Driving and Side Task Performance: The Effects of Display Clutter, Separation, and Modality

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ABSTRACT

New in-vehicle and telematic devices may create additional tasks that drivers will perform while driving. To the extent that these devices degrade driving performance there will be serious safety concerns. The current study examines the effects of display clutter from overlay, display separation and modality on vehicle control and hazard detection as well as performance on a concurrent in-vehicle task. Twenty-five drivers in a fixed-base wrap-around simulator drove urban and rural routes while engaging in a secondary phone number read-back task presented by different displays. Visual displays were located either overlaid on the visual horizon, in an adjacent location just above the vehicle hood, or on a head-down display located near the mid-console. Alternatively, digits were present auditorily. In general, the results did not show any display differences for measures of vehicle control, even across more difficult road types and side task loads, suggesting that drivers were protecting the primary driving task in these conditions. The lack of an increased costs associated with the head-down display suggests that drivers are able to use ambient (e.g., peripheral) visual resources to maintain vehicle control. There were also no differences between overlay, adjacent, and auditory display for responses to critical traffic events, though there were some non-significant advantages for adjacent relative to overlay for responses to the first, truly unexpected event. There were also costs associated with the spatially separated head-down display, suggesting that effective hazard detection requires more focal visual resources. It was also shown that there were dual-task costs for vehicle control compared to single-task driving conditions, however there were no added costs for the detection of road hazards in dual-task conditions. Performance on the side task was equivalent for overlay and adjacent displays, while drivers with the head-down display took longer to initiate the side task and took longer to complete it. The auditory display yielded faster side task response times but longer completion times. Overall, the adjacent display best supported performance on all relevant tasks. The findings are discussed in terms of models of visual attention and multiple resources.
INTRODUCTION

The driving environment is rapidly becoming more complex and more demanding, as automobile manufacturers move towards the infusion of new telematic devices and technology into their production vehicles. Even the most conservative predictions estimate that the telematics industry will grow exponentially to $13 billion by 2010, however could reach as high as $100 billion pending customer demand and government-imposed regulations (Ashley, 2001). Cell phones, in particular, have received a considerable amount of press in recent years as well as an extensive treatment in the research literature (e.g., Strayer & Johnston, 2001; Haigney & Westerman, 2001; Hancock, Lesch, & Simmons, in press; Parkes & Hooijmeijer, 2001). Although there are currently more than 135 million cell phone users in the U.S. alone (CTIA, 2002), these devices are only part of the current flood of telematic devices which will find their way into future automobiles, including integrated communications systems and other wireless applications and platforms (Kalellis, 2000). As motorists demand more and more in-vehicle services, from email and internet access to entertainment to navigation support, the issues of driver distraction and dual-task performance become increasingly relevant to highway and traffic safety.

One major concern is the potentially high visual component of the interaction with telematics. Depending on the nature of the information being accessed, the driver may be required to scan frequently from the outside world to the in-vehicle device. As drivers spend more time with their eyes focused inside the vehicle, they will be less likely to detect and respond to other traffic elements. In recognizing the potential for drivers to interact inappropriately with telematic devices, a federally funded standard (SAE J2365) was developed by the Society for Automotive Engineers (SAE), which recommends a maximum of 15-seconds allowed for interacting with driver information systems while the vehicle is stationary (Green, 1999). Although this standard was developed for navigation-related tasks, it may be equally valid for other in-vehicle tasks such as internet, email, and other Intelligent Transportation System (ITS) applications. However, even with positive implementation of this standard and appropriate behavior on the part of drivers (which is highly unlikely), actual interaction with in-vehicle devices—in a dynamic and rapidly changing traffic environment—may be too long or untimely, especially when considering safety critical events, which could easily arise within a short time span. As such, the costs associated with accessing information from in-vehicle displays and devices are of critical concern.

As more telematics find their way into today’s automobiles, drivers’ abilities to perform multiple tasks is of heightened importance; specifically, the information access costs of performing secondary in-vehicle tasks. These costs, as they relate to display location (relative to the outside world) and the presentation modality (visual or auditory), and their impact on driver safety and performance provide the framework for the present research.
Visual Information Access and Driving

The primary task of driving is typically broken down into three subtasks: vehicle control, hazard awareness, and navigation (Dewar, Olson, & Alexander, 2002; Wickens, Gordon, & Liu, 1998). An additional task may be considered the communication of intent to other drivers (e.g., turn signals). Control involves the driver’s interaction with the vehicle in terms of speed, direction of travel, and position on the roadway. Hazard awareness refers to the maintenance of a safe path. This is accomplished through the detection, identification, and execution of appropriate responses to other objects in the environment (e.g., other vehicles, pedestrians) as well as the adherence to various regulatory and warning signs and other prevailing conditions (e.g., road characteristics or geometry). The higher order task of navigation involves the selection, planning, and execution of a particular trip. Each of these tasks may involve quite different forms of information, from route indicators to dynamic and changing gap sizes and vehicle separation in traffic to the relative location of the shoulder line.

The performance of these tasks depends on a number of mechanisms—resource demand, task structure, and attention switching and allocation—all of which will influence the effectiveness of time-sharing for multiple tasks (Wickens & Hollands, 2000). In general, task performance requires a certain amount of mental resources in order to complete or meet the task demands (Kahneman, 1973). The term ‘resources’ carries the connotation that they are both limited in nature and can be allocated to different tasks (Wickens, 2002). The overall limit or capacity of available resources may be determined in part by arousal and mental workload. In contrast, the amount of resources required or allocated for a given task will depend on task difficulty and the effort invested. As such, highly automatic processes (e.g., walking) or easy tasks (e.g., maintaining vehicle position on a straight roadway) will require fewer resources than more novel or difficult tasks. For very difficult tasks, or for multiple tasks, there may be insufficient resources to accomplish the task (or tasks) and performance will suffer as a consequence, especially if the capacity of available resources is diminished a priori. There have been a number of studies that suggest that mental resources are not derived from a single unitary source, but may in fact involve multiple resources which differ along a number of dimensions (see Wickens, 1980 for a review).

The multiple resource model characterizes tasks along four dimensions—processing stage, perceptual modality, visual channel, and processing codes—and the extent to which concurrent tasks share common resources along each dimension there will be increased task interference (Wickens, 2002; Wickens & Hollands, 2000). For example, to the extent that multiple tasks share common sensory modalities (i.e., visual) will there be degraded performance on one or both of the tasks. That is, two highly demanding visual tasks will compete for visual attention, which often can only be allocated to one place at a time, thereby disrupting task performance. There is, however, an added distinction within the multiple resource model which differentiates between visual channels: focal and ambient (Previc, 1998; 2000). Focal vision, generally referring to the foveal region, is used in tasks requiring discriminating fine details (e.g., reading). Ambient vision, in contrast, utilizes peripheral vision for tasks involving perception of orientation and ego-motion. It is important to note that focal vision is not characterized exclusively by foveal vision, nor is ambient vision characterized exclusively by peripheral vision in this model. The multiple resource model posits that tasks that utilize separate visual channels
may be time-shared more effectively than tasks which tap the same channel. In the driving environment, vehicle control and guidance may be time-shared because they rely (though not exclusively) on separate channels. For example, research has shown that vehicle control can be maintained through the use of the ambient (peripheral) channel and improves with experience (e.g., Summala, Nieminen, & Punto, 1996). Guidance, on the other hand, involves the focal channel to a greater extent in the detection and identification of potential hazards. Hills (1980) estimates that over 90% of driver information is visual so the degree to which visual tasks can be time-shared effectively is an important consideration. However, understanding resource demand and task interference is not sufficient. It is also important to understand how people distribute and allocate their attention to various tasks when confronted with this interference and potential decrement, an issue we now explore.

Wickens (2001) outlines a model of visual attention in which four main factors drive the allocation of attention to particular events and objects in the environment: salience, expectancy, effort, and value (known as the SEEV model). Highly salient objects or events, such as flashing warning lights or loud sounds are more likely to attract or capture one’s attention than are less salient ones. Salience is related to bottom-up (stimulus-driven) processes (Egeth & Yantis, 1997). In contrast, top-down (knowledge-driven) processes guide attention on the basis of expectancy and value. Observers direct their attention to locations or sources where relevant information is expected. For instance, pilots may attend more closely to the outside world during breakout approaches because expect to see the runway. Drivers may attend to a green traffic light because they reason to believe it will change before they reach the intersection. Observers will also tend to allocate their attention to information sources that are relevant to (or have an inherent value in) the tasks or goals at hand. Drivers will attend more to their forward path because intruding objects and obstacles are very relevant to the goal of safe and collision-free driving. Finally, attentional allocation may be modulated by the amount of effort required to shift attention from one information source to another. For instance, observers may be less inclined to attend to an information source that requires them to make a large head movement or follow a series of steps to access the information. The SEEV model is a useful means of conceptualizing how attention may be allocated or directed to various information sources, based on task characteristics and goals as well as observer traits or predispositions. While multiple resource models may predict potential interference between concurrent tasks, the SEEV model may account for the apportioning of decrement across these tasks.

Although multiple resource models suggest that different driving tasks may be time-shared through separate visual channels, in-vehicle tasks, which typically are considered secondary tasks, may introduce increased competition for visual and focal resources. The extent of this competition will, of course, depend on the nature and modality of the information being presented for this secondary task. It is assumed that many of the current and future in-vehicle systems require a certain degree of focal visual attention. Checking the speedometer, verifying the status of the climate controls, and checking a navigation display are all tasks which likely require focused attention. As such, it is important that drivers adopt scanning strategies that will allow them to monitor these different information sources. These scanning strategies, in turn, will be highly influenced and modulated by the different components of the SEEV model. Wierwille (1993) outlined a deterministic model of sampling behavior in which scanning to and from the roadway is regulated by the amount of time required to extract information from an in-
vehicle display. For example, if the display task cannot be completed in 1.5 seconds, the driver will likely glance back to the roadway and continue in this cycle until the task can be accomplished. Although the times described in this model are somewhat arbitrary, research has shown support for the notion that drivers will use a series of shorter glances in order to complete an in-vehicle task (e.g., Gellatly & Kleiss, 2000; Dingus, Antin, Hulse, & Wierwille, 1989). Even though drivers will use scanning strategies to complete in-vehicle tasks, Wierwille and Tijerina (1998) have documented the relationship between increased in-vehicle visual demands and accident occurrence based on frequency-of-use input data and accident statistics. This investigation used existing data on the demands on various in-vehicle tasks (i.e., the time required to complete the task; e.g., checking the speedometer, or adjusting the climate controls) and the frequency with which these tasks are completed. From these values, the investigators established different models for exposure time which were cross-checked against accident statistics. The in-vehicle tasks explored in this analysis, however, were based on then-current systems and not on telematic devices, which could yield a different pattern of interaction and, consequently, accident involvement.

In general, there will be increased performance decrements for concurrent tasks when task difficulty for one, or both tasks is increased (Wickens, 2002). More difficult tasks require more attentional resources and the interference between similar tasks will be more pronounced in such instances. In the driving context, different driving maneuvers such as turning or driving through curves are associated with greater attentional demands than driving on straight-aways (Hancock, Wulf, Thom, & Fassnacht, 1990; Matthews, Sparkes, & Bygrave, 1996). As such, these road conditions have an impact on the performance of in-vehicle tasks. Tsimhoni & Green (2001) found that decreased curve radius was associated with decreased glance duration to an in-vehicle navigation task and longer gaps between glances, though only slightly increased time to complete the task. Furthermore, increases in the difficulty of the in-vehicle task may have an impact on performance of the driving task if the driver fails to adequately “protect” the driving tasks as the primary task. The model by Wierwille (1993) posits that visual scanning to in-vehicle displays will be determined by the difficulty of the in-vehicle task (in terms of the time required for the interaction). As more glances are required to complete a task, there will be a decrease in time spent with “eyes-on-the-road”, however this does not necessarily translate to degraded performance on the driving task per se, rather it highlights the importance of an optimal attentional allocation policy based on the prevailing traffic conditions.

