as calculations of the

Articulation Index (AI), which may be used to inform or alert the driver through the use of voiced messages and/or warning signals.

Also, due to an inability in this research to objectively obtain driving performance measures from the primary task, future research should investigate the salient concepts within a higher-fidelity simulation environment or a full-scale test vehicle, specifically, one which offers a greater sense of presence or immersion and allows driving measures to be linked to the secondary task performance. Because of limitations in the display size of the game window (approximately 480 x 240 pixels), participants may have experienced a minimum amount of immersion with the available display apparatus.

Development will continue on improving the auditory display concepts in this study. Improvements will also be made in the secondary task which will involve adding more realistic navigational operations. Ideally, a validated, higher fidelity simulation apparatus could be used as the primary task which will allow collection of objective driving performance measures. An apparatus such as the Systems Technology Incorporated (STI) Driving Simulator would be a particularly amenable choice. This simulator has been validated in a number of environments, including The University of Iowa, and Battelle Human Factors Transportation Center (Allen, Rosenthal, and Parseghian, 1995).

This type of simulation would allow programmable vehicle dynamics, measurement of various driving performance measures, e.g., lane deviations, steering reversals, presentation of various auditory and visual stimuli, and different driving scenarios, all of which may be linked via digital input/output cards to a secondary task-dedicated microprocessor (Allen, Rosenthal, and Parseghian, 1995).

With this type of simulation environment, the aforementioned data in addition to measures such as the location of the information to be acquired, could be compared to acquisition time and accuracy to determine if there are differences in performance. If significant differences exist, evidence may be offered in support of the concepts represented in thesis study.

In conjunction with auditory prompts, the simulator would also enable the exploration of techniques for improving the visual display as well, such as highlighting, marking, and sizing of information. Eventually, further efforts also may be undertaken to examine the prioritization of auditory messages from different sources, e.g., collision versus navigational information, in order to develop the concepts on a systems rather than a component level (Verwey, W. B., Alm, H., Groeger, J. A., Janssen, W. H., Kuiken, M. J., Schraagen, J. M., Schumann, J., van Winsum, W., and Wontorra, H., 1993; Verwey, 1991).

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APPENDIX A

TELEPHONE SCREENING QUESTIONNAIRE

TELEPHONE SCREENING QUESTIONNAIRE

Licensed male commercial truck driver? Y N

General

Name: Age: Phone:

Approximate height and weight:

Native English speaker? Y N

Tinnitus or head noises? Y N

Ear wax history? Y N

Hearing or vision problems? Y N

Noisy hobbies? Y N

Employment History

Years of experience?

Accident frequency?

Day or night accidents?

Percent of night-time driving?

Miles driven (on-the-job) per week?

Type of company, e.g., private carrier, owner/operator?

Type of truck driven?

APPENDIX B

EXPERIMENTAL PROCEDURES

Auditory Prompt Experiment, Room 513: Procedures

1. Enter room, turn on lights
2. A/C on low
3. Turn on all equipment
4. Block off IIci keyboard
5. Set Powerbook sound control panel to "system beep"
6. Set tape players to play (ensure that the two tapes in the Sony deck are properly synchronized)
7. Open sidetask, set screenrect, backup data from previous participant, set task interval to "0"
8. Calibrate touchscreen and adjust cursor off-set, fast speed, small area
9. Open VETTE!®, set up conditions: stock, rookie, course 4, set mouse to steer, drive car around corner, pause game
10. Move microphone stand to head center and acoustically calibrate RION (94.0)
11. Record calibration on form (Daily Calibration Form: perform one hour before); move microphone stand to location where monitoring of sound levels can occur throughout the experiment
12. Welcome participant to room 538
13. Present participant with experiment description, informed consent, ask for signature
14. Perform otoscopic exam and audiogram
15. If accepted escort participant to room 513
16. Ask participant about music selection and program CD player to play prescreened songs from chosen CD
17. Tell participant to sit in drivers seat as would be comfortable for about 2.5 hours (mark with tape), adjust prompt speaker height and distance from head such that the participant's ear canal is approximately at the midpoint of the speaker height and the participant's head is approximately one inch from the foam headrest, then introduce different noise types
18. Explain secondary task, visual reference (primary display), hand reference according to script (return to 10 and 2); emphasize to participant to take advantage of the directional prompt (message)
19. Allow participant to perform secondary task as instructed (10 practice trials)

