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Does Workload Modulate The Effects of In-Vehicle Display Location on Concurrent Driving and Side Task Performance?

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ABSTRACT

The infusion of new in-vehicle technologies (IVTs) into automobiles may have important implications for driver safety, especially to the extent that these devices interfere with the primary driving task. One important issue is the placement or location of in-vehicle displays—specifically, whether the spatial separation between the IVT and the outside world is reduced (as in the case of head-up displays, HUDs) or whether the two are highly separated (as in the case of head-down, console displays). A previous study by Horrey and Wickens (2002) showed that driving performance (lane keeping, speed control) was equivalent when drivers used a HUD or a head-down display (HDD) to complete a secondary side task, suggesting drivers were able to protect the driving task even as the display separation increased. However, they further showed degraded response times to critical hazard events when drivers were using the HDD. The current study sought to extend these results to more challenging driving conditions. Twelve drivers in a fixed-base warp-around simulator drove highly curved rural roads in either high or log fog conditions while engaging in a secondary phone number read-back task presented on different in-vehicle displays. The ten-digit phone numbers were presented in either a head-up location (just above the hood of the vehicle) or on a head-down LCD panel, located near the mid-console. As with the previous study, there were no differences across display type, suggesting that drivers were able to protect the primary task of driving, even in highly demanding driving situations. This protection came however at the expense of side-task performance, with slower response times and longer response durations with the HDD compared to the HUD. Drivers also indicated higher subjective workload when interacting with the HDD compared to the HUD and baseline driving conditions. Response times to the critical hazard events were slower for the head-down display, although a subset of these events did suggest the presence of some adaptive strategy for interacting with the HDD to enhance safety. The findings are presented in terms of models of visual attention and multiple resources and then compared to the findings of Horrey and Wickens (2002).

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INTRODUCTION

New in-vehicle technologies (IVTs) and systems may provide drivers with detailed information regarding current routes and navigation, local traffic, road hazards and construction, as well as other wireless web and cellular applications. As more and more IVTs and telematics find their way into automobiles, drivers may be more likely to access these systems while driving. The obvious ramification of these systems occurs when they interfere with the maintenance of safe and proper vehicle control.

In many cases, IVTs deliver visual information, which must be accessed through eye scans in order for the driver to successfully interact with the system. However, because so much of the information required for driving is visual (e.g., Hills, 1980) the potential interference (noted above) may be expressed in terms of competition over limited visual resources (Wickens, 2002). In general, as drivers spend more time looking "inwards" towards in-vehicle displays they will, by default, spend less time scanning the outside world for driving-related information. This will increase the likelihood of missed traffic events and road information and, quite likely, increase the possibility of an accident or collision. As drivers adopt scan strategies to access both road information as well as display information, the separation of the two sources of information becomes an important consideration. Information access costs, as they relate to display separation, provide the foundations for the current study. Specifically, how different display separations may impact drivers' abilities to maintain proper vehicle control as well as their abilities to respond to critical, "emergency" traffic events.

A recent study by Horrey and Wickens (2002) investigated these issues in various simulated driving contexts. The current research seeks to expand and build on some of the findings from this study. Here we review some of the relevant theory and findings, provide a brief discussion of the precursor study, and follow with a description of the adjustments and design of the current study.

Driving and Visual Resource Competition

Driving is typically considered a combination of three subtasks: vehicle control, hazard awareness, and navigation (Dewar, Olson, & Alexander, 2002; Wickens, Gordon, & Liu, 1998). Lower level activities, such as the positioning of the vehicle in one's lane and control of vehicle speed account for a good deal of the vehicle control task. Hazard awareness involves the general understanding of the immediate environment, including the detection and identification of potential hazards and obstacles—many of these unexpected—as well as the selection and execution of an appropriate action in order to maintain a safe forward path. Navigation, a higher-order task, involves selecting, planning, and executing a particular route towards the preferred destination. While most of the information that supports these tasks is visual, there may be differences in the form of visual information across these tasks. For example, research by Summala and his colleagues suggests that vehicle control may be supported by peripheral vision

(Summala, Nieminen, & Punto, 1996), while hazard awareness may rely heavily (though not exclusively) on focused vision (foveal; Summala, Lamble, & Laakso, 1998; Lamble, Laakso, & Summala, 1999).

Summala et al. (1996; replicated by Summala, 1998) examined the impact of IVTs using a technique where drivers were forced to focus their visual attention on a location inside the vehicle (located at various eccentricities) and to rely on peripheral vision to maintain vehicle control (lane keeping). In general, lane keeping ability declined with increasing eccentricity, although experienced drivers showed impairments at only the greatest separations, suggesting that they were better able to make use of peripheral information for vehicle control than were their inexperienced (novice) counterparts. Using the same forced-peripheral technique, Summala et al. (1998) and Lamble et al. (1999) investigated how well drivers were able to detect and respond to critical hazards (i.e., a lead vehicle braking) while focusing visual attention away from the driving scene. In these studies, reaction times to the critical events increased markedly with display separation and did not improve with driver experience. Taken together, these studies suggest that although peripheral vision may be used to support vehicle control, it is not able to sufficiently support hazard awareness, which is better served by foveal vision.

The findings presented by Summala and colleagues offer some support for the notion of separate focal and ambient visual channels (Previc, 1998; 2000). This distinction comprises part of the resources within the visual modality of the multiple resource model of task performance (Wickens, 2002). In this model, focal visual channel relies heavily (though not exclusively) on foveal vision in order to complete tasks that require the discrimination of fine details (e.g., reading). In contrast, ambient vision utilizes peripheral vision to large degree for tasks involving perception of orientation and ego-motion. Multiple resources models posit that tasks which share common resources along a given dimension (e.g., processing stage, perceptual modality, visual channel, processing code) will be time-shared less effectively than tasks which utilize separate resources. For example, a driver may use focal vision to read information presented on a road sign while at the same time use ambient vision to keep the vehicle within their lane, however would be unable to read gauge information presented in the instrument panel, as this would require focal vision. As Summala et al. (1996) demonstrated, ambient vision does have its limitations, with performance becoming degraded at greater eccentricities. Therefore, the introduction of visual in-vehicle information creates a new source of competition for focal resources which will impact not only the availability of these resources for the detection and identification of road hazards but, depending on the location of the display, may also affect the ability to use ambient vision for vehicle control. As such, the information access costs associated with display separation become an important consideration for both focal and ambient driving tasks.

Visual Information Access Costs

Spatial separation is an important component of information access costs, which relate to the amount of cognitive or physical effort required to gather information from a given source. When displays are placed relatively close together, there are lower costs associated with accessing information because the information may be gathered in a single fixation. When eye movements are required (separation from 3 to 4°**,** up to 20 or 25°), there are added costs for the access of information (over and above those for the no-scan region). When displays are located even further apart and head movements are required, the costs are even more pronounced. Wickens (1992) outlines the non-linear function which characterizes the costs associated with the no-scan region, the eye-, and the head-field. A number of studies have shown support for this function (e.g., Sanders, 1970; Sanders & Houtmans, 1985; Schons & Wickens, 1992; Martin-Emerson & Wickens, 1993).

In terms of the focal and ambient visual channels, access costs may be expressed as increased scanning time between display locations. For tasks employing focal vision, this scanning cost is the primary source of degraded performance. For tracking tasks employing ambient vision, scanning too may sometimes be required, reflected as an information access cost in the delay in noticing a tracking error that needs to be corrected. However a cost to tracking may also result without scanning, resulting from the degraded representation of perceived error information in the peripheral visual field (Levison, Elkind, & Ward, 1971, Allen & Jex, 1968).

A number of automotive studies have examined information access costs associated with head-up displays (HUDs), which present information closer to the forward field of view of drivers than traditional head-down displays (HDD; i.e., instrument panels). These studies generally demonstrate reduced access costs for HUD information and increased time with the eyes on the road (due to the reduced scanning costs, e.g., Kiefer, 1991; 1995; Okabayashi, Sakata, Fukano, Daidoji, Hashimoto, & Ishikawa, 1989). Other studies have shown HUD benefits in the detection of objects in the outside world (e.g., Kiefer, 1998; Sojourner & Antin, 1990) as well as better lane tracking and velocity control (Kaptein, 1994). A more detailed review of these and other studies can be found in Horrey and Wickens (2002). Collectively, these studies demonstrate the greater performance costs associated with more distant displays however, many suffered from methodological shortcomings. For example, many did not include dual-task situations or failed to assess performance on both tasks; oftentimes, drivers were passive observers of driving scenes rather than active "controllers", and; often there were no discrete events which approximated the hazard awareness task of driving. A recent study by Horrey and Wickens (2002), described below, sought to address a number of these concerns. (Note that in automobile HUD studies, the HUD can either be placed to overlay the primary roadway environment, or projected just below it. In the former case, the HUD may perceptually mask certain roadway obstacles, a condition examined by Horrey and Wickens, and typical of most aviation HUD studies. However this condition was not examined here. Only the lower projected HUD was employed, a configuration that appeared to offer the best overall performance in Horrey and Wickens' experiment.)

In their simulation study, Horrey and Wickens (2002) examined performance on vehicle control and hazard awareness as drivers drove through environments of varying complexity. Throughout the experiment, drivers completed a digit readback task (i.e., call back of visually presented 4, 7, and 10 digit phone numbers) which was presented in an adjacent head-up position (7° below the horizon line, above the hood of the vehicle) or on a head-down, console mounted LCD display (positioned approximately 38° from the driver's forward line of sight: 22° head-down and 31° lateral offset). The digit shadowing task included three different levels of task load: four-, seven-, or ten-digit strings. Vehicle control performance was assessed by measures of lane keeping and speed control, while drivers were engaged in the secondary task. Additionally, drivers were presented with several critical events (at random times during the drive) which required an overt maneuver in order to avoid a collision. In general, there were no differences between the display conditions for the vehicle control parameters, suggesting that drivers were able to use ambient vision to support the vehicle control task or they adopted an appropriate scan strategy which allowed them to protect the driving task at the greater display separation. (For example, using a visual occlusion technique, Tsimhoni and Green (2001) have shown that with modest road curvature, driving performance (lane keeping) is disrupted equally by the use of a head-down display (HDD) of IVT information and the visual occlusion of the driving scene for the equivalent period of time. These findings suggest that drivers, in the Horrey and Wickens' study, may have required multiple eye scans to attain the observed protection of the driving task.) This protection of lane keeping was true even for the more difficult road situations (e.g., curved sections with the highest digit task load). However, in contrast to lane keeping, responses to the critical events were degraded when drivers interacted with the HDD. This suggests that ambient vision was not sufficient for hazard detection, and that focal vision may be required (as was shown in the studies by Summala and colleagues, which are reported previously). Alternatively, these findings may also suggest that any given scan strategy (if adopted) can be fallible in instances where precise and timely responses are required.