Thus, the visual nature of the driving environment demands a certain degree of time-sharing between different sources of visual information. Time-sharing will be more successful for tasks that use separate visual channels (Wickens, 2002), however for those that require similar channels, success will depend on an appropriate scan strategy to access both sources of information in a safe and timely fashion (Wierwille, 1993). There are several factors which will influence the likelihood of attending to a given source of information, including salience, expectancy, effort, and value (Wickens, 2001). Presumably, future in-vehicle tasks will involve some form of displayed information which will be accessed by the driver at various times. One important factor in determining the interference between the driving tasks and the secondary in-vehicle tasks is the spatial separation between the relevant sources of information, a concept related to the information access costs of a given information display.
Information Access Costs

Information access costs relate to the amount of cognitive or physical effort required to obtain information from a given display or source. Spatial separation is one important component of access costs. A secondary display located relatively close to a primary one will have much lower information access costs than one that is located further away either because scanning may not be necessary at all, or because the scans (saccades) may be short. In contrast, sources of information that are superimposed (i.e., spatial separation of 0°) may introduce qualitatively different information access costs pertaining to display clutter rather than scan costs. Wickens (1992) describes a model of information access costs and display separation. Costs, in this model, were characterized by a non-linear function based on eye movements and head movements of increasing magnitude. As shown in Figure 1, at small degrees of separation there are relatively low access costs which are stable within a no-scan region. This region is characterized by displays which can be accessed within a single eye fixation and the size of this region will depend on a number of display characteristics (e.g., text size or acuity demands) as well as individual differences (e.g., useful field of view; Ball, Roenker, & Bruni, 1990). When information can no longer be accessed in a single fixation, eye movements will be required. The costs associated with increased scanning within the eye field are relatively small due to the ballistic nature of eye movements (Wickens, Vincow, Schopper, & Lincoln, 1997), though these costs will be amplified in a cluttered display field (i.e., with intervening objects between the displays; Wickens, 1992). The eye field extends to about 20 or 25° of separation, though Bahill, Alder, and Stark (1975) note that most naturally occurring eye movements are less than 15° in magnitude.

As spatial separation increases beyond 20°, head movements become progressively more involved in the access of visual information (Previc, 1998; 2000) and the costs associated with these head movements increase with spatial separation. According to the SEEV model, increased spatial separation will increase the effort required to access information from a distance source (Wickens, 2001). Effort, in this case, may reduce the likelihood of scanning to and from the information source, hence decreasing resolution for the currently-unattended task or rendering its information altogether unavailable. Higher separation will also decrease the overall salience of discrete events occurring in the periphery. As such, normally salient events, such as a pedestrian stepping out from behind a van, may fail to capture the driver’s attention because their attention is currently diverted to highly separated information display.

There have been several studies which support the information access function depicted in Figure 1. Early work by Sanders (1970) and Sanders and Houtmans (1985) found evidence of these separate fields for information access. However, these studies used a discrete dot judgment paradigm rather than a continuous tracking task. Later work by Schons and Wickens (1993) and Martin-Emerson and Wickens (1992) offered further support for this function in more complicated aviation tasks. These studies will be reviewed in later sections.
A final consideration for display separation is when visual information is spatially superimposed (i.e., spatial separation of 0°). In real-world settings this overlay may be accomplished through the use of head-up displays (HUD). A HUD is a device that uses specialized optics to present information on the forward field of view of a driver or pilot (Gish & Staplin, 1995). Overlaying information may help mitigate the effort of scanning between multiple displays (by eliminating the spatial separation of the displays), increase the likelihood of

Figure 1. Information access costs as a function of visual display separation. Top: representation of an open field. Bottom: access function in a cluttered display field. The uncertainty of the break point is related to individual and task-related differences in the UFOV (from Wickens, 1992).
detecting critical events in either display, and enhance the use of peripheral vision for one or both of the tasks. However, when information is superimposed in a HUD these benefits may be offset by the increased clutter in the visual field and the need to switch attention from one display to the other in the absence of any eye or head movements. When displays are separated, there are three strong cues associated with attention shifts from one to the other: lens focal adjustment, ocular vergence adjustment, and gaze shifting via head and eye movements (Weintraub & Ensing, 1992). The absence of these cues in head-up and overlay conditions may contribute to the impaired ability to switch attention effectively, a condition known as attentional (or cognitive) capture (Gish & Staplin, 1995; Tufano, 1997). The information access costs associated with clutter and overlay, especially in conjunction with unexpected events, will be addressed first, followed by a review of the costs associated with display separation.

**Clutter and Overlay**

A series of studies in the aviation domain have examined the effects of HUDs and information superimposition on various aspects of flight. In general, these studies involve comparisons of HUDs and head-down displays (HDD)—a display separation issue—however, are considered separately because they involve true superimposition of information (i.e., 0° separation). Therefore, we expect that the costs and benefits associated with each display format to have very different theoretical underpinnings than spatially separated display alone.

In a meta-analysis of the HUD literature, Fadden, Wickens, and Ververs (2000) examined the costs and benefits of HUDs compared to head-down presentation of equivalent information. Twenty-two experiments were included in this analysis that measured tracking and/or detection performance while using one of the display locations (many of which are reported here). The majority was in the context of aviation, though ground vehicles were represented in four of the studies. The results supported an overall advantage for HUDs for both primary tracking performance as well as event detection though this advantage is offset when the data are further reduced. In particular, the HUD benefit demonstrated during cruise and taxi operations is reversed during landing, again suggesting that HUD benefits may be moderated by high levels of workload. Another factor in the meta-analysis was event expectancy. HUD benefits were consistent when an event was expected (e.g., runway acquisition following cloud breakout), however there were HUD costs associated with unexpected events (e.g., runway incursion during approach) compared to baseline HDD conditions. The importance of the costs associated with unexpected events cannot be underscored, for it is such events that often pose the greatest threat to safety (Wickens, 2001). The traffic environment is highly diverse and unpredictable and critical events, which often are unexpected (or at least temporally uncertain) tend to be the norm but not the exception.

A series of studies (many of which are included in the meta-analysis by Fadden, et al, 2000) have demonstrated the benefits of HUDs on primary flight path tracking and airspeed monitoring, however have also examined discrete event expectancy. For example, Larish and Wickens (1991) investigated the impact of display location on the response to expected and unexpected events. Pilots flew with either a HUD or a HDD (10.7° below external scene image). The expected task involved the detection of warning signals presented throughout the flight. Unexpected events (strong wind shear and runway incursion) were each presented a single time.
For expected events, there was a HUD advantage for response times in both low and high workload conditions. However, in conditions of high workload, response times were 7 seconds longer to unexpected events for the HUD compared to the head-down condition. In a replication of this study however, Wickens, Martin-Emerson, and Larish (1993) found no difference in response to unexpected event across display condition, nor did Martin-Emerson & Wickens (1997) in a similar investigation. It should be noted that in these two studies, the investigators also failed to replicate the HUD benefits that have been observed for the expected events. In an examination of conformal and non-conformal HUDs, Wickens and Long (1995) found costs associated with head-up symbology in responses to unexpected runway incursions compared to HDDs. Another study by Fadden, Ververs, and Wickens (2001) showed evidence of delayed responses to critical, yet unexpected events (e.g., wind shear; taxiway traffic incursion) when using HUD symbology compared to HDD presentation, while the effects were reversed for expected events (e.g., runway detection). Other researchers have also associated head-up display clutter with slowed (or missed) responses to unexpected, critical events (Fischer, 1979; Fischer, Haines, & Price, 1980; Larish & Wickens, 1991).

Although the findings for event expectancy appear to be mixed in some of the reported studies, the meta-analysis by Fadden, et al. (2000) clearly indicates that expectancy is an important factor in modulating the costs and benefits of HUDs, with the head-up performance benefits in detecting expected events disappearing or even reversing for events that are unexpected. Part of the difficulty in examining such events (and indeed, the cause of the mixed results noted above) is the relatively low statistical power involved in these comparisons. Truly unexpected, surprise events must occur a single time per research participant rather than the repetitive target presentations that are typical of research methodologies. However, Hofer, Braune, Boucek, and Pfaff (2000) showed that previous knowledge of the types of events that could occur was not sufficient to counteract degraded responses to these events using a HUD. Pilots were instructed beforehand to monitor and indicate potential real-world events (e.g., traffic incursion) as well as certain display events (e.g., offset imagery), though they were not informed as to the nature of the events. Overall, HUDs were associated with a higher proportion of missed events than was the HDD. Furthermore, HUDs accounted for all of the missed events in accident-likely situations. These findings suggest that HUD decrements may hold for events which are temporally uncertain, in addition to those that are entirely unexpected.

There have also been some notable studies on information overlay outside the aviation domain. Neisser & Becklen (1975) and Becklen & Cervone (1983) used a novel research paradigm to examine clutter in its most extreme conditions (and more recently, Simons & Chabris, 1999). In this paradigm, participants viewed two videos which were optically superimposed. When instructed to do so, participants were capable of monitoring one of the action sequences while ignoring the other. However, they very rarely were able to detect very odd and salient events in the unattended channel (e.g., a gorilla walking through the middle of a basketball game). This research suggests that, even though the displays occupy the same visual space, they are not necessarily processed in parallel. Hence, attentional switching from one display domain to the other is necessary when information is superimposed. The difficulties associated with this attention shift likely contribute to the missed events expressed in these studies as well as with those noted in the aviation studies described above.
Using a basic manual-tracking paradigm, Wickens, Dixon, and Seppelt (2002a) examined the effects of visual display separation on dual-task performance. Participants performed a multi-axis compensatory tracking task in one portion of a display monitor while monitoring for and completing a digit shadowing task presented at various eccentricities, including a superimposed (0°) condition. The digit task consisted of reading back strings of four, seven, or ten digits (corresponding to phone numbers of various lengths). The results showed increased response duration (i.e., speech time) when the secondary digit task was superimposed on the tracking task compared to an adjacent presentation (7° offset), suggesting that performance suffered due to clutter effects. There was also a decrease in tracking inputs and increased error during the response interval, which could indicate that participants altered their tracking strategies in order to make the superimposed text more legible. While this research did reveal some dual-task costs associated with display overlay, there were no discrete (or unexpected) events which may have amplified the relative costs of clutter and superimposition.

The important issues of display overlay and clutter may be of heightened importance in the driving context because the outside world in this domain will remain the primary source of critical information for the driver (Gish & Staplin, 1995). Furthermore, the spatial constraints and timing of certain traffic events may be less forgiving than in the aviation domain. The costs of clutter must therefore be minimized in order to ensure effective and timely extraction of relevant information. Stokes, Wickens, & Kite (1990) also highlight the importance of the changing visual background for surface vehicles, compared to aircraft, for display clutter. As such, the tradeoff between visual scanning and display clutter is an important one that needs be examined within the same paradigm.

To date, HUDs have been widely applied in the aviation domain but have enjoyed only limited exploration in the automotive domain. The nature of the information presented in a HUD ranges from telltale status indicators (e.g., speedometer; brake and oil lights) to conformal and non-conformal displays of the outside world (e.g., vision enhancement systems) but may also encompass any number of in-vehicle tasks requiring the presentation of visual information. Another important distinction is that the head-up presentation of information in automobiles is not typically superimposed over relevant outside world information (hence, its exclusion from the current “clutter” discussion). Rather, automobile HUDs often present information superimposed on the roadway just above the hood of the vehicle—a location where critical, driving-related information would be unlikely. As such, these studies will be reviewed in terms of the information access costs associated with display separation.

Visual Display Separation

Information access costs in display separation may be expressed as an increased reluctance to invest the effort to scan to widely spaced displays, increased time required to make such scans, or decreased salience of and, consequently, degraded responses to discrete events occurring in the peripheral display. These costs are reflected in the review of the literature, which encompasses research from multiple domains.