20. Clear data field
21. Begin data collection on secondary task control condition (participant number: 1= 1st participant, secondary task only), record PDN on data sheet
22. After completion of control condition, explain primary task according to script
23. Allow participant to practice primary task, give directions of course to be taken, and change task interval on sidetask to 8
24. If participant feels comfortable with primary task, restart game, set participant number to (2), and continue to dual-task data collection
25. After 10 trials, pause primary and secondary task and ask participant to rate configuration: "OK, on a scale of 1 to 7 (7 being the most difficult), how would you rate the last series of trials?"
26. When finished with each condition, ask participant whether he needs a break
27. If the participant crashes (requires restart - pause secondary task, restart game and wait until car moves around first corner to begin secondary task again) or receives a ticket (pause secondary task, clear ticket screen quickly, press 1 to restart, and wait until car moves around first corner to begin secondary task again), record the incident on the data sheet
28. Monitor the data field to anticipate the end of a condition sequence (10, where another rating is required and adjustment of noise type may be required)
29. After a break period, readjust the chair to the taped marks on the floor and ensure that the participant's head is still about 1 inch away from headrest
30. Monitor sound levels throughout the experiment
31. At the end of the experimental session, thank and pay the participant
32. Backup data from field, export to Excel (command - B for background, click on field, then Command - A, Command - C, open Excel data file, Command - V)
33. Set microphone stand at head center, leave for next day
34. Record a calibration measurement from RION
33. Turn off equipment, lights, leave A/C on low

APPENDIX C

DESCRIPTION OF EXPERIMENT

Description of the Auditory Prompt Experiment
Written Instructions to the Participant

This experiment is intended to determine if auditory cues given to a driver will help the driver use an in-vehicle display used for navigation. If you become a participant in this experiment, you will be asked to take part in one screening session (30 minutes), one training session (30 minutes), and one experimental session (about 2- 1/2 hours).

In the screening session, you will be asked to read and sign an informed consent form, have your outer ears visually examined, and receive a hearing test. If you qualify as a participant, the experimenter will show you the equipment which will be used in the experiment, and give you instructions concerning how to operate it. If you have any questions, please ask the experimenter at any time. The experimenter will provide an answer to the best of his ability, but 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 portion of the training session, you will be asked to respond to an auditory or visual message instructing you to touch a particular letter on the side-task display screen. You will be asked to look at the screen in front of you and place your hands on the steering wheel. To respond to the messages, simply touch the screen with your right index finger where the letter appears. **Respond to the messages as quickly as possible.** During some trials you will *see* a one sentence message telling you to look for a particular letter on the side-task display screen. The visual messages will take the form: "Touch the letter X on the next screen". During other trials, you will *hear* a message telling you to look for a particular letter on the side-task display screen. The auditory messages will come from the two small loudspeakers, directly behind your head. Listen closely to the auditory messages; some of them will sound like they are coming from only one loudspeaker. **When this occurs, you will be asked to begin looking for the letter on the same side of the screen as the loudspeaker from which you heard the message. For instance, if the messages come from only the right loudspeaker, then you should look on the right side of the display screen for the letter.**

In the second portion of the training session, you will be asked to become familiar with controlling a driving simulation game. The experimenter will show you the apparatus, which includes a steering wheel, brake pedal, and an accelerator pedal. You will be practicing the game for about 10 to 15 minutes, following a route specified by the experimenter. Try to stay on this route. If you crash or receive a ticket while operating the game, the experimenter will reset the game for you. Please try to maintain control of the car (in the game) at all times.