Wickens (1992) notes that there will be increased performance decrements for concurrent tasks when task difficulty is increased (for either, or both tasks). While the study by Horrey and Wickens (2002) investigated different road types and complexity (e.g., straight urban and rural; curved rural), none of the roads were overly demanding. For example, there were very few changes in elevation (most drives were on level terrain) and the majority of the curves were of constant radii, which were highly predictable and did not require many steering corrections (i.e., the maneuver was relatively stable once the vehicle entered the curve). Because of the safety implications inherent in the application of any IVT, we sought to reexamine the impact of the different display locations in conditions of higher driver workload by imposing more variable and less predictable road curvature, more elevation changes (to make speed control more difficult), and by the reduction of road visibility (through fog) in some conditions. Specifically, with increased driving difficulty, we sought to determine whether the null effects of vehicle control for head-up and head-down IVT information (from Horrey & Wickens, 2002) would persist.

Present Research

The current study sought to extend the findings of Horrey and Wickens (2002) on the effects of visual display separation on vehicle control and hazard awareness, however in highly demanding driving situations.

In this simulator study, participants drove through highly curved rural traffic environments which also included a number of elevation changes. Furthermore, half of the drives were completed in dense (high) fog conditions, where visibility of the road ahead was severely limited. Concurrently, drivers engaged in a the same secondary digit phone number read-back task employed by Horrey and Wickens (2002), however in this study only the highest (ten-digit) task load was used, simulating the voice dialing of a displayed phone number (with area code). This side task was presented either in an adjacent HUD (7° below the horizon line) or on a head-down LCD screen (located 38° from the forward line of sight). When the digits appeared, drivers were required to read them aloud. We hypothesized that, to the extent that drivers were protecting the driving task on these more difficult roads, side task performance with the HDD would be highly degraded compared to the HUD. However, if drivers were not protecting the driving task, we expected vehicle control performance to be much poorer with the HDD compared to the HUD.

Driving performance was determined by lane keeping and speed control throughout each drive as well as by the response to twelve critical events that occurred at random locations. Each event required an emergency maneuver in order to avoid a collision with an obstacle. In the display conditions, these events coincided with the presentation of a secondary digit task. We hypothesized that the HUD would yield superior performance for these events (though still degraded relative to baseline (no side task) performance). We also hypothesized that responses to the events in high fog conditions would be slower due to the decreased salience of the events relative to good visibility conditions, and that this "salience effect" would be amplified in peripheral vision (head down condition), since the event would be less likely to call attention to itself, and depend more on an upward glance to the roadway to assure detection. Side task performance measures included the response time to the digits (i.e., time to initiate the response), the length (duration) of the response, and the response accuracy. All dual-task conditions were compared to baseline (no side task, or no driving) conditions. We also assessed mental workload using a NASA-TLX scale (Hart & Staveland, 1988) to assess the magnitude of our workload manipulation.

METHODS

Participants

Twelve participants from the University of Illinois volunteered for this study (aged 18 to 28 yrs, M = 22). This group was equally balanced between men and women. All had valid driver's licenses (M = 5 yrs of licensure) and, on average, drove 7500 miles per year. All participants were screened for normal or corrected-to-normal visual acuity. A brief description and demographic account of each participant can be found in Appendix A. Drivers were paid $8 for their hour of participation.

Additionally, two participants withdrew from the study after experiencing mild symptoms of motion sickness from the simulation. Data from these participants is not included in any of the subsequent analyses.

Materials

Simulator Hardware and Software

This research was conducted using the Beckman Institute Driving Simulator at the University of Illinois. The fixed-based simulator consists of a 1998 Saturn SL positioned in a 360° wrap-around environment (see Appendix B). For the current study, driving scenes were only projected over 130° of the forward field and on 130° of the rear field. The in-vehicle display information was presented on an AEI 6.4" LCD monitor with 640 x 480 pixels of resolution.

Driving scenarios and simulator dynamics were coordinated through GlobalSim's Vection Simulation Software™ and HyperDrive Authoring Suite™ Versions 1.4.2 (see Horrey

& Wickens, 2002, for a detailed account of the simulation software and configuration). Specific environments and events are discussed further in subsequent sections.

Driving Environment Overview

Six roadways were developed for the purpose of this study, consisting of two-lane bi-directional rural roads. These roads included large amounts and varying degrees of curvature as well as frequent elevation changes. Each roadway took approximately 5 minutes to complete (traveling at the posted speed limit). In the oncoming lane of traffic, there was a low level of ambient traffic (roughly 8-9 per minute). There was no traffic in the driver's lane. For three of the driving scenarios, a low level of fog was introduced, which allowed for relatively good visibility (to the order of 1000 m; see Figure 1A). In the other three scenarios, the level of fog was increased such that visibility was cut to roughly 75 m (see Figure 1B). At various points throughout these drives, the participants encountered critical events, which required an overt response maneuver in order to avoid a collision. These are described below.

Critical Events

Lane Obstacle. At various points throughout the drive, a static lane obstacle (in the form of a dog) appeared in the driver's lane of travel (see Figure 1C). In the good visibility (low fog) conditions this dog was initially masked by the roadway geometry (e.g., over the crest of a hill). In the poor visibility (high fog) conditions, the fog effectively masked the approaching dog. In both cases, drivers were allowed approximately 2.5 seconds to recognize the hazard and initiate a safe response maneuver. In the non-baseline trials, the secondary digit task was initiated approximately 1 second prior to the event onset (i.e., the moment the obstacle became visible). Because this hazard event occurred once per drive, we consider the effects of order and anticipation in subsequent analyses to determine whether performance for critical events improved over the course of the study.

Oncoming Lane Drift. Periodically, an approaching vehicle would drift from the opposing lane into the driver's lane (see Figure 1D). When the separation between the two vehicles reached a minimum of approximately 3 seconds, the event was triggered, (ideally) forcing drivers to make an evasive steering maneuver towards the shoulder of the roadway. The lateral movement of the oncoming vehicle occurred relatively rapidly and ceased after the vehicle was one-third of the way into the driver's lane.

Response times for lane obstacle events were measured from the moment the obstacle was visible until the driver made a measurable response. In contrast, lane drift events did not have clearly defined entry times (because the vehicles were, for the most part, visible on the road ahead prior to the event; Olson, 2002). Therefore, the onset of these events was defined as the moment the vehicles started their lane departure (i.e., when the opposing vehicle's heading began to shift). Braking responses were recorded as soon as the pedal was depressed 5% (random non-depressed activation typically fluctuated from 0 to 2%). Because the roadways were highly curved, we were forced to define steering responses by the rate of change of steering wheel angle over a brief time interval rather than a specific deflection angle. A change in deflection angle of 100° per second (over a 0.25 s interval) was adopted because it far exceeded the normal range of steering inputs and corrections and was readily apparent in the data stream for event maneuvers.

Figure 1. Traffic environments and critical hazard events used in the study: (A) Low fog conditions; (B) High fog conditions; (C) lane obstacle event (dog; shown in low fog); (D) Lane drift (oncoming vehicle; shown in low fog).

Response time for these events was recorded until the beginning of the steering wheel deflection. In cases where participants made both types of response maneuver, the fastest response (either braking or steering) was used as the response time for the event.

Procedure

At the start of the hour-long session, participants completed a simulator sickness screening questionnaire (Appendix C) and an informed consent form (Appendix D). Visual functioning was measured using a Snellen Visual Acuity Chart. Participants were required to exhibit a normal or corrected level of 20/30 acuity. Participants meeting the visual requirements were provided with a brief description of the experimental tasks (see Appendix E for complete verbal protocol).

After a brief introduction to the simulator hardware (e.g., LCD screen, input buttons, abort switch), drivers were seated in the vehicle and adjustments were made to suit the size and preference of the driver. Following this description, drivers were given a 5-minute training session during which time they familiarized themselves with the responsiveness of the steering wheel, accelerator, and brake pedals, as well as the general dynamics of the simulator.

As noted previously, drivers each completed 6 drives which were arranged into two different experimental blocks (one low fog and one high fog). Within each block, drivers completed three drives with the different secondary task displays: the adjacent HUD, the console HDD, as well as a single-task baseline (no secondary task) drive. For each drive, drivers were instructed to observe and obey traffic laws and to respond to traffic as they normally would. Participants were also encouraged to keep their vehicle centered in their respective lane and to maintain a speed close to the posted limit (55 mph). Additionally, participants completed a short baseline block for the secondary task (in which no driving was required). All of the experimental blocks and the drives within each block were counterbalanced (see Appendix F).

For two of the three drives per block, participants were instructed to complete a digit-shadowing task (i.e., where they were required to read back strings of digits presented visually; Horrey & Wickens, 2002). All number strings were 10-digits long and were presented in one of two visual locations: in a simulated HUD superimposed on the roadway (approximately 7° below the horizon line) or on a console-mounted LCD screen (approximately 38° diagonally offset from the center of the horizon line; 34 cm below and 37 cm to the right; see Figure 2). See Appendix G for an image of the displays and visual angle of the displayed digits. The digit-shadowing task was more or less continuous; with digit strings presented every 1 to 4 seconds following the completion of the previous string. For this task, participants were instructed to respond to the digits as quickly as possible but not to compromise safe driving. When the participant noticed the presentation of digits, they were required to press a steering wheel-mounted button at the beginning of their response. When they completed their response, they pressed the button once again.

Driving measures of lane position and velocity were recorded throughout the trials, as well as secondary task performance (i.e., time to initiate verbal response, duration of verbal response, and accuracy of response).

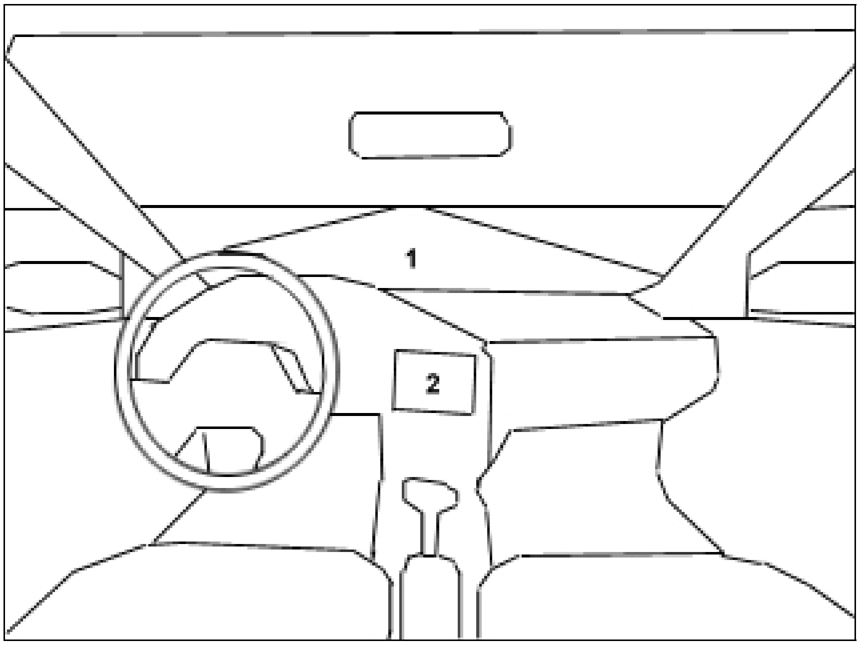

Figure 2. Display configuration for the (1) adjacent, (2) head-down conditions. Adapted from Summala, et al. (1998) and Horrey & Wickens (2002).