Schons and Wickens (1993) examined spatial separation for a visual course deviation indicator displays. Pilots in this study flew a number of approaches with this display positioned
at different eccentricities, ranging from 0° to 37.5° from the primary attitude indicator. The primary tasks were flight path tracking and airspeed tracking. Increasing spatial separation of displays did increase tracking error on the primary tasks because of the increased effort and scanning costs associated with larger display separations. The findings also offered some evidence to support the eye-field theory, with discontinuities in performance on some measures occurring near the 17° eccentricity, suggesting that this may be the transition from the no-scan region to the eye field (see Figure 1; Wickens, 1992; Sanders, 1970). Similarly, Martin-Emerson and Wickens (1992) examined the effects of varying angles of visual separation of information on dual-task performance. Participants performed a compensatory tracking task while monitoring for a target presented at various angles of separation. These angles ranged from 0° (superimposed) to 35° down. In addition, workload was manipulated by varying the control input bandwidth. As the visual angle increased, so did the response time to the target. Further reduction of the data showed that information access costs did not increase significantly from 9.6° to 22.5° of separation, or from 0° to 6.3°. These findings could lend support to the near ballistic nature of eye movements within the eye field, with increased saccade length imposing only slightly augmented access costs (Wickens, 1992).

In the study described in the discussion on display clutter, Wickens, et al. (2002a) also displaced the secondary digit tasks at various vertical and horizontal eccentricities (either 7 or 15° below the central task; or 7, 15, 32.5, or 46° to the right of the central task). The separation analyses were divided into two categories, one examining near separation assessing scanning costs within the eye field (Previc, 1998), and one examining the far separation outside the eye field. First, response times to the 15° offsets were slightly albeit significantly longer (0.10 s) than for 7° offsets. This cost was presumed to be a result of the increased time to notice the onset of the target digits at larger eccentricity. There were no effects on tracking performance during the response time interval. Again, this suggests that the time costs were associated with noticing the appearance of the secondary task. During the response interval (i.e., during the verbal response), however, there was increased tracking error at the wider eccentricities, an effect the authors attributed to degraded peripheral vision for the tracking task. Tracking error during this interval showed support for the general non-linear function of information access costs depicted in Figure 1 (Wickens, 1992). Side task response duration was longer at the wider eccentricity for the longer digit strings (increased side task load), suggesting participants required more glances to the digits to complete the more difficult secondary tasks (as demonstrated by other studies; e.g., Tsimhoni & Green, 2001; Gellatly & Kleiss, 2000). For the far separation, the findings were less clear for the effects on tracking performance. However as was the case for near separation, there were longer response times and response durations for the more eccentric targets. This research does show support for increased information access costs with display separation. The findings suggest that the costs are partly due to the increased time it takes to notice the onset of the secondary task. Participants may not have monitored the distant information channels as closely as the near ones because of the effort involved in switching back and forth from the display (Wickens, 2001). As noted previously, this study did not assess the impact of display location and information overlay on the detection and response to discrete primary task events, which is often touted as an important consideration in such display presentations.

In another study, Caird and Chugh (1997) examined the impact of display location on participants’ ability to respond to a surprise target while engaged in a manual-tracking task and
secondary display task. In addition, they explored the critical event onset by manipulating the timing of the target event relative to the start of a display task (+100, +250, +1000 ms). Sixteen older participants completed a two-axis tracking task (keeping a target vehicle centered in a particular region) while performing a visual search or verbal memory task and monitoring for the appearance of a pedestrian. The head-up task appeared $4^\circ$ below the participants’ line of sight and the head-down task appeared $15^\circ$ below. The visual search task had participants determine whether one line in a group of eight was shorter than the rest. The verbal memory task, in contrast, had participants indicate whether any of three visually displayed probe letters matched a previously memorized set (of four letters). The presence of the HUD and HDD task increased response times to the sudden pedestrian appearance compared to baseline conditions (by 831 ms and 803 ms, respectively). Results demonstrated that the dual-task interference created by the display task followed different time courses for head-up versus head-down presentation. Response to the pedestrian appearance was slower for the HUD condition when the onset of the target came 100 or 250 ms after the task onset. When the target appeared 1000 ms after the task onset, performance was worse for the HDD condition. This finding can be explained by the increased time costs of making an eye movement to access the information presented in the head-down condition. Because of these costs, we can expect that the time course for the different displays would be different and hence, responses to critical events would be more impaired later in the time course for more distant displays (i.e., after the eyes have moved). Performance on the tracking task during the concurrent secondary task was not reported in the current report.

Research in the driving domain has produced a number of studies comparing head-up and head-down performance on a number of display- and driving-related tasks. For example, Kiefer (1991) examined visual sampling of drivers using head-up and head-down speedometers. The HUD was located in a central location, $6^\circ$ below the horizon while the head-down speedometer was located in the conventional dashboard display (separation angle not reported). Sampling behavior was observed in terms of the speedometer scanning cycle (SSC; time to move eyes from the roadway to the speedometer and back again). Overall, the head-up display yielded a shorter mean SSC time than the head-down speedometer (on the order of 150 ms). There was also increased glance frequency and total time in SSC for the head-up speedometer. These differences, however, decreased on successive trials suggesting that there may have been a novelty effect associated with the initial use of a HUD. The author suggests alternatively that this may have also been due to attentional capture by the HUD symbology.

Keifer (1995) re-analyzed some of his earlier reported work (1991) in order to gain a better understanding of the “eyes-on-road” benefit of HUDs. Specifically, he examined the time-course for each of the components of the SSC described above: the transition time from the road to the display, display fixation time, and transition time from the display to road. The results showed a significant time saving for the HUD for road-display and display-road transitions, with marginal improvements for fixation time. The transition time benefits is consistent with the increased information access costs of making eye and head movements, assuming that the head-down location is of great enough eccentricity to require the latter. Okabayashi, Sakata, Fukano, Daidoji, Hashimoto, & Ishikawa (1989) also showed that responses to head-up speedometer information were quicker than head-down presentations of the same information under all driving conditions and speeds (straight, curved; 40–100 kph). In this study, head-up symbology appeared $10^\circ$ left and $8^\circ$ down from the participant’s line of sight, whereas the head-down
display was centered laterally, 20° down from the line of sight. This HUD advantage was larger on straight roads than curved, which could indicate that workload is moderating the benefits of HUD information. Gish and Staplin (1995), in their review of HUD research, suggest that HUD benefits may be reduced or even reversed when workload is increased. While these reported studies demonstrate the time-costs to access information that is presented at larger separations, they do not explore tradeoffs in performance on the primary driving task.

Kiefer (1998) attempted to explore dual-task performance in his examination of the effects HUD speedometer information on driver response times to a pedestrian. In this study, older drivers wore liquid-crystal glasses (to limit their view of the forward scene) and sat in a parked vehicle for the duration of the experiment. The driver’s task was to read vehicle speedometer information followed by a distant speed limit sign. They were further instructed that a pedestrian would appear on some trials and they were required to indicate by a button press when they detected this event. On trials where pedestrians were present, participants were instructed to cease the speedometer task and respond solely to the pedestrian. Head-up presentation of the speedometer was at 4.6° below drivers’ line of sight, whereas head-down presentation was 18.5° below this line. Overall, pedestrian detection speed and accuracy with the HUD was superior to that in the head-down condition, supporting the view that there were smaller information access costs in switching from the display task to the outside world. However, the shutter glasses and static nature of the task did not promote a very realistic driving situation. Furthermore, pedestrians always appeared in the same locations perhaps allowing participants to anticipate their appearance. Indeed, event expectancy has been shown to be an important factor in moderating the benefits of HUD information (e.g., Fadden, et al., 2000).

Kaptein (1994) examined the impact of HUD speedometer presentation on velocity and lateral vehicle control. In this simulator study, drivers drove through a generic driving environment while using a head-up speedometer gauge (presented at 3° below the horizon line) or a conventional dashboard instrument panel (the angle of separation was not reported). The driving task consisted of maintaining a prespecified speed limit without using the brake and to keep the vehicle positioned within its respective lane (made difficult through varying crosswinds). Headwinds also presented a challenge for the velocity control task. Drivers made fewer lane departures while using the HUD than while using the HDD, and had reduced error on the velocity control task, indicating information access costs for the HDD for both the primary (lane keeping) task as well as the secondary (velocity control) task. Kaptein (1994) also did not examine discrete event detection.

Gish, Staplin, Stewart, and Perel (1999) examined automotive head-up displays and their impact on performance on in-vehicle tasks and safety critical roadway events. A HUD was positioned 5° below the driver’s line of sight and presented navigation, speed monitoring, or collision avoidance information, depending on the task being completed. Alternatively, information was presented on a HDD positioned 20° below the line of sight. Participants completed a number of tasks at different times while they viewed videos of driving scenes. First, they received and acted upon navigation information that was presented on the display, indicating whether the upcoming street name appeared in the displayed list and, if present, the appropriate direction to turn. Second, they monitored the vehicle speed, indicating whether it matched the posted speed limit or not. Third, they responded to the presentation of collision
warning information on the display, which was linked to external environmental events only 75% of the time (with 25% of trials being false alarms). Drivers were instructed to brake to road hazards when necessary but to avoid braking to false alarms. Various hazard events were used throughout the study, including pedestrian and vehicle incursions as well as some non-naturalistic events and surprise events. The results showed that the accuracy of brake responses to hazard events (i.e., correct detection) was similar for both head-up and head-down conditions, however the response times did favor the HUD with performance advantages ranging from 95 to 212 ms, depending on age group. Because the near-threshold surprise events were detected so infrequently in both display conditions, conclusive evidence regarding display advantage was lacking. For the in-vehicle navigation task, there did not appear to be any differences in response accuracy between the two display conditions, nor for the speed-monitoring task. However, response times for these in-vehicle events, where display differences may be best expressed, were not measured or reported here. Drivers using the HUD were able to inhibit a braking response more effectively when the collision alert was a false alarm, suggesting that the near proximity of the display to the outside world allowed for more efficient scanning for the presence or absence of a target. This HUD advantage was reversed for the oldest age group; however this reversal was attributed to the fact that older drivers failed to notice many of the head-down warnings. In these cases, their responses were interpreted as being accurate. Overall, this study showed separation costs for the detection of hazards in the outside world as well as costs in responding to erroneous display information (false alarms). As with other studies, however, there was no control (tracking) task, which precludes any time-sharing comparisons for the focal-ambient components of driving.

Sojourner and Antin (1990) examined HUDs and conventional speedometer indicators in conjunction with various tasks in a driving environment. Participants watched videotaped driving scenes while completing a speed-monitoring task, a navigation task, and a target detection task. For the speed-monitoring task, participants were required to indicate deviations from the posted speed limit that were greater than 5 mph. Speedometer information was either presented head-up just above the hood of the vehicle or head-down in the instrument panel. The spatial separation of the two displays was not reported. Concurrently, they monitored the driving route in the video and indicated whenever it deviated from a memorized route. Finally, they needed to detect and respond to a sudden target appearance (a green ball on the roadway) in the center of their lane, to the left, or to the right. This salient event occurred 10 times throughout the drive. Overall, drivers using the HUD missed 3 of the green ball targets, while HDD users missed three times as many. This difference was not significant however. Response times to this target were significantly faster with the HUD (570 ms) compared to the HDD (1010 ms) condition. Furthermore, in the HUD condition 100% of the speed violations were detected compared to 92% in the HDD condition. Both findings offer support for reduced information access costs for more proximal displays. Again however, the repetitive nature of the target detection task may have allowed drivers to anticipate the occurrence of the target stimuli. Unfortunately, the study involved only monitoring tasks, as the participants were passive observers of the driving scenes. It was also unclear whether the presented speed information was coupled to the actual speed in the driving scenes. If it was, then drivers would have a redundant source of information which they could use (as in the real-world) to monitor speed peripherally rather than focally.
In contrast to the research on the head-up display of speedometer information, Grant, Kiefer, Wierwille, and Beyerlein (1995) examined the effects of HUD warning detection and identification. Drivers in an actual vehicle in low-to-moderate traffic situations were required to detect and identify an unexpected red “brake” display icon that would appear in either a head-up or a head-down location. This warning was presented roughly 5° to the right of the head-up speedometer information in the HUD condition, whereas the warning in the head-down condition was presented 13° to the left of the speedometer (the locations of the HUD and the HDD were not specified). The brake warning was selected for its criticality in terms of indicating a brake system malfunction, though it was not clear whether drivers using the system were informed of the meaning (e.g., whether it indicated system failure, parking brake activated, or “brake now!”). This telltale was presented for either 1 second or 10 seconds, though these values were not counterbalanced (the short duration always preceded the long duration). Results showed that drivers using the HUD were more likely to detect the target. Eighty-eight percent of drivers in the head-up condition detected the warning on the first presentation compared to 25% in the head-down condition. Furthermore, the detection of the telltale occurred sooner (in terms of presentation number) with the HUD versus the HDD. In terms of detecting critical information on the secondary display, there are definite costs associated with spatial separation. The warning, however, was not meaningful in this particular driving context (apart from the use of the term “brake”) nor was it coupled to emergency traffic events. In addition, there were no measures of driving performance in conjunction with these secondary display tasks and it is not clear from the procedure whether the drivers were instructed to actively monitor the telltales for warnings.