In the experimental session, you will be asked to drive the driving game in addition to performing the side-task. **During this portion of the experiment, your primary job will be to drive the simulated car in the computer game. Always give the game the highest priority.** The side-task duties are secondary, and will involve choosing letters on the display screen, just as in the practice session. Remember, it is still necessary to respond to the instructions as quickly as possible, but control of the game is the most important job. After a certain number of messages, the experimenter will ask you to estimate how difficult the game was to operate with the configuration you just experienced. Follow the procedures outlined in the instructions EXACTLY. It is very important that you be as accurate as possible in your estimation.

You will be given a demonstration of these procedures, and an opportunity to try it yourself before the actual experiment begins. For all the instructional conditions, you will be asked to respond by pressing the appropriate letter on the side-task display. Again, you will have the opportunity to ask questions at any time before the experimental session begins. Also, if you have questions regarding the operation of the equipment during the experimental session, please feel free to ask them. The experimenter can pause the game and side-task at any time. IF POSSIBLE, please try to wait until a break period to ask other types of questions. You will have many such opportunities during the course of the experiment.

Please sign below to indicate that you have read and understood these instructions.

____________________________ ____________________________

Participant's Printed Name | Participant's Signature

APPENDIX D

PARTICIPANT INFORMED CONSENT

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

Title of Project: The Effect of Auditorially-Presented Prompts to Reduce Visual Search Time and Increase Accuracy of Target Acquisition of Simulated Navigational Information

Principal Investigator: S. Gregory Micheal

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a study which will investigate the use of auditory instructions for the purpose of helping a driver deal with navigational information which is presented in the visual domain more efficiently.

II. PROCEDURES

The procedures to be used in this research are as follows: 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 the screening is to determine whether your hearing and seeing ability today qualifies you to participate in the experimental session.

First, your right and left ear hearing will be tested with very quiet tones played through a set of headphones to ensure that you can hear the auditory messages which will be given during the experiment. You must be very attentive and listen carefully for these tones. **You will be asked to <u>depress</u> the button on the hand switch and <u>hold it down</u> whenever you can hear the tone and <u>release</u> 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. During the experimental session, you will be asked to listen to one-line instructions guiding your next course of action; however, at other times during the session, there will be only a written instruction which you must read on the sidetask display in order to proceed with the next action. Therefore, your vision will also be tested to ensure that you can read the instructions and the letters on the displays involved in the experiment. Then, if qualified, you may participate in a research experiment which will investigate the effect of using an auditorially-presented prompt to assist the operator in acquiring designated navigational information presented to the visual domain.

There is no known risk to your well-being posed by 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. BENEFITS OF THIS RESEARCH

Your participation in this project will provide the following information that may be helpful. First, data taken from the telephone screening questionnaire will establish certain characteristics of the sample of the population being studied (licensed, male commercial truck drivers). Second, it is the ultimate goal of this experiment to improve the safety and efficiency of commercial trucks. This experiment represents a small step in the pursuit of such a goal. It is expected that the results of this study will lead to further topics of 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 also receive a summary of the results of this research when completed. Please leave a self-addressed envelope. **To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.**

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than individuals working on the project without your written consent. 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.

The experiment will be monitored and taped by a video camera. The tapes will only be reviewed by the principal investigator, will be kept in a locked room, and will be erased after they are no longer needed.

V. COMPENSATION

For participation in this project you will receive _________ for each portion completed, for a total of _________.

VI. 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 of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or equipment.

VII. 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, by the Department of Industrial and Systems Engineering.

VIII. 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

IX. PARTICIPANT'S PERMISSION

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 acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I will contact:

<u>S. Gregory Micheal</u> Investigator	<u>231-9086</u> Phone
<u>Dr. John G. Casali</u> Faculty Advisor	<u>231-5073</u> Phone
<u>Ernest R. Stout</u> Chair, IRB Research Division	<u>231-9359</u> Phone