On each trial, two critical events occurred at random points. As described above, for non-baseline drives these events followed the presentation of secondary task information. Perception-response time (PRT), maneuver type, and maneuver success were recorded for each of these events. Measures of PRT include the time to identify a hazard, choose the appropriate course of action, and initiate the chosen action (Olson, 1996).

Each block lasted approximately 12 minutes except the secondary task baseline block, which approximated 2 minutes. Between each block, participants completed a NASA-TLX rating of their workload for the previous block of drives (see Appendix H). This multi-scale system rates mental and physical demand, perceived time pressure, perceived level of performance, frustration level, and mental effort. Additionally, participants were offered a short rest between blocks and were also afforded the opportunity to rest between drives within a block.

Following the completion of the experimental blocks, participants completed a brief questionnaire (Appendix I) and were remunerated for their participation.

Experimental Design

The experimental design was a within design with the variables of Display Type (Adjacent HUD, Console HDD, No Display) and Visibility (High Fog, Low Fog).

RESULTS

We assessed performance on the two driving tasks (vehicle control and hazard avoidance) and the side task through a number of analyses across display types and visibility conditions. In general, we adopted a Bonferroni correction to control family-wise error rates in the post hoc analyses.

Driving Performance

Lane position was measured in meters from the center-point of the driver's lane and was recorded from the start of a drive and taken until the end (given that the side task was more or less continuous, we did not parse out response intervals here). The absolute deviation from this center-point was used in a repeated measures ANOVA for Display Type (HUD; HDD; Baseline) and Visibility (High Fog; Low Fog). As shown in Figure 3, there was a significant main effect of Visibility ($\underline{F}_{(1, 11)} = 17.7$, $\underline{p} = 0.001$), with smaller deviations in the high fog conditions ($\underline{M} = 0.50$ m) than in the low fog ($\underline{M} = 0.59$ m). There was however no significant main effect for Display Type ($\underline{F}_{(2, 22)} = 1.6$, $\underline{p} = 0.22$), nor a significant Display x Visibility interaction ($\underline{F}_{(2, 22)} = 1.4$, $\underline{p} = 0.28$). Together, these findings suggest that drivers are adapting their behavior in the more demanding high fog conditions to protect the driving task (and in this case, performance was actually enhanced by this protection). The improved performance in the fog also suggested that driver's were able to access sufficient information regarding the roadway to maintain good lane keeping. Indeed, the level of fog adopted in the current study did not effectively mask the region of the roadway where drivers have been shown to gather the most information related to lane-keeping (Land & Horwood, 1995). We also note that drivers were able to protect the driving task when interacting with the HDD compared to the HUD. This replicates the findings by Horrey and Wickens (2002), however extends them to more challenging road conditions. This HDD protection may be due to the use of ambient vision for vehicle control or the result of an appropriate scan strategy for interacting with the console display. The findings also demonstrate the protection of the driving task in dual-task conditions (both HUD and HDD) relative to baseline (single-task) conditions.

Speed control was examined by measuring the average velocity for a given condition as well as through the variability in velocity (standard deviation) over the course of a given drive. The average velocity for each condition is presented in Figure 4. A repeated measures ANOVA for vehicle speed did not reveal a significant main effect for Display ($\underline{F}_{(2, 22)} = 1.9$, $\underline{p} = 0.17$), nor a significant Display x Visibility interaction ($\underline{F}_{(2, 22)} = 0.36$, $\underline{p} = 0.70$). There was, however, a marginally significant effect of Visibility (after Bonferroni correction; $\underline{F}_{(1, 11)} = 5.0$, $\underline{p} = 0.05$), with lower speeds adopted in the high fog conditions ($\underline{M} = 22.4$ m/s) than low fog ($\underline{M} = 23.9$ m/s). These reduced speeds again may indicate an adaptive behavior in the protection of the driving task (in terms of safety) when the forward view is severely reduced.

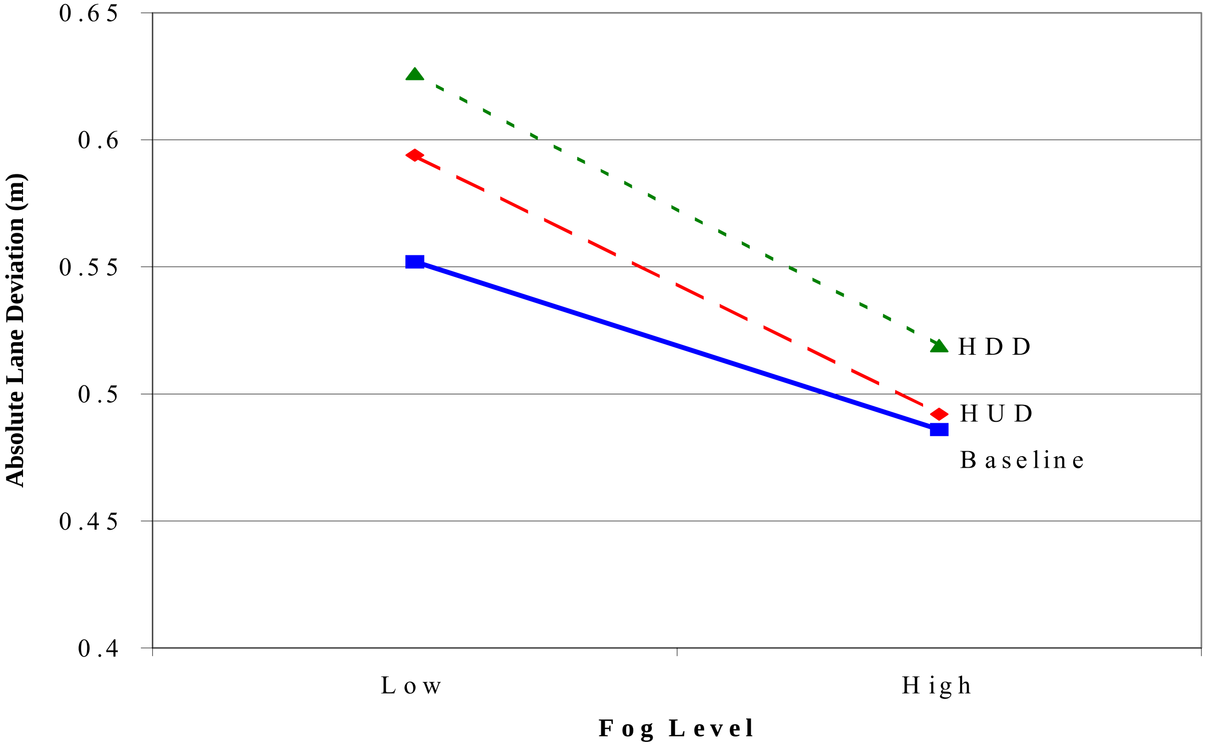

Figure 3. Absolute lane deviation by display and fog level.

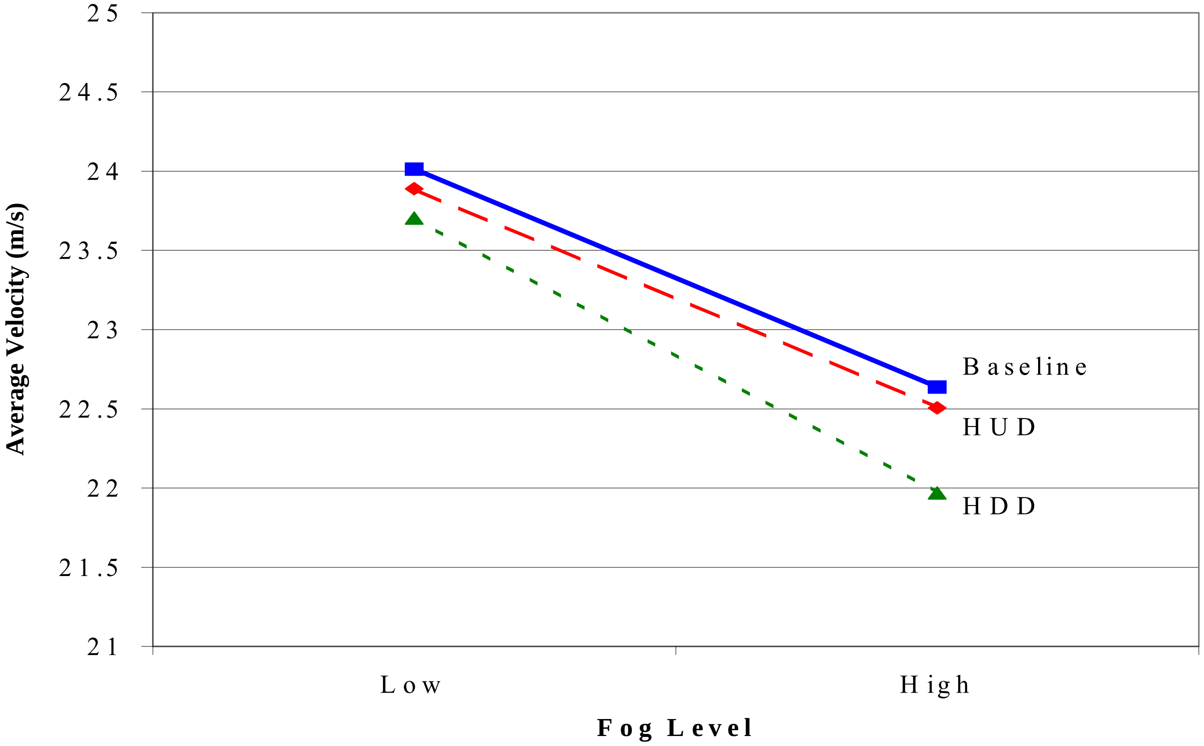

Figure 4. Average velocity by display and fog level.

We also examined the standard deviations of vehicle velocity, as this is indicative of drivers' abilities to keep a fixed velocity throughout the drive. A repeated measures ANOVA for Display and Visibility revealed significant main effects for both variables ($\underline{F}_{(2, 22)} = 28.6$, $\underline{p} = 0.001$; $\underline{F}_{(1, 11)} = 8.2$, $\underline{p} = 0.02$; respectively). As shown in Figure 5, velocity deviations were greater in high fog conditions ($\underline{M} = 3.0$) compared to low fog ($\underline{M} = 2.6$), possibly because changes in roadway elevation were more difficult to anticipate and adjust for in the foggy conditions. Post-hoc analyses did not reveal any differences between the two display conditions (HUD vs. HDD; $\underline{t}_{(11)} = -1.6$, $\underline{p} = 0.13$), however both the HUD ($\underline{M} = 2.9$) and HDD ($\underline{M} = 3.1$) conditions differed significantly from the baseline condition ($\underline{M} = 2.4$; $\underline{t}_{(11)} = 7.9$, $\underline{p} < 0.001$; $\underline{t}_{(11)} = 6.6$, $\underline{p} < 0.001$; respectively). This indicates that there were dual-task costs associated with the speed control task compared to baseline, however drivers were able to protect the task from further degradation in the head-down condition. The Display x Visibility interaction was not significant ($\underline{F}_{(2, 22)} = 0.60$, $\underline{p} = 0.56$).