Srinivasan, Landau, & Jovanis (1995) examined the effects of display location for navigating with in-vehicle route guidance systems. Drivers navigated a simulated route using turn-by-turn instructions which were presented in a HUD (just above the hood of the vehicle; no separation angle was provided) or a HDD location (the head-down location was not clearly defined), while performing a concurrent monitoring task. For this task, drivers monitored colored squares presented near the edge of the roadway and indicated whenever the squares changed to diamond shapes. Response times to this monitoring task were shorter for the head-up turn-by-turn condition compared to the HDD, suggesting a reduced salience of peripheral information associated with larger display separations. There were too few navigation errors over the course of the study to draw any meaningful conclusions for display separation.

There have been a number of other studies investigating automotive HUDs in the context of peripheral detection performance (e.g., Bossi, Ward, & Parkes, 1994; Fukano, Okabayashi, Sakata, & Hatada, 1994; Isomura, Kamiya, & Hamatani, 1993), recognition and reading times (e.g., Iino, Otsuka, & Suzuki, 1988; Inuzuka, Osumi, & Shinkai, 1991). In general, there are HUD or smaller separation benefits for the tasks employed though many of these studies suffer from small sample sizes, single task or unrealistic dual-task conditions, a lack of methodological detail, and / or other issues.

In contrast to these HUD studies, Summala and colleagues have used a unique technique to examine the impact of in-vehicle technology on driving performance. In the “forced peripheral driving” paradigm, drivers are instructed to focus their visual attention in a single location (e.g., on an in-vehicle display), rather than shift their attention back and forth from the display to the roadway, and use their peripheral vision to maintain safe vehicle control. Though this paradigm
does not explicitly investigate the time costs of scanning from one source of information to another, it does permit the exploration of time-sharing for different driving tasks while visual attention is focused in particular spatial locations. Summala, et al. (1996; replicated by Summala, 1998) used this paradigm to examine drivers’ maintenance of lane position while engaged in a secondary, in-vehicle task. Drivers fixated on a secondary task display located in one of three different locations: 7° below the horizon line (on top of the vehicle dash); 23° from the horizon line (beside the conventional speedometer display); and 38° from the horizon (34 cm down and 36 cm to the right, near the mid-console of the vehicle). There were four secondary tasks presented over the course of the drive (either attentional or arithmetic): a digit shadowing task (naming the digit aloud; attention-easy); counting the number of fours presented on the display (attention-difficult); adding a constant three to the number presented (arithmetic-easy); or summing the last two digits presented (arithmetic-difficult). The primary measure for lane keeping was the proportion of the drive distance that a driver could reach before crossing a lane boundary. Results showed that the average distance cleared varied greatly for both experienced and inexperienced drivers for all display conditions and secondary tasks. Lane keeping performance declined with increased display eccentricity however was not affected by secondary task difficulty suggesting that the in-vehicle tasks drew upon different resources than the ambient (peripheral) tracking task. The results also indicated that novice drivers showed greater impairments in lane keeping with smaller display eccentricities (i.e., speedometer location) than did the experienced drivers (who were impaired only at the largest eccentricity), suggesting that experienced drivers were able to use more peripheral information to control their vehicle. The investigators were unable to assess the performance of the secondary task, however they did report the number of missed secondary task items. A non-significant relationship between increased display eccentricity and higher proportion of missed items was found.

Using the same forced-peripheral technique, Summala, Lamble, and Laakso (1998) investigated drivers’ responses to discrete lead vehicle-braking events. The display in this study was position either 16° below the horizon line, 27° below the horizon (beside the speedometer), or 50° from the horizon (near the center console). Again, drivers focused exclusively on the display while following a lead vehicle. Reaction times to the braking lead vehicle increased markedly with increased eccentricities of the secondary-task display. Compared to baseline measures, the low eccentricity condition was 0.9 seconds slower while the medium and high eccentricities were 2.1 and 2.9 seconds slower, respectively. Unlike the lane keeping results reported by Summala, et al. (1996), performance for detection events did not improve with driver experience. Lamble, Laakso, and Summala (1999) conducted a similar study on drivers’ ability to detect the braking of a lead vehicle, however they expanded the number and range of display locations. Drivers were required to monitor an LED display exclusively (without scanning) and indicate whenever the number four appeared. This secondary task appeared in one of nine different offsets (relative to the drivers central line of sight), ranging from 4° to 34° in the vertical direction and 0° to 90° in the horizontal direction. In control conditions, the drivers were instructed to focus on the lead vehicle (0° offset). Results showed that detection times for the lead vehicle braking increased as the eccentricity of the foveal in-car task increased, up to a loss of 2.8 seconds for the largest eccentricity. Costs associated with vertical offsets were higher than for those in the horizontal direction. At 4° below the horizon line (a location consistent with many HUD applications), there was poor detection thresholds, however this may have been due
to non-transparent nature of the LED display. Performance was best (save for the 0° eccentricity) when the display was located on top of the dashboard, 17° to the right of the steering wheel.

The studies by Summala and colleagues demonstrate the relationship between the ambient visual channel and the primary task of vehicle control and also lend support to a multiple resource view of the driving task. Drivers are able to maintain lane position to large degree through peripheral vision alone and this skill develops with experience, however this ability declines as the spatial separation between the in-vehicle display and the roadway increases. The studies also suggest that peripheral vision is not sufficient for the hazard awareness task, with degraded performance in responding to discrete events. Such performance does not improve with experience. As such, in-vehicle tasks that require focal visual attention may permit the driver to maintain proper lane position and control (to a certain degree) using ambient vision but will impair performance on hazard awareness tasks requiring common focal resources. While these studies reliably demonstrate focal-ambient visual channel interference and the effects of spatial separation, the “forced peripheral driving” paradigm does not adequately capture how visual attention will actually be deployed when interacting with in-vehicle technology. For instance, drivers were instructed to focus solely on the display rather than shift their attention back and forth from the display to the road, as may be the case in real-world interactions. Furthermore, the tasks did not appear to be overly difficult, perhaps allowing drivers to attend more to the peripheral information than may be the case with more complex and comprehensive in-vehicle tasks. They also did not examine performance tradeoffs for the two tasks by assessing secondary task performance.

In general, research on visual spatial separation in automobiles yields positive benefits for HUDs and reduced display separation, in terms of accessing information presented in the display. In many cases, the studies failed to create dual-task situations or failed to assess performance on concurrent tasks. The dual-task paradigms often did not employ a continuous tracking task, but rather had drivers passively view driving scenes and complete less realistic monitoring tasks. In addition, responses to discrete events may not have been entirely unexpected, thereby limiting the applicability of the HUD benefits to actual surprise events. Oftentimes, researchers employ only two display locations (head-up versus head-down), with the exception of Summala and colleagues (Summala, et al., 1996; Lamble, et al., 1999) who employed multiple locations. Though the results from these studies were very telling, the forced-viewing protocol employed in this paradigm sufficiently changed the driving task to make generalization to real-world situations difficult.

Auditory Presentation of Secondary Information

An alternative to visual in-vehicle information is an auditory presentation of the relevant information. Such a presentation would alleviate the necessity to scan from one display to another as well as offset the potentially negative effects of display clutter. According to the multiple resource model, tasks involving auditory and visual task stimuli should be time-shared more effectively than tasks involving two visual stimuli because they use different perceptual modalities (Wickens, 2002). Wickens and Liu (1988) review the literature comparing cross-modal (auditory-visual, AV) with intra-modal (visual-visual, VV) information presentation. They
highlight the mechanisms by which benefits or costs could be expressed by one or the other presentation type. In addition to the benefits from use of separate modalities in processing auditory versus visual information noted above, the benefits of auditory presentation should be more pronounced as the spatial separation between the two visual information sources increases (hence, increasing information access costs). However, this effect may be modulated by proximal information sources which tap focal and ambient vision differentially. For instance, a focal display task located near the roadway may allow the driver to use peripheral vision to maintain accurate lane position (Summala, et al., 1996). Third, VV coupling may allow observers to switch their attention from one source to another more effectively. There is some evidence to suggest that switching attention between modalities has greater costs than switches within a modality (e.g., LaBerge, VanGelder, & Yellott, 1971; Spence & Driver, in press). Finally, preemption is an important consideration with the auditory modality because of its alerting characteristics. Under some circumstances, a discrete auditory task may draw attention away from an ongoing, and more important, visual task (onset preemption; Spence & Driver, in press). Wickens, et al. (2002a) note, however, that such preemption may also be strategic in nature. When longer strings of verbal information are presented, the observer may elect to preempt the primary task in order to act upon the auditory information before it is forgotten. Visual information, on the other hand, does not need to be rehearsed because it is generally available for longer durations on a display. Helleburg and Wickens (2002) found evidence of strategic preemption in their investigation of air-traffic controller-pilot communication, in a dual-task (flying while communicating) paradigm. Wickens, Goh, Helleburg, and Talleur (2002b) found that preemption disappeared when auditory messages were shorter in duration, thereby not requiring rehearsal.

There have been a number of studies comparing visual and auditory presentation modalities (see Wickens & Liu, 1988 for a review). The Wickens, et al. (2002a) study reviewed above further examined the effects of visual versus auditory modality. In the auditory condition, four-, seven-, or ten-digit strings were presented a single time to participants engaged in a manual-tracking task. They did not know beforehand the length of the string being presented. In general, response times to the auditory stimulus were faster (a benefit) than for the adjacent (near) visual presentation. The response durations for the auditory condition were longer than for the visual condition presumably because of the interference inherent in the verbal code between the speech response and rehearsal. This is further supported by the fact that this pattern of interference did not manifest itself until the digit strings were or exceeded seven digits in length (i.e., exceeding the capacity of working memory). During the response interval there was an increase in tracking error relative to the visual presentation. However, this finding was reversed as visual spatial separation increased, with greater tracking error for the greater eccentricities compared to auditory performance. The results further suggest that the auditory presentation may have caused onset preemption with respect to tracking task performance, rather than strategic preemption.

While a good deal of research has shown the degradation of driving in the presence of auditory inputs, there have been relatively few which examine cross-modal presentation of the same information. In the study reported above, Gish, et al. (1999) also included an auditory condition for the secondary task presentations in addition to the HUD and HDD conditions. Participants completed a navigation task, a speed-monitoring task, and a collision-warning task.
while engaged in a simulated driving task. Auditory messages matched those presented visually with the exception of the navigation instructions, which were presented one at a time rather than as a list (as in the visual conditions). Brake response accuracy and response times for various external events were superior in the auditory condition compared to both visual displays, suggesting improved time-sharing with the auditory-visual modalities compared to visual-visual. Performance on the navigation task with the auditory display was superior, with fewer incorrect responses, however this may be attributed to the modification of the auditory presentation and the consequent reduction in task load. The auditory display also yielded superior performance in the speed-monitoring task relative to the visual displays despite suffering a larger dual-task performance decrement relative to single task conditions. When a collision false alarm was presented, drivers in the auditory condition were less likely to correctly inhibit their braking response perhaps because of automatic response capture elicited by the auditory stimulus.