APPENDIX E

PARTICIPANT SCREENING FORM

APPENDIX F

SCRIPT TO BE READ TO PARTICIPANTS

Auditory Prompt Experiment, Room 513: Script

To be read verbatim to each participant

1. The secondary task has been designed to simulate the method by which information might be presented to a truck driver in the future. For the purposes of this experiment, we have made the information simple, in the form of letter buttons. You will first be asked to respond to an auditory or visual message instructing you to touch a particular letter on the side-task display. You will be asked to look at the screen in front of you and place your hands on the steering wheel at approximately the 10 o' clock and 2 o'clock position. To respond to the messages, simply touch the screen with your right index finger where the letter appears and return your hand back to the steering wheel at the 2 o'clock position. When you select the letter, depress the screen firmly and quickly. You will see the letter turn black and you will hear a beep. This is your confirmation that you selected a letter. **Some screens will have more letters than others. Try to respond to the messages as quickly as possible.**

During some trials you will *see* a one sentence message telling you to look for a particular letter on the side-task display. The visual messages will take the form : "Touch the letter X on the next screen". You don't need to press the letter on this screen, but on the screen following it. During other trials, you will *hear* a message telling you to look for a particular letter on the side-task display. The auditory messages will come from the two small loudspeakers, directly behind your head. Listen closely to the auditory messages; some of them will sound like they are coming from only one loudspeaker. **When this occurs, you will be asked to begin looking for the letter on the same side of the screen as the loudspeaker from which you heard the message. For instance, if the messages come from only the right loudspeaker, then you should look on the right side of the display screen for the letter. Take advantage of this directional cue, it eliminate half of the possible choices before you even begin looking for the letters. This will be the only condition out of the three which will help you in this way.**

Also, you should try to remain as quiet as possible throughout the experiment, and although you may enjoy listening to the music, we must ask that you not talk, hum, whistle, or sing, otherwise you may not hear the messages.

Do you have any questions?

Let's try a practice session (4 trials)

2. The primary task is the computer driving game which you have already seen. You will be asked to try to maintain control of the vehicle at all times. This is most important. It will be difficult at first, but you will be given time to practice. Don't get discouraged. The experimenter will help you through this portion of the experiment.

This is the steering wheel. Try to keep both hands on the steering wheel at all times. This will be important when we later combine the primary and secondary tasks (to be sure that all participants have an equal starting point when they choose the letters on the sidetask display). Again, try to keep your hands in the 10 o' clock and 2 o'clock position. Although you should keep both hands on the steering wheel, be careful not to apply too much pressure because it is somewhat fragile.

This is the pedal apparatus. The pedals are where you would normally expect them to be; the accelerator is on the right and the brake is on the left.

Try to maintain the speed limit at all times. The white number to the right of the tachometer indicates the speed limit on the particular portion of road on which you are driving. Look at the speed limit indicator frequently, because it will change from time to time (as you move onto different roads).

This is the speedometer, also monitor this closely, otherwise you will get a ticket. The other displays in the vehicle's interior are not important. You only need to worry about the speedometer and the speed limit. After you have practiced, you are to try your best to avoid crashing or receiving a ticket.

The experimenter will give you directions during the practice session, indicating where you should turn. This course has been selected so that you can follow it easily; it consists of 4 right-hand turns. Pay attention to where you should turn, because you will be following this route throughout the remainder of the experiment. If you should accidentally deviate from the specified route, or if you crash, the experimenter will reset the game for you.

Do you have any questions?

Let's try a practice session (approximately 15 minutes)

--Turn one--Make a right turn onto the interstate, you will see the road gradually turning to the right. Once you are on the interstate, note the yellow center line, and try to keep the car on the right side.

--Turn two--Up ahead you will see a sign for Sunset Blvd. Stay in the right lane and gradually turn right, continuing on the interstate.

--Turn three--Up ahead the road forks. Take the road which gradually goes off to the right.

--Turn four--Up ahead you will see the ocean (the blue area). As the ocean gets closer, monitor your speed and begin slowing down. At the end of the road turn right. Now you are headed in the direction of the first turn again. Continue on this course.

Do you feel comfortable driving the game?

OK, now we're going to try both at the same time...