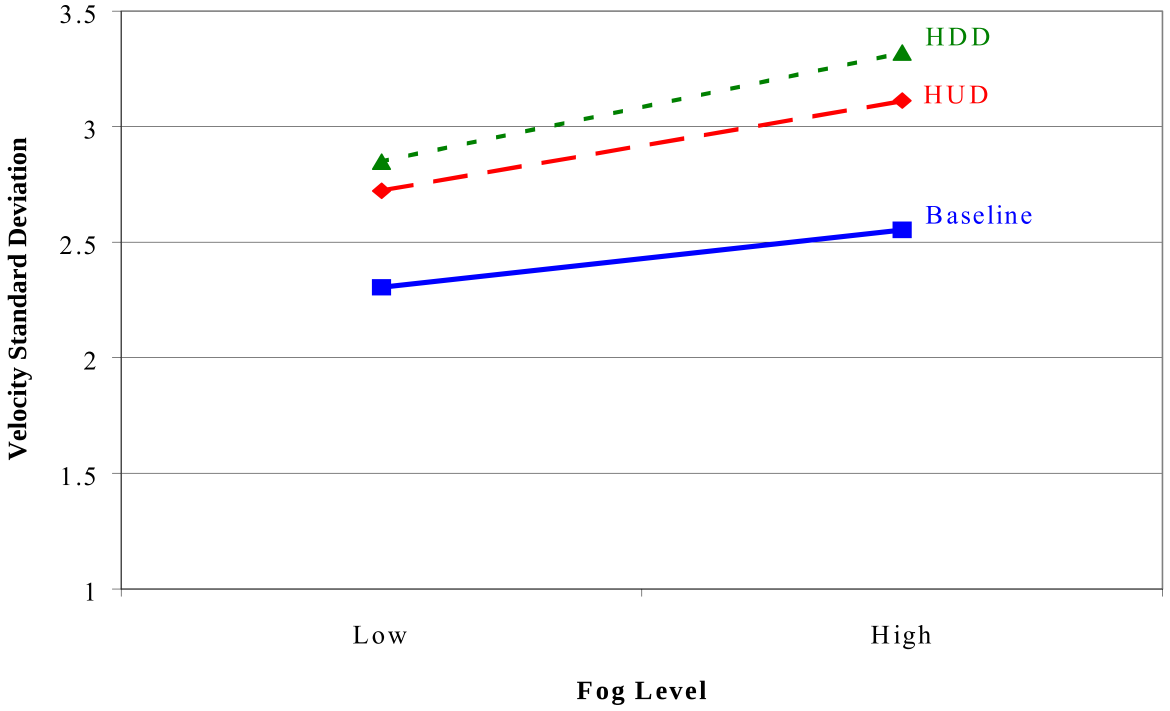

Figure 5. Velocity standard deviation by display and fog level.

Thus, the current results show support for the protection of the primary driving task across display conditions, although there was greater variability in the velocity deviations with the HUD and HDD conditions. The results further suggest enhanced protection of the driving task (regardless of display condition) when poor visibility persists. As noted previously, the vehicle control task may be time shared with the side task because it uses ambient visual channels and does not depend exclusively on focal resources. Such ambient vision was not impaired at the lower level of visual quality imposed by the high fog in the current condition. More importantly, these results are consistent with those found by Horrey and Wickens (2002), however extend to higher workload conditions.

Response Times to Critical Events

Each participant encountered twelve discrete events over the course of the experiment. Half of these events were lane obstacles while the other half represented lane incursions by an oncoming vehicle. Because each event differed somewhat, we examined these event types independently.

Lane Obstacle

A repeated measures ANOVA for response times to this critical event revealed significant main effects for Visibility and Display Type ($\underline{F}_{(1,10)} = 5.77$, $\underline{p} = 0.04$; $\underline{F}_{(2,20)} = 11.31$, $\underline{p} = 0.001$; respectively). The Visibility x Display interaction was not significant ($\underline{F}_{(2,20)} = 0.08$, $\underline{p} = 0.92$). As shown in Figure 6, responses were more rapid in the high fog condition ($\underline{M} = 1.04$ s) compared to the low fog ($\underline{M} = 1.29$ s), suggesting that drivers may have been more vigilant of the driving task in conditions of degraded visibility (i.e., more protective of the task). Figure 6 also demonstrates the Display differences, with response times being degraded in the HUD ($\underline{M} = 1.20$ s) and HDD ($\underline{M} = 1.39$ s) conditions relative to baseline ($\underline{M} = 0.92$ s; $\underline{t}_{(11)} = 5.80$, $\underline{p} < 0.001$; $\underline{t}_{(11)} = 4.53$, $\underline{p} = 0.001$; respectively). The difference in response times between the two display types represented a non-significant trend, with 0.19 s slower responses while using the HDD than the HUD ($\underline{t}_{(11)} = 1.69$, $\underline{p} = 0.12$). This finding replicates that of Horrey and Wickens (2002) and again suggests that the increased display separation between the head-up and head-down locations degrades drivers' abilities to detect traffic events in their periphery (i.e., due to the competition over focal resources). Interestingly, the HDD cost was not amplified by low fog, suggesting that there was <u>not</u> a differential attention capture effect of the hazard, present in low fog, absent in high fog. Rather, we assume in both conditions, detection depended upon an upward scan to bring the hazard into foveal and focal vision.

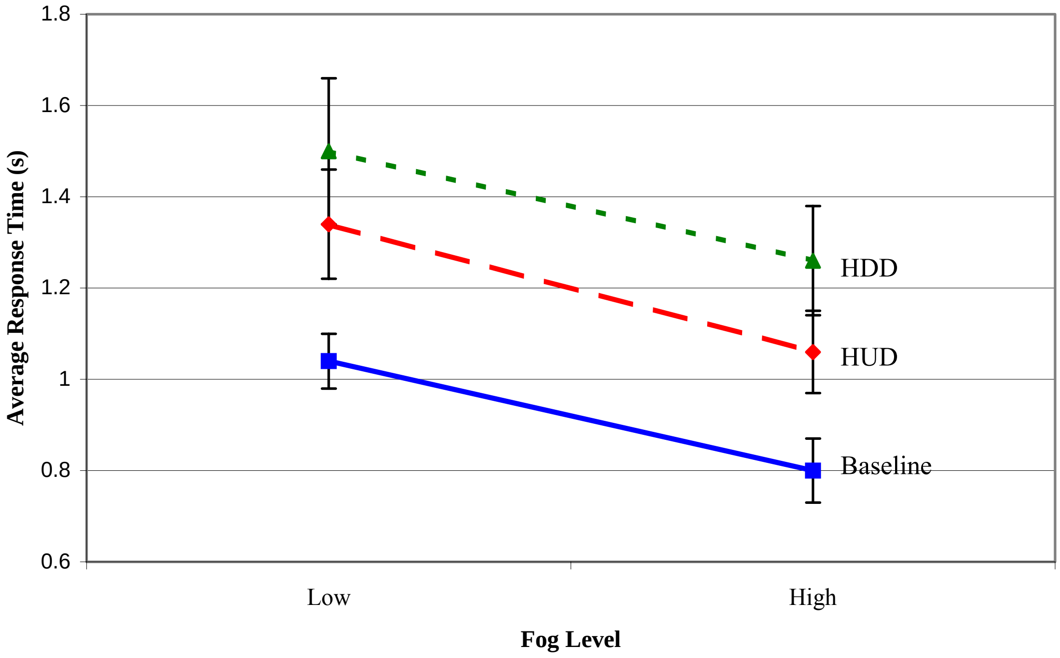

Figure 6. Response times to lane obstacle events by display and fog level.

Lane Drift

Response times to the lane drift events were analyzed using a repeated measures ANOVA. As shown in Figure 7, there was a non-significant trend for Visibility condition ($\underline{F}_{(1,10)} = 2.68$, $\underline{p} = 0.13$), with faster response times in the high fog ($\underline{M} = 1.11$ s) than low fog ($\underline{M} = 1.23$ s) conditions. This is consistent with the findings for the lane obstacle event (reported above). There was a significant main effect for Display Type ($\underline{F}_{(2,20)} = 7.38$, $\underline{p} = 0.004$), with slower responses in the HUD ($\underline{M} = 1.25$ s) and HDD ($\underline{M} = 1.22$ s) conditions than baseline ($\underline{M} = 1.04$ s; $\underline{F}_{(1,11)} = 10.39$, $\underline{p} = 0.008$). There were, however, no overall differences between the HDD and HUD conditions ($\underline{F}_{(1,11)} = 0.10$, $\underline{p} = 0.75$)—an effect which may be best interpreted in the context of the significant Display x Visibility interaction ($\underline{F}_{(2,20)} = 4.50$, $\underline{p}= 0.02$). As Figure 7 demonstrates, response times for the HDD do not differ across Low and High Fog conditions (unlike for the lane obstacle events, as shown in Figure 6; $\underline{F}_{(1,10)} = 0.01$, $\underline{p} = 0.91$). This may be indicative of another strategy adopted by drivers to protect the driving task while using the head-down display—a strategy which would not necessarily benefit performance for the discrete lane obstacle events (Figure 6; since these events are not dynamic elements of the driving environment to the same degree as the oncoming vehicles). More specifically, drivers may have recognized the potential risk presented by oncoming vehicles and therefore strategically delayed the initiation of the response to the secondary task in the head-down condition until they were satisfied that they were not in any immediate danger. This strategy would benefit performance in the low fog condition however not in the high fog condition because of the lack of preview available to them in the latter condition (hence, the flat slope observed for the HDD condition). This strategic delay for the head-down IVT information is also supported by the side task response times, which will be reported in later sections. The improved performance in high fog in the HUD and baseline conditions is likely due to increased vigilance and scanning to the outside world (as in Figure 6), a strategy that was also seen to improve lane keeping performance (Figure 3).