Matthews, Sparkes, and Bygrave (1996) examined driving performance in conjunction with a secondary reasoning task, presented either visually or auditorily. Participants engaged in a low-fidelity simulated driving task on a desktop PC consisting of straight and curved stretches of roadway. The reasoning task was a grammatical working memory task where participants had to judge the truthfulness (i.e., respond “true” or “false”) of simple sentences. These sentences were presented either auditorily or as a visual part of the dynamic road environment (i.e., on overhead traffic signs). Response times and accuracy for the reasoning task and vehicle heading error and various headway parameters were recorded for the driving task. The results offered poor support for the modality predictions based on multiple resource theory. No dual-task interference was observed for the visual task, perhaps because drivers were able to use focal visual channels to complete the secondary task and ambient channels to maintain correct heading. The authors, however, did not use the multiple resource distinction of focal-ambient channels in their interpretation of the findings. Auditory presentation was found to impair performance on the driving and reasoning tasks, but only on curved sections of the roadway relative to straight roads, thus supporting the notion that dual-task performance will be sensitive to increased difficulty of one or the other task (Wickens, 2002). There was no comparison of secondary task performance (visual or auditory) in single-task conditions.

Verwey (2000) examined the effects of driver age and driving context on performance of visual and auditory secondary tasks. Drivers drove a route in an instrumented vehicle while doing one of two in-vehicle tasks. The visual task consisted of detecting the presence of a target stimulus presented on a dashboard-mounted display. The auditory task, on the other hand, required participants to add twelve to a digit presented auditorily. It was assumed that both tasks were sensitive to driver workload though it is important to note that the tasks were not the same in both conditions (i.e., detection vs. arithmetic). Drivers were instructed to drive as they normally would and to perform the secondary task when the road conditions allowed. The drives consisted of different densities of traffic, familiar or unfamiliar roads, different roadway velocities, and various road situations (e.g., straight, curves, turn maneuvers). Although the difference in task across modality precluded any meaningful comparisons, it is interesting to note that the results demonstrated large differences in visual secondary task performance across different traffic situations. The effects of road situation on the auditory task, however, were less pronounced suggesting that drivers may be able to allocate more resources to this secondary task across a wider range of visually loaded traffic environments than in the visual condition. These
However, results may be due to different processing requirements of the two tasks, rather than modality differences.

Srinivasan, et al. (1995) included an auditory condition in their examination of route guidance systems, described above in the section on visual separation. Auditory presentation of turn-by-turn navigation instructions consisted of two discrete messages, occurring at various distances from the required turn. Responses to the discrete shape-monitoring tasks were shortest with the auditory display compared to visual display conditions (both HUD and HDD). Again, there were too few navigation errors to make any meaningful comparisons. These findings suggest that the auditory presentation of instructions availed more visual resources for the scanning task and, consequently, resulting in reduced response times to these events.

There has been considerable support for enhanced time-sharing for cross-modal task combinations (Wickens & Liu, 1988) however this benefit is not always consistent across methodologies (as illustrated in some of the research presented above). A number of driving studies yield benefits of auditory-visual task coupling compared to visual-visual coupling for navigation and route guidance information (e.g., Gish, et al., 1999; Labiale, 1990; Liu, 2001; Parkes & Coleman, 1990; Srinivasan, et al., 1995). Other driving researchers have found no difference for cross-modal tasks compared to intra-modal (e.g., Lee, Gore, & Campbell, 1999) or increased costs associated with the cross-modal presentation (e.g., Lee, 1997; Matthews, et al, 1996). Many research endeavors, however, do not examine the optimal placement of visual secondary task information (therefore imposing information access costs associated with display separation) or utilize different visual and auditory tasks which may favor performance for one or the other modality (e.g., Verwey, 2000). Thus, examining multiple visual display locations as well as different modalities for the same task information may provide some important findings.

**Summary & Present Research**

The introduction of new in-vehicle technologies into the automobile creates additional tasks that drivers may perform concurrently. Drivers will need to access information from multiple sources in order to complete these tasks while maintaining safe vehicle control and guidance. The extent to which these multiple tasks compete for similar resources will determine the amount of task-interference and subsequent performance degradation for one, or both tasks (Wickens, 2002).

Information access costs for visual tasks are more pronounced when spatial separation between information sources is increased, especially for tasks that require focal visual attention (Schons & Wickens, 1993; Martin-Emerson & Wickens, 1992). A number of studies have demonstrated benefits of reduced scanning using HUDs compared to head-down presentation of similar information, in terms of tracking performance on a primary task, response to display related information, and response to events in the outside world (e.g., Wickens & Long, 1995; Sojourner & Antin, 1990). These benefits however may be reduced or even reversed in conditions of high workload (Gish & Staplin, 1995) or in response to unexpected events (Fadden, et al., 2000; Tufano, 1997; Weintraub & Ensing, 1992). This degradation may be attributable to the increased visual clutter inherent in the overlay of multiple displays. Other research has shown that safe vehicle control can be reasonably maintained using peripheral vision alone, though this
ability degrades with increased eccentricity (Summala, et al., 1996). Detection of critical events and hazards, however, is seriously impaired when using peripheral vision alone, especially for larger separations (Summala, et al., 1998; Lamble, et al., 1999).

In contrast to visual presentation, information may be presented auditorily. Since visual and auditory information share different perceptual resources, they may be time-shared more efficiently than two visual inputs (Wickens, 2002). Numerous studies have supported this performance advantage (see Wickens & Liu, 1988 for a review). Auditory inputs, however, may preempt performance on a primary task by virtue of its alerting characteristics (Helleburg & Wickens, 2002; Spence & Driver, in press).

Past research on information access costs in the driving context has employed a wide variety of different methodologies, task demands, and performance measures. In general, few have reported performance measures for both a continuous vehicle control task and discrete hazard detection as well as a secondary in-vehicle task, in order to examine performance tradeoffs. Furthermore, few (if any) have examined secondary task performance with multiple visual display separations (including overlay) as well as cross-modal (visual and auditory) information presentations, in conjunction with a vehicle control task and response to critical (unexpected) traffic events. Such comprehensive examination is necessary in order that the joint contributions of ambient vision (vehicle control) and focal vision (event detection) can be assessed, as these are influenced by the attentional mechanisms of clutter filtering (from overlay), information access (from separation), and multiple resources. The current research seeks to address these issues.

In this simulator study, participants drove through traffic environments of varying difficulty and complexity while engaged in a secondary digit read-back task (the same used by Wickens, et al., 2002a). Driving difficulty was manipulated through straight versus curved sections of roadway, as well as rural and urban roadways in order to assess the impact of increased primary tracking demands on secondary task performance. We hypothesized that, to the extent that drivers were “protecting” the primary driving task (i.e., optimal resource allocation), performance on the secondary task would be degraded on more difficult sections of roadway. To the extent that they were not, then driving performance itself would suffer more on curved sections, particularly with more difficult secondary tasks. At various times throughout the drive, strings of four-, seven-, or ten-digits were presented either visually or auditorily to the driver, which were subsequently recalled vocally. The location and modality of the digit presentation varied across block, with digits presented at three different visual separations (0, 7, or 38°) or auditorily through the car speakers. Digit length was manipulated in order to better address the influence of preemption in the auditory condition (i.e., by increasing working memory load). In general, we expected more rapid responses to the auditory task because of the potential for memory decay in these conditions. Driving performance was measured by lane keeping and also by the response to ten critical events that required an emergency control response (e.g., pedestrian incursion, oncoming lane drift). Each event varied considerably and the frequency of occurrences was minimized in an attempt to render them unexpected. These events coincided with the onset of a secondary task (with the exception of the baseline condition). It was hypothesized that an adjacent head-up (non-overlapping) presentation of the digit task would yield superior performance on both hazard detection and secondary display
tasks relative to overlapping HUD presentation (cluttered display) and a HDD console (spatially separated). It was also expected, to the extent that the driving and display tasks demanded shared visual resources, that auditory presentation of the digit strings would benefit performance on both tasks.

Secondary task performance measures included the time to initiate the response, the duration of the speech response, and the accuracy of recall. Driving performance measures consisted of lane position and deviation, steering wheel inputs, as well as response times and response accuracy for the critical events. Dual-task performance was compared across display location and modality. Single-task performance of both driving and the secondary task was also measured.
METHODS

Participants

Twenty-five participants from the University of Illinois volunteered for this study (aged 18 to 29 yrs, $M = 22$). This group was comprised of 15 men and 10 women. All had valid driver’s licenses and, on average, drove 4750 miles per year. All participants were screened for normal or corrected-to-normal visual acuity. A description of each participant can be found in Appendix A. Drivers were paid $6 for each hour of participation.

Of these participants, two were forced to withdraw from the study after experiencing symptoms of motion sickness from the simulation.

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 front of a 210° wrap-around forward screen and a 45° rear field (see Appendix B). Six Epson PowerLite 703C projectors with 1024 x 768 pixels of resolution project the simulation onto separate 1.5 m high by 2 m wide Walltalkers’ Nuvurite™ projection screens. Seven custom computers powered the simulator. Auditory messages were presented through a 3D-surround Monsoon sound system. The head-down (in-vehicle) display was an AEI 6.4” LCD monitor with 640 x 480 pixels of resolution. Participants’ verbal responses were recorded with an Olympus DR-81 digital audio recorder.

The simulator dynamics and environments were coordinated with GlobalSim’s Vection Simulation Software™ Version 1.4.1. Vehicle control dynamics were configured for the Saturn SL. Driving environments and scenarios were created on a Compaq Evo using GlobalSim’s HyperDrive Authoring Suite™ Version 1.4.1. This tile-based program allows users to create driving environments of differing road types (single to multi-lane), road geometry (straight to varying degrees of curvature), culture (low-density rural to high-density urban), and signal type (no controls to signalized traffic control). Ambient traffic, pedestrians, and other environmental features can be incorporated into the driving environments either passively (i.e., they do not interact with the simulator vehicle) or actively (i.e., they are programmed to complete certain actions at specific points). Events and dynamics are controlled through a TCL programming script. Specific environments and event scripting are discussed further in subsequent sections.

**Driving Environment Overview**

Two closed-loop driving environments were developed for the purpose of this study. Each environment was configured; such that drives in either direction would share the same road characteristics but experience different critical events. As such, drivers were exposed to four different routes over the course of the study. Each route consisted of two-lane bi-directional rural
roads (both straight and curved sections) and four-lane bi-directional urban roadways as well as various transitional roads between these different settings (see Appendix C for examples of these roadways and Appendix D for the HyperDrive™ tiles used). As such, there were three road types: urban straight, rural straight, and rural curved. Straight rural stretches made up roughly 33% of the total route (approximately 6-7 min). Curved rural stretches were roughly 33% (ca. 6-7 min) of the total and straight urban stretches made up the remainder of the drives. Moderate levels of ambient traffic were present on each of the road types (at a rate of approximately 9-10 vehicles per km of roadway). No parked vehicles were present on the rural stretches, however many were present on both sides of the roadway in the urban setting (approximately 20 vehicles per block, positioned on both sides). In the urban setting, static pedestrians were presented at a rate of 7-8 per block. Each route shared these common characteristics, however differed in terms of the critical events encountered in separate driving blocks. The specific events are outlined below.

**Critical Events**

*Pedestrian/Animal/Bicycle Incursions.* These unexpected events occurred during the urban portion of a given drive, but no more than one time per experimental block. The pedestrian, animal, or bicycle incursion originated on the right hand side of the road from between parked vehicles (typically form behind larger vehicles). Time-based triggers were used to initiate the incursion event, allowing drivers approximately 2.5 seconds to respond to the incursion (i.e., to steer or brake). In non-baseline conditions, this event trigger occurred in conjunction with the onset of a digit recall task (either visual or auditory). The entity’s incursion ceased after moving a quarter of the way into the driver’s lane (see Figure 2A-C). Appendix E outlines the visual angles for each entity, at the event onset. Each incursion type occurred only once throughout the experiment in order to reduce the likelihood of practice effects and/or expectancy.

*Vehicle Incursion.* The configuration of this event was similar to the incursion described above, however this occurred in the rural setting. Again, the time-based trigger initiated a vehicle incursion from the right (response window of approximately 2.5 seconds). The vehicle was initially obscured by a row of shrubs and, after being triggered, came to a hard stop close to the edge of the simulator vehicle’s path (see Figure 3D). Again, Appendix E provides the onset visual angles.

*Parked Car Pullout.* This lane incursion occurred during an urban stretch. For this event, a right-side parked car rapidly pulled out into the driver’s lane from behind a large delivery truck (see Figure 3A).