3. In the experimental session, you will be asked to drive the driving game in addition to performing the side-task. **During this portion of the experiment, your primary job will be to drive the simulated car in the computer game. Always give the game the highest priority.** The side-task duties are secondary, and will involve choosing letters on the display screen, just as in the practice session. Remember, it is still necessary to respond to the instructions as quickly as possible, but control of the game (not receiving tickets or crashing) is the most important job. Remember to stay on the course that you learned in the practice session. After a certain number of messages, the experimenter will ask you to estimate how difficult the game was to operate with the configuration you just experienced. You will be asked to rate the difficulty on a scale of 1 to 7 (1 being the least difficult and 7 being the most difficult). It is very important that you be as accurate as possible in your estimation. Remember to choose only one number from 1 to 7, and also remember that this is not a test of your skill or ability. It is an indication to the experimenter of what aspects of the system may need to be improved.

APPENDIX G

SAMPLE DATA SHEET

SAMPLE DATA SHEET

Subject	P/D/N SEC'Y	P/D/N DUAL	% Acc.	Mean Rxn. Time	Crashes (C)/ Tickets (T)	Rating

APPENDIX H

DAILY CALIBRATION FORM

Auditory Prompt Experiment, Room 513: Daily Calibration Form

Conditions

- All noise measurements are A-weighted Leq (Fast) using RION octave band analyzer (30 s duration), prompt is Lp
- Prompt loudspeaker height 44", microphone at head center

Definitions

Ambient: A/C on low, all computers on, all audio equipment on (tape players running with all outputs set to zero), game running
Acceptable Range: 50 dB to 60 dB

Noise 1: Portion of recorded truck cab noise only on a three minute continuous tape (original recording made by Morrison (1993); same representative 30 second portion of tape used for calibration)
Acceptable Range: 72 dB to 76 dB

Noise 2: Portion of recorded truck cab noise and background speech on two 90 minute tapes (to avoid the five to seven second pause while the tape switches direction; same representative 30 second portion of tape used for calibration)
Acceptable Range: 72 dB to 76 dB

Noise 3: Noise 2 in addition to a compact disc of the participant's choosing (prescreened CDs based on relatively constant sound pressure levels; tracks on the CD which did not reach the criteria were programmed out; same representative 30 second portion of CD used for calibration)
Acceptable Range: 72 dB to 76 dB

Prompt: Diotic auditory prompts recorded in SoundEdit™ Pro at 22 KHz (the phrase "Touch the letter" used for calibration)
Acceptable Range: 76dB to 80dB

Day: ____________________
Time: ____________________
Participant Number: ____________________
RION: ____________________
Ambient: ____________________
Noise 1: ____________________
Noise 2: ____________________
Noise 3: ____________________
Prompt: ____________________

APPENDIX I

SUBJECTIVE WORKLOAD RATING SCALE

SUBJECTIVE WORKLOAD RATING SCALE

Extremely Difficult	Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy	Extremely Easy

VITA

Mr. S. Gregory Micheal, born September 16, 1968, received a B.A. in psychology in 1990 from Marshall University, in Huntington, WV. Upon completion of a M.S. in Industrial and Systems Engineering (specializing in Human Factors) at Virginia Polytechnic Institute and State University in 1995, he intends to pursue a Ph.D. in the same program.

Before entering the program at Virginia Tech in 1992, he learned the fine art of French and Continental cuisine under a Scottish executive chef in Charleston, WV. During his undergraduate career, he was employed as a general training manager in a restaurant, as well as a test-driver and courier at The Sports Car Clinic in Charleston, WV. As a graduate student, he has worked in the Displays and Controls, Vehicle Analysis and Simulation, and Auditory Systems Laboratories. He was also awarded a two-year research fellowship for Intelligent Vehicle-Highway Systems by General Motors in the Auditory Systems Laboratory. Other research interests include virtual reality, human-computer interface design, and architecture.

He is a member of the Human Factors and Ergonomics Society (HFES), American Society of Safety Engineers (ASSE), and the Intelligent Transportation Society of America (ITS). His outside interests include researching advanced technologies, "surfing" the Internet, automotive maintenance and racing, photography, cooking, and Star Trek.