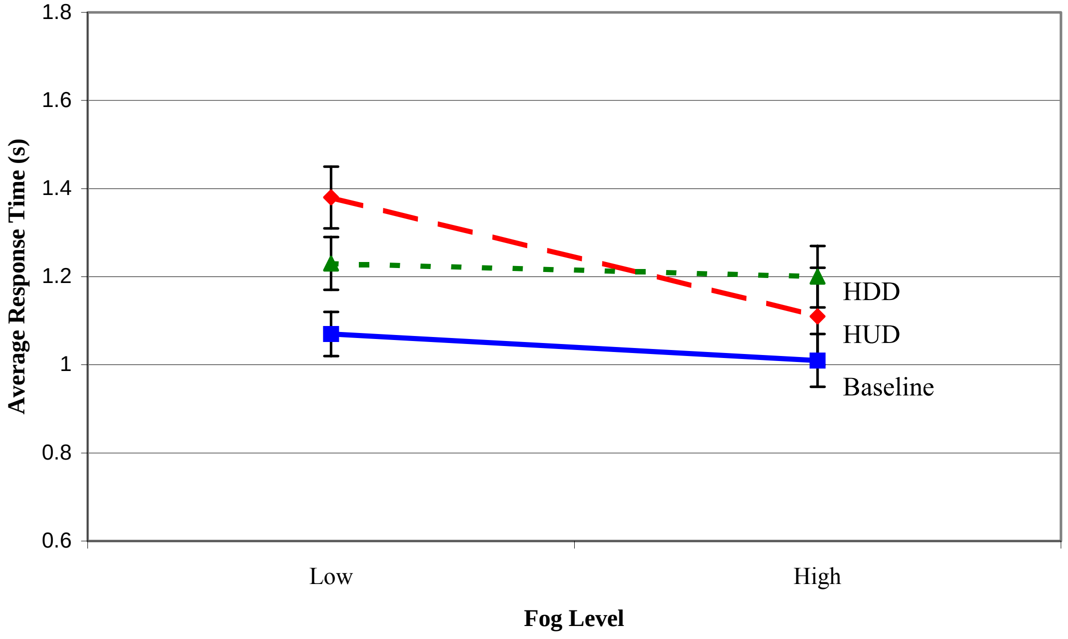

Figure 7. Response times to lane drift events by display and fog level.

Event Order: Effects of Experience

We examined the performance for the critical hazard events over the course of the study to determine whether response times improved. In general, response times are most degraded to truly surprising, unexpected events (e.g., Gish & Staplin, 1995)—events, which are most likely to be represented by the initial (first) event encountered in the current study. To explore this, we compared response times to the initial event occurrence (for both event types) and compared this to the aggregate of the remaining occurrences of the same event. As expected, a repeated measures ANOVA revealed a significant effect ($F_{(1,23)} = 10.04$, $p = 0.004$), with longer response times for the first event ($M = 1.31$ s) compared to subsequent events ($M = 1.11$ s).

We further examined display differences in response times for the initial lane obstacle event. A one-way ANOVA revealed a marginally significant main effect for Display Type ($F_{(2,9)} = 4.02$, $p = 0.06$), with slower responses from drivers using the HDD ($M = 1.55$ s) compared to the HUD ($M = 1.25$ s; $t_{(6)} = 1.95$, $p = 0.10$) and baseline ($M = 1.15$ s; $t_{(6)} = 2.94$, $p = 0.03$) conditions. There was no difference, however between the HUD and baseline conditions ($t_{(6)} = 0.66$, $p = 0.54$). It should be noted that these tests involved relatively low statistical power due to a small N.

In summary, the responses to the critical events revealed some important findings. First, there were dual-task costs in response time to these events, relative to single-task, baseline conditions. This is not consistent with those findings reported in Horrey and Wickens (2002), a difference which suggests that the increased workload and difficulty of the current task was sufficient to incur greater task interference, associated with the competition for focal visual resources, and consequent performance degradation (e.g., Wickens, 2002). Second, there were additional costs associated with the presentation of information presented head-down, relative to the head-up presentation, suggesting that ambient vision is not sufficient in the effective response to road hazards and that focal visual attention is required. Focal vision is required in the effective interaction of drivers with both IVT displays (HUD and HDD), however the near-proximity of the head-up presentation reduces the degree of scanning required to monitor both the display and the roadway as well as reduces the degree of degradation of information in the periphery (as it is closer to foveal vision). There are conditions, however, where drivers can use knowledge of the road ahead (i.e., oncoming (and visible) vehicles) to moderate the effects of the head-down presentation, and effectively respond to these hazards when the need arises. Third, we note that drivers responded more rapidly in the high fog conditions suggesting that they accurately recognized these more difficult conditions and appropriately attended to the driving scene more closely (i.e., were more vigilant). Finally, we note that response times improved over the course of the study, with the initial unexpected occurrence of these events representing the most problematic (in terms of safety).

Side Task Performance

Side task performance was assessed by three different measures. First, the time from the side task onset until the response was initiated was recorded as the response time (RT). We also recorded the length of the verbal response (response duration) as well as the accuracy of the response. Here, we present the analyses of RT and duration. Given the nature of the task, accuracy performance was at or near ceiling for all participants so will not be analyzed or discussed in depth.

As shown in Figure 8, a repeated measures ANOVA for side task response time revealed a significant main effect for Display Type ($\underline{F}_{(1,\ 10)}$ = 5.7, $\underline{p}$ = 0.04), with slower responses in the HDD condition ($\underline{M}$ = 1.2 s) compared to the HUD ($\underline{M}$ = 1.0 s). These findings suggest costs associated with the protection of the driving task for the more distant HDD. They may further indicate the decreased salience of the side task when located in peripheral vision (i.e., HDD) or a decreased likelihood of actively monitoring the display when it is located further from the roadway. Such a finding would be consistent with the notion that drivers where more inclined to protect the driving task by strategically delaying the side task (especially as in the case of the lane drift event reported above). The Display x Visibility interaction was not signification ($\underline{F}_{(1,\ 10)}$ = 2.7, $\underline{p}$= 0.13), nor was the Visibility main effect ($\underline{F}_{(1,\ 10)}$ = 0.15, $\underline{p}$ = 0.71), suggesting that these performance costs were equivalent across visibility condition. The above analyses did not include the baseline condition, as it did not have both levels of visibility. To evaluate dual-task costs associated with the side task we collapsed the HUD condition across fog and compared it to the baseline condition. This analysis demonstrated significantly slower RTs when the side task was performed with the driving task (HUD condition; $\underline{M}$ = 1.0) than when performed alone (baseline; $\underline{M}$ = 0.78 s; $\underline{t}_{(11)}$ = -2.7, $\underline{p}$ = 0.02). The results support the notion that there are costs associated with the protection of the driving task we reported earlier. In general, these costs are smaller with the HUD, however are much larger with the HDD.

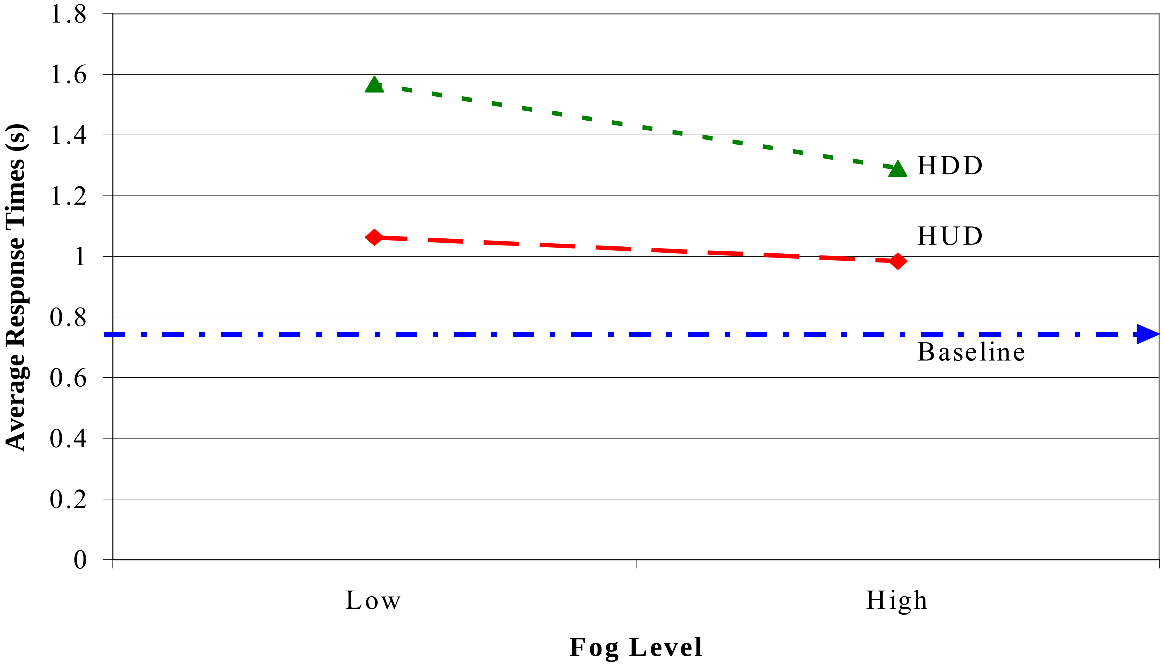

Figure 8. Average response time by display and fog level.

Similarly, a repeated measures ANOVA was applied to the response durations across Display Type (without the baseline condition). As shown in Figure 9, there was no overall difference between the low and high fog conditions ($\underline{F}_{(1,\ 11)}$ = 0.98, $\underline{p}$ = 0.34). There was however a marginally significant effect for Display Type ($F_{(1, 11)} = 4.4$, $p = 0.06$), with the HDD ($M = 4.5$ s) yielding longer response durations than the HUD ($M = 4.2$ s). The Display x Visibility interaction was also significant ($F_{(1, 11)} = 6.5$, $p = 0.03$). At low levels of fog, response durations were no different across the HUD and HDD conditions ($t_{(11)} = 0.51$, $p = 0.62$). However at high levels of fog, response durations with the HDD ($M = 4.7$ s) were slower than with the HUD ($M = 4.1$ s; $t_{(11)} = 3.0$, $p = 0.01$). These findings complement the previous ones with respect to the protection of the driving task. The longer response durations with the HDD in high fog conditions likely indicate an increase in the number of glances made to and from the display in order to complete the task and yet still maintain vigilance too the dangerous (low visibility) roadway (i.e., while trying to minimize the length of each glance downwards). In contrast, the HUD did not share similar costs possibly because of its proximity to the roadway. As with the analyses for side task RT, we collapsed the data for the HUD across fog conditions in order to assess dual-task costs with the presence of the driving task. This analysis did not reveal any differences between the HUD and baseline condition ($t_{(11)} = -0.57$, $p = 0.58$), suggesting that the addition of the driving task did not degrade performance except when the display was located further from the roadway (as the above analyses suggest). That is, vocal articulation of the digits in the HUD was not inhibited by the competing driving task, although such activity may have disrupted speed control (Figure 5) via a competition for response related resources.