*Wide Right Turn.* For this event, an initially parked car on a rural cross road, turn right into the opposing lane of traffic. The curve radius of this vehicle, however, exceeds the lane so the vehicle crossed over into the driver’s lane (see Figure 3B).
Figure 2. Critical traffic events used in the study: (A) Pedestrian incursion, (B) Dog incursion, (C) Bike incursion, and (D) Vehicle incursion.
**Oncoming Lane Drift.** This event occurred along a straight stretch of rural road. A distance-trigger initiated the approach of this vehicle from further down the road. When the vehicle separation reached approximately 3 seconds, this vehicle strayed from its own lane into the driver’s lane. This movement occurred relatively rapidly and ceased after the vehicle was one-third of the way into the driver’s lane.

**Oncoming Lane Drift (Turn).** This event is the same as the one described above, however occurred on a curved stretch of rural road (see Figure 3C). The timing parameters are the same.

**Intersection Light Change.** The traffic lights in all of the urban stretches were green for the driver’s direction of travel. For this event, however, the light changed from green to yellow to red. The timing of the light was such that a hard braking response would be required in order to stop before the intersection stop line. Otherwise, continued forward travel would result in the light changing to red before the vehicle cleared the intersection.

**Left-Turn Across Path (LTAP).** In the urban setting, an oncoming vehicle makes a rapid left-turn across the path of the driver’s vehicle (see Figure 3D). This turn was not initiated from the left-turn lane, rather from the center lane (i.e., the lane to the right of the turn lane). The turn was initiated approximately 3 seconds in front of the driver’s vehicle.

Response times for the incursion events (Pedestrian, Dog, Bike, Vehicle, Parked Car Pullout) were measured from the moment that the event was triggered by the simulator vehicle until the point where the driver initiated a measurable response (i.e., steering or brake). The Lane Drift events and the Wide Right Turn event did not have as clearly defined entries as did the incursion events (Olson, 2002). As such, response times for the latter events (Drift, Wide Turn) were measured from the moment the intruding vehicle began to move towards the simulator vehicle’s lane (e.g., when the opposing vehicle’s heading began to shift). Finally, response to the Light Change was measured from the moment the light changed to yellow. A steering response to the events was defined as a wheel deflection of 5° or greater in the direction opposite the traffic hazard. A brake response was defined as a rise in brake position from the default zero-value. The fastest of these two response types (in cases where both occurred) was taken as the response time for the event.

**Procedure**

Prior to participating, recruits responded to an email or phone simulator sickness questionnaire (see Appendix F). Participants completed an informed consent form (Appendix G) and a brief demographic questionnaire (Appendix H) at the start of the 120-minute session. A Snellen Visual Acuity Chart was used to assess visual functioning. Participants were required to exhibit near normal, or corrected-to-normal, levels of acuity (minimum 20/30). Participants meeting the visual requirements were then provided with a brief description of the experimental tasks (see Appendix I for complete verbal protocol).
Figure 3. Critical traffic events used in the study, cont.: (A) Parked car pullout, (B) Wide right turn, (C) Oncoming lane drift (turn), and (D) Left-turn across path.
After being seated in the simulator, adjustments to the seat were made, followed by an introduction to the various components of the driving simulator. In particular, the response button (i.e., the horn) on the steering wheel, the simulator abort switch (which terminates the simulation), and the LCD display used in the head-down visual condition. Participants were then given a five-minute training session to familiarize themselves with the simulator control dynamics.

The five experimental blocks were counterbalanced into ten different trial orders (Appendix J). Each participant completed a block with each of the four different display conditions (HUD Overlay, HUD Adjacent, HDD Console, and Auditory) as well as a baseline block for the secondary task performance. Participants were instructed to drive and respond to traffic as they normally would and to observe and obey traffic rules, especially the posted speed limits. The speed limit for rural and urban settings was 55 mph and 30 mph, respectively. Participants were also required to follow directions in order to successfully navigate the route. Route information was presented via directional signs placed within the simulation. This route information, however, was never presented in conjunction with a secondary task or traffic event.

As participants navigated through the routes, they were asked to complete, as best they could, a secondary digit callout task. This task was presented through one of four different displays and varied in difficulty (string lengths of either 4, 7 or 10 digits). This task was similar to that employed by Wickens, et al. (2002). There were three different visual display locations and one auditory display. The first visual display (Overlay) was presented in a simulated head-up display superimposed on the horizon line (0° separation; see Figure 4). This location provided the maximum amount of display clutter, as it overlaps with the main source of road information for experienced drivers (Mourant & Rockwell, 1972; Chapman & Underwood, 1998). The second location (Adjacent) was in a head-up display superimposed on the roadway just above the hood of the simulator vehicle (approximately 7° below the horizon line; see Figure 4). This location commonly used in experiments on automotive HUDs, as the display imagery does not overlap with any of the traffic environment (see Gish & Staplin, 1995 for a review). Both these displays were positioned directly in front of the driver (i.e., no horizontal offset). The third visual display (HDD) was located on an LCD display positioned near the center console of the simulator vehicle (approximately 38° offset from the center of the horizon line; 34 cm below and 37 cm to the right; see Figure 4). Appendix K shows a picture of the display and describes the relative size of the digit strings on each of the visual displays. The final display was auditory, which presented the digit strings through the simulator vehicle’s speaker system. Digits strings were presented either visually or auditorily with a random inter-stimulus interval between 10 and 30 seconds. Participants were instructed to respond to the digits as quickly as possible, however not to compromise safe driving in doing so. Upon noticing the digits, participants pressed the vehicle horn, read out the digits contained in the string, and then pressed the horn a second time when finished their response. Driving performance measures of lane position and steering wheel deflection were recorded during completion of this secondary task as well as throughout the trial when no secondary task was present (baseline). Also, performance for the secondary task was assessed by the time to initiate, the time to complete, and the accuracy of the read back.
During each block, participants were exposed to two or three critical events that required a response from the driver (i.e., braking and/or steering response). For non-baseline conditions, these events coincided with the onset of a secondary task (as described above). The secondary task in these conditions consisted of a 7- or 10-digit string, in order to examine more difficult task combinations. These events were presented in random locations throughout the drive. Perception-response time (PRT) and response type (brake and/or steer) were recorded for each of these events. The measure of PRT includes the time required to identify a hazard or event, select the appropriate response, and initiate the response (Olson, 1996).

Each experimental block lasted approximately 20 minutes, with the exception of the baseline block for the secondary task, which lasted 5 minutes. This block included the auditory and head-up (horizon) visual displays of numerical digits but no driving task to complete. The inter-stimulus interval in this block was between 3 and 7 seconds. Participants were offered a short break in between each block. After the 5 experimental blocks were completed participants completed a brief post-experimental questionnaire (Appendix L), which queried basic driving habits, potential risk-taking behavior, and other aspects of the interaction with the simulator. These data are not used in any of the reported analyses. Following the questionnaire, participants were remunerated for their participation.

**Experimental Design**

The experimental design was a within design with the variables of Display Type (HUD Overlay, HUD Adjacent, HDD Console, Auditory), Road Type (Urban Straight, Rural Straight, Rural Curved), and Task Load (Control, 4-digits, 7-digits, 10-digits). Driving data in the control (no...
load) condition were sampled at random intervals when there was no secondary task present. Because the critical events were encountered a single time by each participant under different display conditions, they were examined using a between variable of Display Type, and were not examined in terms of Road Type or Task Load (since these were not manipulated for the critical events).
RESULTS

Performance on the driving task (vehicle control and hazard avoidance) and the secondary digit task was assessed through a number of analyses across display and road types. In general, a series of conditionalized planned comparisons was employed to investigate specific hypotheses, rather than omnibus analyses (Keppel, 1982). For each string, a modified Bonferroni test was used to control the familywise error rate (see Keppel, 1982, for detailed explanation).

Data from six participants were excluded from the overall analysis of driving and secondary task performance because of missing data values for some of the conditions. However, some data from these participants were included in the analysis of the critical traffic events.

Driving Performance

Several planned comparisons examined the effects of clutter (HUD Overlay vs. HUD Adjacent), display separation (HUD Adjacent vs. HDD Console), display modality (HUD Adjacent vs. Auditory), and dual-task interference (Display vs. No Display). Display comparisons were made across Road Type (urban straight; rural straight; rural curved) for measures of lane position and speed control. The effect of Task Load (4-digits, 7-digits, 10-digits) was examined only for measures of lane position.

Lane position was determined by measuring the absolute deviation of the vehicle (in meters) relative to the center of the vehicle’s lane. For the display conditions, measures were recorded from the onset of the secondary task until the completion of the verbal response—a duration of approximately 3-5 seconds. For the baseline, No Display condition, measures were recorded during random, single task intervals (i.e. driving alone) over the course of the study. These deviation data are shown in Figure 5, which reveals that there was a significant main effect of Road Type for all Display conditions (p < .001 to p = .004), with higher rural velocities and more difficult curved sections each contributing to increased lane deviations. The findings follow intuitively and will not be explored further except in terms of any potential Display by Road interactions. Performance measures are presented collectively in Figure 5, while the specific tests are outlined below.

A repeated measures ANOVA comparing Overlay and Adjacent conditions did not reveal a significant effect of Display ($F_{(1,17)} = .23, p = .64$) nor a significant Display by Road interaction ($F_{(2,34)} = .52, p = .60$), suggesting that the increased clutter of information overlay did not degrade driver’s vehicle control within their lane (see Figure 5). Adjacent and head-down presentations were compared to assess the impact of display separation and information access costs on vehicle control. Again there was no effect of Display ($F_{(1,19)} = .01, p = .93$) or Display x Road interaction ($F_{(2,38)} = .02, p = .98$) suggesting that drivers were either able to use peripheral vision to control the vehicle while engaged in the HDD task or they adopted scan strategies to allow them to switch attention to and from the roadway appropriately. There were no differences in lane deviations between the Adjacent visual presentation and the Auditory presentation, in terms of a Display main effect ($F_{(1,19)} = .55, p = .47$) or a Display x Road interaction ($F_{(2,38)} = $...
As such, the modality of information presentation did not appear to have any differential impact on lateral vehicle control.

While there were no apparent costs of clutter, separation, or modality for lane position, comparisons to single-task baseline (No Display) conditions did suggest lane-keeping costs for dual-task performance. Specifically, the aggregate of the visual conditions did show a significant effect of dual-task interference (lane deviations: Dual-Task, $M = .42$ m; Single-Task, $M = .32$ m; $F_{(1,17)} = 35.37$, $p < .001$). There was however no Display x Road interaction ($F_{(2,34)} = .37$, $p = .69$) indicating similar dual-task costs across road and maneuver types. Similarly, there was dual-task costs for the auditory condition relative to baseline (Dual-Task, $M = .42$ m; Single-Task, $M = .32$ m; $F_{(1,20)} = 25.18$, $p < .001$) but no interaction ($F_{(2,40)} = .39$, $p = .68$) with Road type.

The effects of Task Load (4-digit, 7-digit, 10-digit) and Display Type were examined through a repeated-measures ANOVA. There were no main effects of Display ($F_{(3,60)} = 1.02$, $p = .39$) nor for Task Load ($F_{(2,40)} = 1.48$, $p = .24$), suggesting that drivers in all display conditions appropriately protected the driving task, even for higher task loads. The Display x Task Load interaction was not significant ($F_{(6,120)} = .64$, $p = .70$). Because of the safety implications, we examined the potential “worst case” scenario: lane deviations for the 10-digit task load on curved road sections. A repeated-measures ANOVA examining the effects of Display Type in these driving conditions did not reveal any differences across display types ($F_{(3,57)} = 1.04$, $p = .38$). This lends further support to the notion that drivers in the current study were able to protect the driving task across the different display types, even in the most difficult driving conditions (encountered in the current study).

Speed control was examined by measuring the standard deviation of vehicle velocity during secondary task or baseline intervals. The findings for this string of analysis are presented
in Figure 6. As with performance on lane tracking, there was a significant effect of Road Type across all planned comparisons ($p < .001$), with the urban setting yielding the largest deviations in speed control, followed by curved rural stretches then straight rural stretches. These differences may be due, in part, to curved rural stretches effects of real world driving to the slower urban speeds in the simulator environment. Again however, the effects of Road Type will only be examined in the context of an interaction with Display Type.