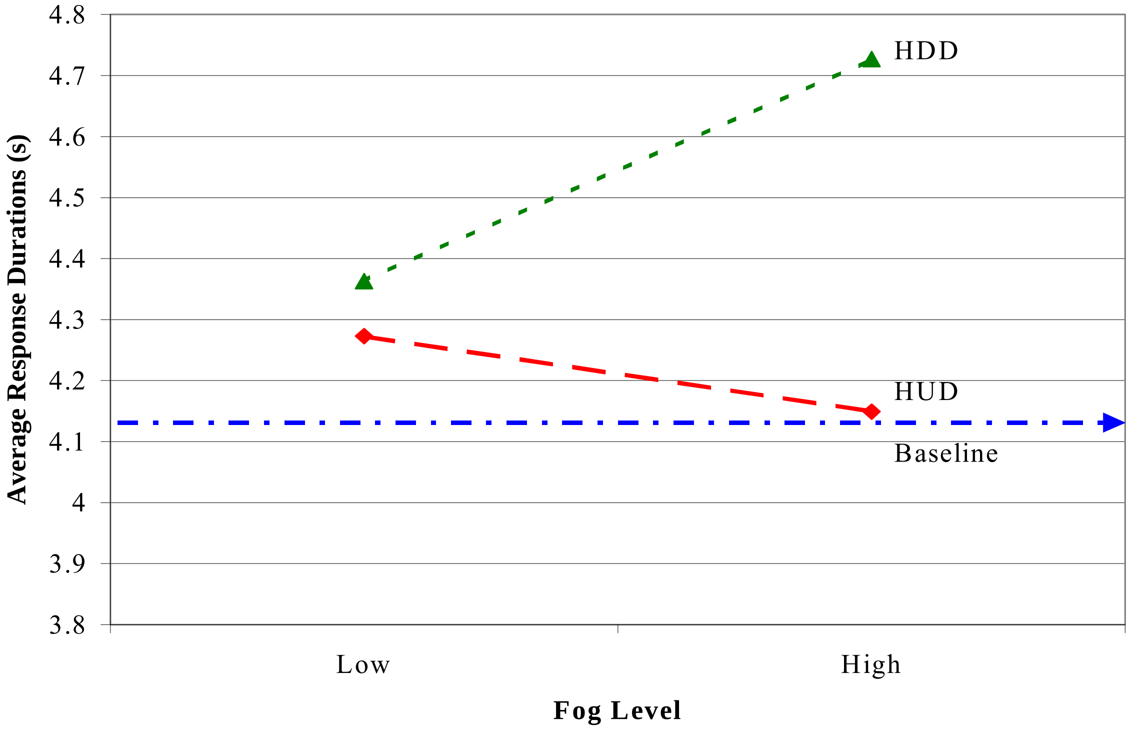

Figure 9. Average response durations by display and fog level.

The results from the analyses on side task performance compliment the notion that drivers are protecting the driving task in these demanding driving conditions. First, there are delayed responses to the side task information relative to baseline conditions, and these costs are greater when the display is located in a head-down position. Second, while there were no differences in response durations across display type in low fog conditions, there are high time costs associated with the HDD in high fog conditions. This follows intuitively since we would expect that, in order to protect the driving task to the same degree as with the HUD, drivers using the HDD would need to tradeoff performance elsewhere. Indeed this tradeoff is most evident in the response durations (and to some extent, the RT data).

Subjective Mental Workload

Finally, we had participants assess their mental workload after each block of trials using the NASA Task Load Index. Composite NASA TLX scores are shown in Figure 10 generally reflect the effects observed in primary and secondary task performance. A repeated measures ANOVA revealed a significant main effect for Display Type ($\underline{F}_{(2, 22)} = 60.1$, $\underline{p} < 0.001$) such that subjective mental workload was rated highest with the HDD ($\underline{M} = 8.4$), intermediate with the HUD ($\underline{M} = 6.6$), and lowest in the baseline condition ($\underline{M} = 2.4$). There was also a significant effect of Visibility ($\underline{F}_{(1,11)} = 6.8$, $\underline{p} = 0.03$) with higher workload ratings in high fog conditions ($\underline{M} = 6.4$) than low fog conditions ($\underline{M} = 5.3$). The Display x Visibility interaction was not significant ($\underline{F}_{(2, 22)} = 1.06$, $\underline{p} = 0.37$).

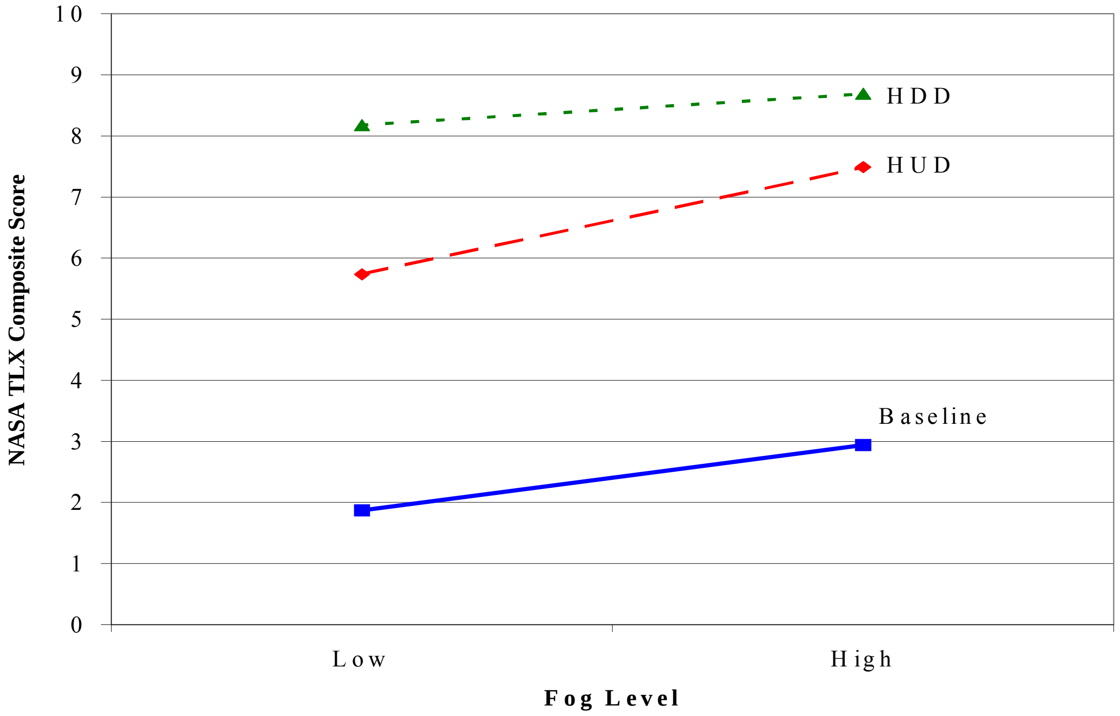

Figure 10. NASA TLX composite scores by display and fog level.

The NASA TLX scores reflect the increased resource demands associated with the different display and driving conditions. As the reported data shows, drivers did a good job of allocating the necessary resources to driving (i.e., the protection of the driving task), to adjust for the resource scarcity—one such adjustment being the strategic reduction of vehicle speed in high fog conditions.

Individual Differences

Finally, in a strictly exploratory investigation, we examined the differences in performance on various measures for the driver who had the slowest response times to the critical events and the driver who had the fastest response times to these events. The purpose of this profiling was to examine the interaction of the different measures (for the primary and secondary tasks) and to see whether there were any trade-offs. Most importantly, it suggests that differences between the "safe" and "unsafe" driver—in this small sample—can be modeled by differences in the strategy of attention allocation, rather than differences in the capacity for dual task performance (i.e., the size of a "resource pool"). This conclusion has important consequences for the benefit of attention strategy training (Gopher, 1993).

Table 1 outlines a number of performance measures for these two drivers. The most compelling finding is the trade-off in response times for the critical hazard event and the side task. We note that this tradeoff exists even for normal driving (i.e., the slowest performer is quicker at side tasks but has larger decrements for the vehicle control task than does the fastest performer). The findings further suggest that the initial steering response adopted by the fastest driver was more effective in the avoidance of collisions than was the braking strategy. There did not appear to be any demographic factors which could account for differences between these two drivers.

Table 1. Select performance measures for the slowest and fastest drivers in response to the critical hazard events.

	Measures	Slowest	Fastest
1	RT to critical events	1.40 s	1.01 s
2	Initial response maneuver	Always brake	Always steer
3	Number of collisions	10	5
4	Side task RT (for events)	0.91 s	2.56 s
5	Side task response duration (for events)	4.51 s	6.26 s
6	Average lane deviation (overall)	0.53 m	0.43 m
7	Average velocity (overall)	26.3 m/s	23.4 m/s
8	Average velocity deviation (overall)	3.2 m/s	2.8 m/s
9	Side task RT (non-events)	0.83 s	2.0 s
10	Side task response duration (non-events)	3.8 s	4.7 s
11	Overall NASA-TLX scores	3.1	3.4

DISCUSSION

Drivers are becoming increasingly exposed to various in-vehicle technologies, which may compromise safety. The current study sought to extend the findings of Horrey and Wickens (2002) to more difficult driving conditions (i.e., higher workloads), specifically for the adjacent head-up display position and the head-down presentation. Workload in the current study was increased through the use of highly curved road sections, with frequent elevation changes. Furthermore, fog was introduced on half of the trials to reduce the driver's preview of the road ahead. We first examine vehicle control and side task performance, followed by a discussion of the critical hazard events and the implications of these findings.

Driving and Secondary Task Performance

The results of the current study suggest that drivers were appropriately protecting the driving task from degradation, when performing a secondary in-vehicle task. There were no differences across display type (HUD, HDD, baseline) with respect to lane keeping, indicating a strong protection of this driving task. As resource theory would predict, this protection of the primary task came at a cost to performance of the secondary task (Wickens, 2002). We found that response times to the side task were slower for the HUD condition compared to baseline and the time-costs for the HDD condition were even more pronounced (Figure 8). We also note a similar pattern of results with respect to the response durations (Figure 9). Furthermore, the subjective workload rating revealed higher workload costs for the head-down display than the head-up presentation (which, in turn, was higher than baseline driving conditions). Taken together, these results suggest that the protection of the driving task across the display conditions comes at the expense of side task performance as well as driver mental workload. Additionally, these costs are greater for the more separate display condition (HDD). (We note, however, that such findings are, in a sense relieving, as the primary driving task is the more important of the two and has the most relevance to driver safety.)

In contrast to these results, Horrey and Wickens (2002) found dual-task costs associated with lane keeping for an equivalent IVT, relative to baseline driving. This may indicate that in the more challenging road conditions experienced here, drivers were cognizant of the increased demands and made a conscious effort to allocate more resources to this task. This interpretation would suggest that performance on the secondary task in the current study would be degraded to a greater extent than was observed in Horrey & Wickens (2002). Indeed, this could be the case, with secondary task time-costs (for response duration) of 240 ms for the HUD and HDD conditions in the current study, compared to costs of 140 ms for both displays in Horrey and Wickens (2002).

There are a few plausible explanations for the ability of drivers to protect the routine driving task (vehicle control) in the different display conditions. One such explanation is that the tasks of controlling the vehicle and performing the in-vehicle digit task use separate visual channels (Previc, 1998; 2000) and therefore can be performed concurrently with less (or no) degradation (Wickens, 2002). In this particular example, lane keeping is supported by ambient vision (Horrey & Wickens, 2002; Summala et al., 1996) while in-vehicle tasks, which require the discrimination of digits, utilize focal visual resources. We note however that the increased difficulty of the driving environment in the current study may have demanded some focal resources, whereas the easier road conditions adopted in other studies may have been benefited by separate focal-ambient resources to a greater degree (e.g., Horrey & Wickens, 2002; Summala et al., 1996; Summala, 1998).

Alternatively, drivers may frequently scan back and forth from the roadway to the displayed information in order to minimize the length of time spent with their eyes away from the roadway. This strategy may be more likely to the extent that an increasing amount of focal resources are required for vehicle control (as stated above). Wierwille (1993) notes that drivers tend to make multiple glances to in-vehicle information, especially when the extraction of the necessary information exceeds 1.5 seconds. However, as shown by Horrey and Wickens (2002), any such strategy may be fallible when precise and timely response inputs are required, such as in the case of critical road hazards—an issue we address in the next section.

Finally, we note that performance for the lane keeping task improved in the high fog conditions relative to low fog across all display conditions, although there was more variability in the speed control task in high fog. In general, these findings suggest that drivers were appropriately attending to the driving task as the perceptual demand increased. Drivers also compensated by adopting slower vehicle speeds, effectively reducing the bandwidth of the tracking task and making it less demanding. The increased variability in speed control was likely due to the lack of preview for elevation changes in the road ahead, although there was still enough visual information for the maintenance of good lane position (Land & Horwood, 1995).

Hazard Awareness

As argued by Horrey and Wickens (2002), ambient vision may well support vehicle control tasks (such as lane keeping or speed control) however may not be sufficient in the effective detection and identification of road hazards (see also, Lamble et al., 1999). This is also reflected, to a certain degree, in the current results. Specifically, for the lane obstacle event (i.e., the dog), we showed that response times were longer in the head-down condition compared to the head-up presentation. However, the responses to the lane drift event may be indicative of a driver strategy aimed at protecting the driving task of hazard awareness. When conditions permitted (i.e., low fog), drivers using the head-down display may have purposely delayed responding to the side task when there were oncoming vehicles approaching. We have already noted delayed response times to this head-down task, so it is possible that in some cases this delay was due to strategic task postponement. It was noted previously that such a strategy would not benefit drivers in the high fog conditions (because of reduced roadway visibility), nor would it benefit drivers in response to the lane obstacles (because they are not integral components of the traffic environment and cannot therefore be previewed, i.e., they represent more of an "on-setting" event), nor would it be necessary with the head-up display. Furthermore, this strategy would not likely be adopted until after the initial lane drift event occurred (because of participants' changing expectations over the course of the study). Indeed, the analysis of order effects lends itself to this argument, with slower response times to the occurrence of the initial event and faster, more stable response times for the subsequent events (i.e., after such a strategy has been adopted).

In the current study, Figure 6 noted dual-task costs in response times associated with the presentation of the side task. This, however, was not the case in Horrey and Wickens (2002), where drivers responded equally in single- and dual-task conditions. We attribute the performance decrements in the current study to the overall increase in workload (difficulty) of the driving task, which increases the resource competition for *all* tasks. That is, lane keeping itself demanded more attention, rendering less available for unexpected hazard monitoring.

Salience is an important factor when considering the time-sharing of two focal tasks. As information is presented more peripherally (as in the case of the head-down IVT display), it becomes less salient and, as a result, may not be noticed as rapidly as when presented closer to the fovea. This argument would suggest that the responses to the critical events should be degraded in the high fog, relative to the low fog conditions. This was not the case in the current study however, with faster responses times to the critical events in high fog compared to low fog conditions. This discrepancy may be indicative of increased scanning in the high fog conditions, and consequently increased time with focal attention directed towards the traffic environment. This observation is also consistent with the increase in response durations with the HDD in high fog conditions. It also may offer some evidence for the increased need for focal vision as driving difficulty increases.

In summary, drivers were less capable of protecting the hazard awareness task in conditions of increased vehicle control difficulty, as evidenced by the dual-task costs in the current study. This may be a result of increased competition between the two driving tasks (vehicle control, hazard awareness) over limited focal resources—resources which are not necessary when driving conditions are less demanding (Horrey & Wickens, 2002). Importantly, we also note the potential adoption of delay strategies (when conditions permit) for the safe interaction with IVT information.

Comparisons to Horrey and Wickens (2002)

Finally, we revisit some of the key findings in the current study in comparison with those presented by Horrey and Wickens (2002). Table 2 shows the effects of three different manipulations across the two studies: driving load (i.e., the effects of increased curvature (1) or decreased visibility (2)), dual-task load (i.e., the effects of the addition of the HUD side task); and spatial separation (i.e., the effects of HDD versus head-up presentation).

In general, the pattern of results is very similar for the two studies with respect to spatial separation, with performance decrements for hazards responses and for the side task when using the HDD however protection of the vehicle control task under normal driving conditions. The current study, however, extends the findings to more difficult driving situations. In terms of dual-task load, it appears as though the increased driving difficulty in the current study was sufficient to degrade performance on hazard responses and side task duration (as compared to the null or dual-task benefit observed by Horrey and Wickens, 2002). Finally, Horrey and Wickens (2002) observed increased degradation in performance as the driving difficulty was increased (i.e., from straight to curved roads). The current study, however, shows improved performance as visibility decreased—a pattern that suggests that drivers were attending more to the driving task in the high fog conditions. As such, this increased attention benefited lane keeping and hazard awareness.

The important general finding, in comparing the two studies, is that the higher workload in the current study did not disrupt lane keeping, but did impose a cost of dual task loading on response to the unexpected hazards even in the HUD condition, a cost which was not present at the lower loading of the previous study. This emerging cost would seem to implicate the role of focal visual attention, little needed for hazard monitoring in the head-up condition of the first experiment, but here somewhat required to support routine driving, in conjunction with the demands for ambient vision that were present in both studies. In both, the increase in speed variability, associated with dual task load but not modulated by display location, probably reflects the competition for response-related resources associated with articulation of the digit response (Wickens, 2002).

Table 2. Comparison of key findings from (1) Horrey & Wickens (2002) and (2) the current study. **Driving load** was examined in terms of a comparison of (1) curved versus straight roads or (2) high versus low fog; **dual-task load** in terms of HUD versus baseline; and **spatial separation** in terms of HDD versus HUD. Note: (+) indicates improved performance; (0) indicates no effect; (-) indicates degradation in performance; [1] non-significant trend for lane obstacle event; [2] only for HDD; [3] only in high fog.

		Lane keeping	Speed Variability	Hazard RT	IVT RT	IVT Duration
Driving load (1—Straight → Curved; 2—Low → High fog)	1	–	–	n/a	–	0
	2	+	–	+	0	–[2]
Dual-task load (Baseline → HUD)	1	–	–	0	–	+
	2	0	–	–	–	0
Spatial separation (HUD → HDD)	1	0	0	–	–	–
	2	0	0	–[1]	–	–[3]

Implications

The safety implications for interacting with in-vehicle technologies are obvious. As drivers interact more and more with these devices, performance on the primary task of driving may inadvertently become degraded. While drivers are able to protect the driving task of lane keeping while interacting with these systems, there are important costs associated with responses to critical road hazards. Although there were some interesting trade-offs in performance and potential strategies across the two different display conditions, responses to these events were always slowed compared to baseline driving conditions. Indeed, these discrete and unexpected events represent an important aspect of safety inasmuch as they are often involved in many traffic crashes (e.g., objects initially obstructed from driver's view; Treat, 1980).

Displaying information in a head-up location effectively reduces the time required to access it (relative to a head-down location) and the time required to process it. The near proximity of HUD information may afford better time-sharing between focal and ambient tasks, especially as the primary task difficulty is increased. Furthermore, drivers have decreased mental workload when interacting with head-up information.

These findings, together with those reported by Horrey and Wickens (2002) offer converging evidence in support of the use of an adjacent head-up display for in-vehicle information. The current study suggests however that drivers may adapt their behavior (based on previous experience) to enhance the safety of interacting with the in-vehicle devices. Such strategies of task management remain unexplored, and may provide some important contributions to our understanding of the nature of the in-vehicle interaction between the driver and new technologies.

Finally, two observations bear on the importance of resource allocation in the current results. First, drivers in both experiments were relatively proficient at buffering primary task (driving lane keeping) from the higher task demands, by allocating more resources to that task, as the driving task increased (from experiment 1 to experiment 2, and from low fog to high fog), and as the secondary task became more demanding (by moving its display head down). Second, the "most dangerous" driver in the current study, in terms of response to the unexpected hazard, was not less proficient in overall time sharing ability, but rather, showed a non-optimal resource allocation, favoring secondary task performance at the expense of the primary driving-related tasks. Such findings point to the considerable potential importance of training attention allocation skills (Gopher, 1993), in the management of multi-task vehicle environments.

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APPENDIX A. SELECT DETAILS FOR PARTICIPANTS

Participant	Age	Gender	Annual mileage (miles)	Questionnaire Self-Reports[†]				
				Cell phones[1]	Speed[2]	Red light[3]	Sim steering[4]	Sim sickness[5]
1	28	F	500	2	4	1	4	3
2	19	F	2500	2	4	2	4	1
3	24	M	12000	1	3	1	4	3
4	20	M	-	2	4	1	5	1
5	19	F	-	1	4	1	4	3
6	19	F	5000	2	1	1	4	1
7	18	M	11000	2	3	2	4	1
8	20	M	20000	4	4	1	4	1
9	26	F	5000	3	5	1	4	1
10	22	M	7000	2	3	2	4	1
11	20	F	1000	2	4	1	4	2
12	28	M	10000	-	5	1	5	1

[†] Responses are based on a five point Likert scale (1-Never, 2-Rarely, 3-Occasionally, 4-Often, 5-Always).

[1] How often would you talk on your cell phone?

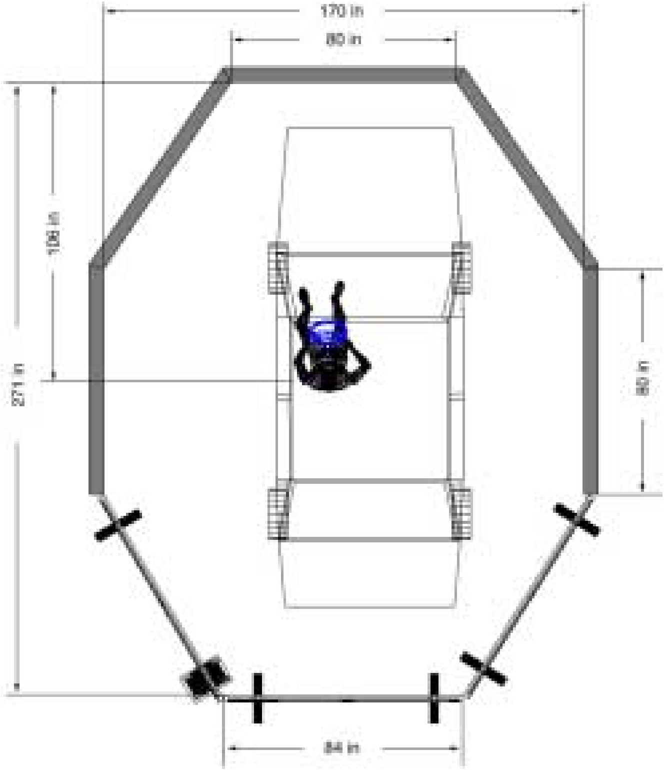
[2] How often would you drive 5-15 mph over the speed limit?