As shown in Figure 6, there were no difference between the Overlay and Adjacent display conditions ($F_{(1,17)} = .003, p = .96$), nor was there a Display x Road interaction ($F_{(2,34)} = .23, p = .80$). As was the case with lane position, it appears as though there are no costs associated with scene clutter for speed control. This holds for costs associated with display separation as well, with no significant differences between the Adjacent and HDD Console conditions ($Display, F_{(1,19)} = .58, p = .46$; Display x Road Type, $F_{(2,38)} = .01, p = .99$). There was, however, a substantially increased variability in velocity for the Auditory condition compared to the Adjacent visual condition ($F_{(1,19)} = 38.64, p < .001$), suggesting that the added rehearsal and memory component of the auditory condition interfered more with speed control than did visual presentation. This finding is consistent with the auditory interference observed by Wickens, et al. (2002a). The Display x Road interaction was not significant ($F_{(2,38)} = 1.92, p = .16$). Since there were no differences across the visual display conditions, these were collapsed and compared against baseline (No Display) performance. The presence of the secondary, display task did appear to increase variability ($F_{(1,19)} = 29.54, p < .001$) and did interact significantly with Road Type ($F_{(2,34)} = 9.53, p = .001$). The increased difficulty of the curved rural sections and the urban stretches relative to straight rural stretches did not impact speed control in the baseline conditions as it did in dual-task, display conditions. Similar yet more pronounced effects were found in
comparing the Auditory condition to baseline performance, with a significant Display main effect ($F_{(1,20)} = 106.04, p < .001$) and Display x Road interaction ($F_{(2,40)} = 21.52, p < .001$).

Thus, there were overall costs associated with dual-task performance for both driving tasks (lane and speed control), relative to single-task conditions, and with regard to speed control, these tended to be amplified in more difficult driving conditions (urban, and curved rural). However, with the exception of the Auditory-Visual differences in speed control, there were no display differences across these vehicle control tasks, even in “worst case” highest load conditions. In particular, there did not appear to be any costs associated with clutter and overlay, nor with display separation. As noted previously, vehicle control may be time-shared with visual secondary tasks effectively (a) because it utilizes ambient visual channels rather than relying solely on focal visual attention and, (b) because brief glances downward may leave the high inertia trajectory of the automobile unaffected, so long as precise steering is not being undertaken. The more focal visual task of hazard detection is addressed below.

**Response Times to Critical Events**

Each participant encountered ten discrete, critical events throughout the study under different display conditions. In the display conditions, these events occurred just after the onset of a secondary 7- or 10-digit (higher load) task. These events were pooled in the following analyses, to increase statistical power in order to reduce the likelihood of making Type II statistical errors, which should be minimized when examining safety-critical events (Wickens, 2001). A total of eight events were collapsed: (1) Pedestrian, (2) Dog, (3) Bike, and (4) Vehicle Incursions, (5) Parked Car Pullout, (6) Wide Right Turn, (7) Oncoming Lane Drift, and (8) Oncoming Lane Drift (Turn). Although these events differed in nature, all generally required an emergency maneuver (e.g., brake or steer) in order to avoid a collision. The Left-Turn Across Path event was dropped from these analyses due to a poor pattern of responses. Specifically, this event did not consistently impose sufficient constraints on the driver to require a critical (and measurable) response. The Light Change event was also dropped from these analyses. Responses for this event were mixed (i.e., some braked for the light, some accelerated through the light, while others coasted through the intersection) and more geared towards a Chi-squares analysis (which is reported below), rather than an analysis of response times.

Figure 7 shows the mean response times to the pooled events as a function of display type. The baseline response time to these events ($M = 1.42$ s) was within a range of times suggested by various researchers for unexpected, surprise intrusions or for expected, yet temporally uncertain events (e.g., Green, 2000; Summala, 2000). Planned comparisons were used to examine the effects of clutter, display separation, modality and dual-task interference.

A two-sample t-test (1-tailed) for Overlay and Adjacent conditions did not yield any differences between the two display locations ($t_{(75)} = -.86, p = .39$), suggesting that the presence of information overlap and clutter did not disrupt drivers’ ability to detect and respond to the critical events. An examination of display separation yielded increased response times for the HDD Console ($M = 1.68$ s) compared to the Adjacent condition ($M = 1.50$ s; $t_{(72)} = -2.49, p = .015$). This degradation in response time to discrete events at larger eccentricities is consistent
with previous findings (e.g., Lamble, et al., 1999). There were no differences in response times across presentation modality (Adjacent visual vs. Auditory; \( t_{(77)} = .45, p = .65 \)). The two HUD conditions (Overlay and Adjacent) were collapsed and compared to baseline (No Display) response performance. This comparison did not yield any differences (\( t_{(107)} = .82, p = .42 \)), nor did a comparison of Auditory and baseline conditions (\( t_{(69)} = .65, p = .52 \)). There was, however, a significant degradation in performance for the HDD (\( M = 1.68 \) s) compared to baseline (\( M = 1.42 \) s; \( t_{(64)} = 3.25, p = .002 \)), again reflecting the costs of visual scanning to the in-vehicle display.

Collision frequencies were explored as a function of display type and presented in Table 1. These events included the pedestrian, dog, bike, and vehicle incursion events, the wide right turn, the oncoming lane drift, and the oncoming lane drift (turn). The parked car pullout event was excluded from this analysis because there were no collisions for this event. The overall high frequency of collision events suggests that, although drivers responded to the events in a timely manner, the nature of the response was not always appropriate (e.g., braking instead of braking and steering to avoid a collision). A Chi-square analysis of the proportion of collisions did not reveal any significant differences between display types (\( \chi^2_{(4)} = 3.21, p = .52 \)).
Table 1. Frequency of collisions by display type for different event types: pedestrian, dog, bike, and vehicle incursion, wide right turn, and both oncoming lane drift events.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Collision Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUD Overlay</td>
<td>13/31 (42%)</td>
</tr>
<tr>
<td>HUD Adjacent</td>
<td>18/36 (50%)</td>
</tr>
<tr>
<td>HDD Console</td>
<td>12/33 (36%)</td>
</tr>
<tr>
<td>Auditory</td>
<td>10/33 (30%)</td>
</tr>
<tr>
<td>Baseline</td>
<td>10/28 (36%)</td>
</tr>
<tr>
<td>Overall</td>
<td>63/161 (39%)</td>
</tr>
</tbody>
</table>

Previous research has reliably demonstrated costs associated with superimposed head-up information and responses to truly surprising, unexpected events relative to head-down presentation (e.g., Fadden, et al., 2000). We examined the first occurrence of an incursion event for the Overlay and Adjacent conditions to see whether there would be degraded performance in response to this critical event. It is assumed that the first occurrence of such events would be truly surprising and unexpected, whereas subsequent ones were more temporally uncertain. A total of six drivers experienced an incursion event (i.e., Dog or Pedestrian) as their initial event while using an Overlay or Adjacent HUD (the remainder of the drivers either (a) encountered different initial events (non-incursion), or (b) were using alternate display formats). Although there were no differences in the response times to these initial events (Overlay, $M = 1.47$ s; Adjacent, $M = 1.46$ s), there were three initial event collisions in the Overlay condition (out of three possible) compared to no collisions (out of three) in the Adjacent condition. Because of the low N, any meaningful statistical analysis was precluded. The collision frequency for the different display types offers some support for the notion that cluttered (superimposed) displays interfere with the effective response to truly unexpected events.

There was also an overall improvement in responses to critical events over the course of the study, with slower response times for the initial event. Again, no statistical comparisons were made on these data however the general trends are depicted in Figure 8.

As mentioned previously, the traffic light change event did not yield consistent responses across drivers. For instance, some drivers would brake to the changing light, while others would remove their foot from the accelerator and coast through the intersection. Still others would coast for a short distance before pressing down hard on the accelerator. Responses were therefore divided into Stop or No Stop categories and subjected to a Chi-square analysis. The results of this analysis, however, did not reveal any differences across display type or baseline conditions ($\chi^2_{(4)} = 4.89$, $p = .30$).

In summary, the responses to the discrete, critical events revealed several important findings. First, there were no dual-task costs in response time to these events for display conditions that did not involve peripheral vision (e.g., baseline, compared to adjacent, superimposed and auditory). Second, there did not appear to be any costs of clutter in detecting
and responding to the critical events (Overlay vs. Adjacent) however, there were increased collisions in Overlay conditions for the initial incursion event compared to Adjacent conditions, pointing to potential implications for display clutter with truly unexpected, surprise events. Third, there were time costs in responding to critical events with increased display eccentricity (HDD) relative to Adjacent (and baseline) conditions.

Secondary Task Performance

For the three visual display conditions, secondary task response time was measured from the onset of the digit-string until the verbal response was initiated. In contrast, response time in the auditory condition was measured from the end of the auditory presentation of the digits until the onset of the participant’s response, a measurement that may have artificially shortened the auditory response time relative to its true value. Planned comparisons again examined the effects of clutter (Overlay vs. Adjacent), display separation (Adjacent vs. HDD), and modality (Adjacent vs. Auditory) for responses to the display task. As with the primary driving measures reported above, there was a significant main effect of Road Type across all comparisons for response time (p < .001 to p = .03), with responses taking longer on straight urban stretches than on straight rural stretches and longer on curved rural sections than on straight rural roads (e.g., the pattern of effects shown in speed deviations in Figure 6). As before, Road Type will only be described in the context of any potential interactions with Display.

A series of repeated measures ANOVAs were performed in the following comparisons, which are represented in Figure 9, along with the baseline RT measures. Response times to the digit task presented superimposed on the roadway (Overlay) did not differ from those presented adjacent to the horizon line (Adjacent; F(1,18) = .68, p = .42), nor was there a Display x Road
interaction ($F_{(2,36)} = 1.84, p = .17$). There was however delayed response to the digit task when it was presented head-down (HDD; $M = 1.18$ s) compared to Adjacent presentation ($M = 1.08$ s; $F_{(2,20)} = 4.44, p = .05$), suggesting information access costs associated with the more eccentric display. This comparison did not yield any significant Display x Road interaction ($F_{(2,40)} = .21, p = .81$). Finally, there were significantly shorter response times for the Auditory condition ($M = .39$ s) compared to the Adjacent visual condition ($M = 1.08$ s; $F_{(1,20)} = 57.25, p < .001$). In some cases, participants began their verbal response before the end or very close to the end of the auditory presentation of the digit strings thus shortening these overall response times. Furthermore, as noted above, this may have been an artifact of the timing mechanism used. There was no Display x Road interaction for the Auditory-Adjacent comparison ($F_{(2,40)} = 1.02, p = .37$).

Of perhaps greater importance (revealed in Figure 9) is the fact that dual-task auditory response time did not differ from single-task auditory conditions (collapsed across road type; $F_{(1,20)} = .22, p = .64$), whereas response times in the visual conditions were slowed down substantially (approximately a quarter-second) by the presence of the concurrent driving task (Visual Baseline, $M = .81$ s; Overlay and Adjacent HUDs, $M = 1.09$ s; $F_{(1,18)} = 27.83, p < .001$; HDD, $M = 1.18$ s, $F_{(1,20)} = 18.82, p < .001$), even in the overlap condition where the visual onset of the secondary task would likely be in foveal vision.

Response duration was measured from the moment participants indicated the start of their verbal response to when they finished speaking (indicated by button push). For these comparisons, there was no main effect of Road Type. Figure 10 illustrates response durations by display type. A comparison of the Overlap and Adjacent conditions did not yield a significant
Display effect ($F_{(1,18)} = 1.30, p = .27$), nor a significant Display x Road interaction ($F_{(2,36)} = 1.55, p = .23$). Response did however take longer in the head-down condition (HDD; $M = 3.10$ s) relative to the Adjacent condition ($M = 2.88$ s; $F_{(1,20)} = 7.56, p = .01$) illustrating further information access costs. Display type did not interact with Road Type ($F_{(2,40)} = 1.05, p = .36$). There was a marginally significant effect of Display type, with longer response times in the Auditory condition ($M = 3.17$ s) relative to Adjacent presentation ($M = 2.88$ s; $F_{(1,20)} = 3.96, p = .06$), suggesting increased within-task code interference associated with the auditory task versus the visual task. There was no Display x Road interaction ($F_{(2,40)} = .02, p = .99$) in this analysis. Finally, dual-task costs were assessed by comparing the Adjacent display and visual baseline conditions and the dual- and single-task auditory conditions. Both tests yielded non-significant results ($t_{(20)} = 1.51, p = .15; t_{(20)} = -1.07, p = .30;$ respectively), indicating no performance costs for response duration associated with dual-task conditions.