[3] How often would you run a red light to get to an important appointment sooner?

[4] The steering of the driving simulator allowed me to make maneuvers correctly.

[5] I felt nauseous in the driving simulator.

APPENDIX B. BECKMAN INSTITUTE DRIVING SIMULATOR (BIDS)



APPENDIX C. SIMULATOR SICKNESS PRE-SCREEN QUESTIONNAIRE

This study will require you to drive in a driving simulator. In the past, some participants have felt uneasy after participating in studies using the simulator. To help identify people who might be prone to this feeling, we would like to ask the following questions.

1. Do you or have you had a history of migraine headaches?

   If yes, please describe:

2. Do you or have you had a history of claustrophobia?

   If yes, please describe:

3. Do you or have you had a history of motion sickness?

   If yes, please describe:

4. <If participant is female> Are you or is there a possibility that you might be pregnant?
5. Any health problems that affect driving?
6. Lingering effects from stroke, tumor, head trauma, infection?
7. Suffer from epileptic seizures?
8. Any inner ear problems, dizziness, vertigo, or balance problems?
9. Are you currently taking any medications?

   If yes, please list:

APPENDIX D. INFORMED CONSENT FORM

Multiple Resource Modeling of the Impact of In-Vehicle Technology on Driver Workload

Research supported by the General Motors Corporation

Principal Investigator: Dr. Christopher Wickens
Institute of Aviation
Aviation Human Factors Division
Willard Airport
#1 Airport Road
Savoy, IL 61874

The purpose of this experiment is to provide data on the sources of in-vehicle distraction. That is, we wish to determine the extent to which in-vehicle technology, such as cell phones, electronic map displays, or e-mail displays diverts the driver's gaze away from the highway. We also wish to establish the extent to which auditory presentation of some of this information, or presentation on a head-up display, can reduce the distracting effects of such technology, or may actually, increase those distractions.

To examine these issues, you will be asked to drive our Saturn driving simulator while performing other side tasks about which you will be instructed. You should drive as you normally would on the highway. On some occasions, we may ask you to wear a small camera attached by a band around your head which can record the direction of your gaze. You will report to room B500 Beckman for the experiments. Depending on the particular experiment, it will last from 1-3 - one hour sessions.

Eye movements are monitored by a device that reflects infrared light off of the lens and the cornea of the eye. The lens, cornea and other parts of the eye absorb a small amount of energy from the infrared light, but the energy is less than 1% of the Maximum Permissible Exposure level as certified by the American Standards Institute (ANSI Z 136.1-1973). This is about as much energy as you get on a bright sunny day.

There are no known risks or physical discomforts associated with this experiment beyond those of ordinary life, and the possibility that the simulation might cause some mild motion sickness. If it does so, please tell the experimenter. You will be paid at the rate of $6/hr. You may terminate your participation at any time, and you will still be paid for the number of hours that you have completed.

We thank you for your involvement. If you have any further questions, please let the experimenter know at any time throughout the experiment, or call Dr. Wickens at 244-8617. If you have any questions about the rights of research subjects, please contact the University Institutional Review Board at 217/333-2670.

Statement of Consent

I acknowledge that my participation in this experiment is entirely voluntary and that I am free to withdraw at any time. I have been informed of the general scientific purposes of this experiment and I know that I will be compensated at a rate of $6.00/hour for my participation. If I withdraw from the experiment before its termination, I will receive my total fee earned to that time. I understand that my data will be maintained in confidence, and that I may have a copy of this consent form.

Signature of **participant**: ______________________________ Date :___________

Signature of **experimenter**: _____________________________ Date: __________

APPENDIX E. EXPERIMENTAL PROTOCOL

Begin with informed consent form, sim sickness questionnaire, and test for visual acuity.

Minimum visual functioning: acuity 20/30.

Today you will be driving through six different scenarios. Each drive lasts roughly 5 to 6 minutes and will consist of highly curved, hilly rural roads in good visibility (low fog) or poor visibility (high fog) conditions. During each scenario, you will be asked to maintain safe vehicle control while completing a secondary digit task (which will be described in a moment). There will also be a shorter (2 minute) scenario in which you will not be required to drive. You will be given a chance to rest between each of the drives.

Seat participant in simulator vehicle, adjust seat to suit size and preference. Ensure that they can reach both pedals, and can clearly see the in-vehicle display and the adjacent HUD position.

During each drive, you will have complete control over the simulator vehicle. We ask that you **obey traffic laws and respond to traffic events as you normally would**. Specifically, we ask that you observe the following (*emphasize these points*):

-On these rural roads, the speed limit is 55 mph. We ask that you try to stay as close to this value as you can. If you deviate too much, you will be notified.

-In addition, we ask that you try to keep your vehicle **positioned in the very center** of your lane.

Do you have any questions about these requirements?

I'd like to give you a quick practice drive so you can get a feel for the accelerator, brake, and steering dynamics of the vehicle. **People often report symptoms of motion sickness while driving in the simulator. If you experience this, please report so. It may be the case that you will not be able to complete this experiment.**

Start Practice trial.

Tasks for Practice:

1. Try both the accelerator and brake pedal.
2. (In rural setting), accelerate this vehicle to 55 mph and maintain this speed. Note the sound of the engine and the visual flow at this speed.

Do you feel comfortable and in control of the vehicle?

(Repeat practice session if deemed necessary. If participant experiences motion sickness and is not able or does not wish to go on, thank them kindly and remunerate them for their time.)

Now I would like to describe your tasks for the remainder of this experiment. As I mentioned before, you will be doing a secondary task during your drives. This task is relatively straightforward: you will read strings of number digits out-loud. These number strings will be 10-digits long and will appear in one of two places: superimposed on the road right above the hood of your vehicle or on this display located down near your center console. **You will always know beforehand how these digits will be presented** (it will be constant for each given scenario).

When the numbers are presented, you will be required to read the numbers back. **As soon as you notice the digits you should try to respond to them as quickly as you can. As soon as you start to respond, you will press one of these buttons a single time (*Show use of button*).** When finished reading them back, you will hit the button again. This second button press will make the digits disappear.

So the sequence is: digits appear, button is pushed once; digits are read or recalled quickly (e.g., "4-5-7-6-5-4-2-4-5-6"); button is push once again.

The number digits will appear every 1 to 4 seconds.

Do you have any questions about this secondary task?

You should try your best to do this secondary task quickly but you should make sure that it **does not compromise safety** or safe vehicle control.

General directions (adjust according to particular block):

At certain points during the drive the simulator will warp to a new location, and start new type of display (or no display). You will be warned when this will happen and you need only follow the instructions on screen. There are three drives within each block, after which a new one will be loaded and you can rest. *Specify fog or no!!*

(*For the secondary baseline trial*), during this trial you will continue to sit in the vehicle however, you will not be required to drive anywhere. Your sole task will be to complete the secondary task. You will input your responses in the same manner as before (i.e., through button pushes). This block will last roughly 5 minutes.

You will be offered a short rest break after each of the blocks. Please report any symptoms of motion sickness.

APPENDIX F. EXPERIMENTAL ORDERS

	Block Order						
Subject	1	2	3	4	5	6	7
1	A1	B1	C1	A2	B2	C2	D
2	C2	A2	B2	D	B1	C1	A1
3	D	B1	C1	A1	C2	A2	B2
4	D	A2	B2	C2	A1	B1	C1
5	C1	A1	B1	D	B2	C2	A2
6	B2	C2	A2	C1	A1	B1	D
7	A1	B1	C1	A2	B2	C2	D
8	C2	A2	B2	D	B1	C1	A1
9	D	B1	C1	A1	C2	A2	B2
10	D	A2	B2	C2	A1	B1	C1
11	C1	A1	B1	D	B2	C2	A2
12	B2	C2	A2	C1	A1	B1	D

Note:
A=Adjacent HUD
B=HDD Console
C=Baseline (No 2nd Task)
D=2nd Task Baseline (No Drive)
1=High Visibility (Low Fog)
2=Low Visibility (High Fog)

APPENDIX G. VISUAL DISPLAYS AND ANGULAR SIZE OF DIGIT STRING

	Adjacent HUD		HDD Console	
	Height	Width	Height	Width
10-digit string	0.7	8	1	9.8

Note: Units are expressed in degrees of visual angle subtended by digit strings from average driver eye point.

APPENDIX H. NASA TASK LOAD INDEX: WORKLOAD RATING SCALE

<u>Adjacent Display (Head-up): Low Fog</u>

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

<u>Console Display (Head-down): Low Fog</u>

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

<u>No Display (Baseline): Low Fog</u>

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

Adjacent Display (Head-up): High Fog

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

Console Display (Head-down): High Fog

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

No Display (Baseline): High Fog

Mental Demand Low____High

Physical Demand Low____High

Time Pressure Low____High

Own Performance Poor____Good

Frustration Level Low____High

Mental Effort Low____High

APPENDIX I. POST-EXPERIMENTAL QUESTIONNAIRE

Age: _________ Gender: _________ Glasses or contacts? _______

1. Do you have a valid Driver's License? Yes No

2. How many years have you had a Driver's License? ________________

3. About how many miles per year do you drive? _______ miles / year

4. How many moving violations have you had in the last two years? ______________

5. Have you had any accidents where you were responsible?

Yes No

Use the following scale to respond to questions 4 through 7.

1	**2**	**3**	**4**	**5**
Never	1-2 times per month	3-4 times per month	3-4 times per week	Everyday

6. How often do you drive?	1	2	3	4	5
7. How often do you drive on city streets?	1	2	3	4	5
8. How often do you drive on rural / country roads?	1	2	3	4	5
9. How often do you drive on freeways?	1	2	3	4	5

Use the following scale to respond to questions 10 through 17.

1	**2**	**3**	**4**	**5**
Never	Rarely	Occasionally	Often	Always

If you were in a hurry to get to an important appointment how often would you (remember there are no right or wrong answers):

10. Run a red light to get to the appointment sooner	1	2	3	4	5
11. Drive at 5-15 mph over the speed limit	1	2	3	4	5
12. Drive around lowered gates at a railway crossing	1	2	3	4	5
13. Speed in a school zone on a Saturday	1	2	3	4	5
14. Do a rolling stop through a stop sign (i.e., not a complete stop)	1	2	3	4	5
15. Tailgate other people to get them to drive faster	1	2	3	4	5
16. Get angry at other drivers for being in your way	1	2	3	4	5
17. Talk on the cellular phone	1	2	3	4	5

Use the following scale to respond to questions 18 through 21.

1	2	3	4	5
Never	Rarely	Occasionally	Often	Always

18. I felt nauseous in the driving simulator.	1	2	3	4	5
19. The driving simulator allowed me to brake appropriately.	1	2	3	4	5
20. The gas pedal and brake in the simulator allowed me to adequately control my speed.	1	2	3	4	5
21. The steering of the driving simulator allowed me to make maneuvers correctly.	1	2	3	4	5

Thank you very much for your time and effort!