The effect of Task Load on side task performance (i.e., response duration) was examined separately in the context of an interaction with Display Type. Planned comparisons were once again used to examine clutter, separation, modality, and dual-task interference. Main effects of Display Type on response duration are reported above and, not surprisingly, longer side task digit strings required significantly longer to speak for all comparisons. As such, only Display x Task Load interactions are reported below.

A repeated measures ANOVA on response duration for Adjacent and Overlay conditions did not reveal a Display x Task Load interaction ($F_{(2,40)} = 2.43, p = .10$). These findings suggest that the increased clutter associated with longer digit strings in the Overlay condition did not impact secondary task speech performance, more so than the shorter strings. As shown in Figure 11, a comparison of HDD and Adjacent presentations did however reveal a significant Display x
Task Load interaction ($F_{(2,40)} = 8.15, \ p = .001$) with costs of display separation being more pronounced at the longest digit strings. Given that vehicle control performance did not differ across these display types, these current data suggest that drivers were adopting an appropriate scan strategy to access the HDD display information, while protecting the primary driving task. Short digit strings could be accessed in a single fixation (hence, no difference in response durations) however; longer digit strings required multiple fixations, therefore taking longer to read back in the head-down condition relative to the adjacent display. A similar pattern was shown for the Auditory-Adjacent comparison (see Figure 11), with the significant Display x Task Load interaction ($F_{(2,40)} = 4.31, \ p = .02$) indicating more pronounced effects of mental rehearsal and code interference for the longer digit strings. An examination of dual-task interference did not reveal any differences relative to single-task conditions for the visual ($F_{(2,40)} = .80, \ p = .46$), nor for the auditory displays ($F_{(2,40)} = 5.0, \ p = .04$) once the modified Bonferroni adjustment was applied.

Finally, accuracy in digit recall was measured as percent-correct for each digit string. In general, all the visual display conditions yielded near-perfect performance and need no further examination across visual display conditions. There were significant costs however for accuracy in the Auditory condition ($M = .86$) compared to visual conditions ($M = 1.0$; $t_{(20)} = -13.29, \ p < .001$). The auditory costs were primarily associated with highest (10-digit) task load (as in Wickens, et al., 2002a). Interestingly, recall accuracy for the auditory condition was improved in dual-task conditions compared to auditory baseline (digit task alone) conditions ($M = .84$; $t_{(20)} = -3.69, \ p = .001$).

In conclusion, regarding the secondary task, there are access costs associated with increased display separation, as evidenced by the longer response times and durations for the more eccentric display. There did not however appear to be any response costs associated with
the overlay condition compared to the adjacent presentation. Dual-task response time costs in the auditory condition were shorter than their counterparts in the visual adjacent condition, perhaps indicating a strategy to reduce the likelihood of memory decay. Response durations were longer for the auditory condition and were prolonged more by high load however, suggesting code interference between the mental rehearsal of the digits and the verbal reproduction of them. These auditory costs were equivalent in single- and dual-task conditions. There was no difference in accuracy across all the visual conditions but decreased accuracy in the auditory condition, though this recall deficit was greater than in single-task auditory baseline conditions.

**Secondary Task Performance for Critical Events**

Secondary task performance was examined in conjunction with the occurrence of critical events in order to determine whether there were any tradeoffs in performance between the driving and side task. Planned comparisons were made between the adjacent and overlay, head-down, and auditory conditions. There were no differences in response time to the secondary task between the adjacent and overlay conditions (with modified Bonferroni adjustment; $t_{(61)} = 2.06, p = .04$), nor between the adjacent and auditory conditions ($t_{(56)} = -1.23, p = .22$). However, response times were significantly slower in the head-down condition ($M = 2.97$ s) compared to adjacent condition ($M = 1.00$ s; $t_{(67)} = -4.14, p < .001$). As shown in Figure 12, this pattern of results matches closely that shown in the response times to the primary task (Figure 7), indicating that there was no performance tradeoff between the two tasks (i.e., sacrificed performance on one task to benefit performance on the other).

![Figure 12](image-url)

Figure 12. Response times to the secondary task during critical events by display type.
Individual Differences in Performance

Finally, we were interested in further examining performance for the worst performing individuals, as these are often those who present the greatest hazard to roadway safety (Wickens, 2001). This was taken to mean the 6 individuals who showed the slowest response times to the critical events (collapsed across display type), rather than any objective measure of overall driving performance. In general, the response times for these individuals did not differ substantially from the others ($M = 1.60$ s versus 1.48 s). Nevertheless, we compared (non-statistically) rankings for responding to the critical events with other performance measures, to see whether this relatively poorer performance was generalized across the other measures. As shown in Table 2, the lower mean ranks for these individuals did not appear to hold for other driving measures, nor for secondary task measures (with lower ranks indicating worse performance).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Critical Event RT</th>
<th>Lane Tracking</th>
<th>Speed Control</th>
<th>Side Task RT</th>
<th>Side Task Duration</th>
<th>Side Task Accuracy</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>16</td>
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<td>10</td>
<td>12.8</td>
<td>12</td>
<td>13.8</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Table 2. Ranks on various performance measures for worse performers on critical event task. Lower rankings indicate poorer performance (out of a highest possible 21).

Finally, we examined the extent to which the profile of display effects on hazard RT, shown across all subjects in Figure 7, also characterized the slowest performers. As shown in Figure 13, the general pattern of performance for these slowest performers was similar to the overall pattern when examined by display type. Thus, the general trend for poorer performance with the head-down display was consistent across all users. It is somewhat interesting to note however that the slowest performance appear to be more hindered by the auditory display, in a way that was not evident for the group as a whole. Thus there is some possibility that a symptom of the slow performers, is their susceptibility to the “auditory preemption effect” that has been observed in other studies (e.g., Wickens Dixon and Seppelt, 2002). This effect may be worthy of further investigation.
Figure 13. Response times to the critical events during critical events by display type for the slowest 6 performers.
DISCUSSION

The current market trend has automobile manufacturers incorporating progressively more telematic devices into vehicles (Ashley, 2001). As more in-vehicle tasks are created by such devices, drivers must be able to ensure that safety will not be compromised—a feat which may be based largely on the costs of accessing information from in-vehicle displays. The goal of the current study was to assess the relative costs associated with display clutter and overlay, spatial separation, and modality on driving performance; specifically, vehicle control and response to unexpected traffic hazards. Because of the obvious safety implications of the results reported here, special consideration will be made for potential Type II statistical errors, where appropriate. That is, it is important to assure that the conclusion of “no difference” between the relevant conditions is not simply the consequence of a comparison made with low statistical power.

Display Clutter and Overlay

As noted in the Introduction, superimposing display information effectively reduces the information access costs associated with spatial separation. Because of the proximity of the displays, overlay may aid in the detection of critical information presented in one or the other sources and it may also better support the use of peripheral vision for one or both tasks. Previous research however has well-documented the capacity for superimposed information to degrade attentional switching from one display source to the other (cognitive capture; Gish & Staplin, 1995) as well as degrade responses to critical, yet unexpected events (e.g., Fadden, et al., 2000). In the current study, secondary task information was spatially superimposed over the horizon line in order to assess the impact on lane keeping, speed control, and response to critical driving events. This superimposed position was compared to the adjacent position, which is actually the more standard location for in-vehicle HUDs (e.g., Kiefer, 1991; Gish & Staplin, 1995).

Driving and Secondary Task Performance

Results of the current research did not reveal any differences between a spatially superimposed display (overlay) and an adjacent display for measures of lane keeping and speed control, nor were there any differences in secondary task performance (response time and response duration). Previous research in aviation has demonstrated HUD benefits for tracking performance and airspeed control compared to head-down presentation of similar information (e.g., Wickens & Long, 1995; Martin-Emerson & Wickens, 1997). The absence of an overlay benefit for these tasks in the current study is likely a result of the near proximity of the adjacent display (i.e., positioned sufficiently close to the driving environment so as not to incur scanning costs). Indeed in the aviation studies, the HUD benefits that are typically reported are observed relative to a head-down condition that corresponds more closely to HDD console condition examined here. The longest digits strings did not degrade performance in the overlay condition relative to shorter strings, even in the most challenging driving situations. It follows that the clutter imposed by the overlaid display does not interfere with vehicle control because these vehicle control tasks rely to a large degree upon peripheral and / or ambient vision, and therefore are less susceptible to clutter effects.
**Hazard Awareness**

Though clutter does not interfere with vehicle control, it is possible that it may degrade detection and response to discrete, critical events. Fadden, et al. (2000) showed that responses to unexpected events tend to be longer in HUD conditions relative to head-down. The current study, however, did not reveal any difference in response times for the overlaid information relative to the adjacent display. Because of the obvious safety implications of missed and delayed responses to critical events, we examined the statistical power of the overlay-adjacent comparison, which tended to support the notion that the observed effects were true (power = .72). The events were all highly salient and occurred in close proximity to the superimposed display, which may have afforded drivers the ability to detect and respond appropriately. More peripheral (and therefore less salient) events or those that are less perceptually salient (e.g., in dim illumination) may demonstrate overlay costs.

There were relatively few critical, discrete events in the current study. Although the occurrence of events was unpredictable and temporally uncertain, only the initial event should be considered a truly surprising, unexpected event. We note that the response times decreased for subsequent events in all display conditions following the first event. For this first incursion event, drivers in the overlay condition collided more frequently with the incursion obstacle (three out of three) than did drivers using the adjacent display (zero of three). Though this observation is strictly anecdotal (due to low N in these conditions), it may have implications for events which are truly unexpected. Previous research has shown similar trends for truly surprise events (e.g., Fischer, et al., 1980; Fadden, et al., 2001; Wickens & Long, 1995; Larish & Wickens, 1991), though these studies typically involve low N, as in the current work.

In general, clutter (as implemented with the digit strings used here) does not appear to adversely impact the vehicle control tasks nor does it degrade performance on the secondary task, relative to a non-cluttered (adjacent) display. There was no overall difference in response time to the critical events, though unexpected (versus temporally uncertain) events may remain problematic for overlaid, cluttered displays.

**Display Separation and Access Costs**

The model of information access costs described by Wickens (1992) posits that scanning costs will increase substantially when head movements are involved. We examined an in-vehicle (head-down) display positioned 38° from the forward line of sight, which extends beyond the eye field (20 to 25°; Previc, 1998; 2000) and into the head field. As such, we might expect costs associated with the required physical scanning between the information sources, the effort required to scan, and the degraded salience of peripheral information at greater separations.

**Driving and Secondary Task Performance**

The current study did not reveal any degradation in lane keeping or speed control for the HDD Console condition relative to the adjacent presentation (located 7° below the line of sight, well
within the eye field; Wickens, 1992). One plausible explanation is that the vehicle control task and the secondary digit task utilize separate visual channels and therefore, according to the multiple resource model, can be time-shared effectively (Previc, 1998; Wickens, 2002). The secondary digit task uses focal visual resources in the fovea to accurately discriminate the digits on the HDD. In contrast, lane and speed control can be largely accomplished through the use of ambient vision, which is well supported by peripheral vision (Previc, 1998; 2000), which can offer drivers critical information regarding their relative position on the roadway or an indication of their relative velocity, through optic flow information. The maintenance of accurate lane position using peripheral vision has been supported by previous research (e.g., Summala, et al., 1996; Summala, 1998), though it is noted that this ability declines as separation increases. Thus, the use of distinct visual channels (focal and ambient) to support the concurrent tasks may afford drivers effective time-sharing for these tasks.

Alternatively, drivers may be adopting an appropriate scanning strategy which allows them to briefly access display information while properly monitoring the driving environment (i.e., protecting the driving task). With the larger display separation for the head-down LCD panel, we might expect that the increased effort associated with eye and head movements to the display might decrease the likelihood of scanning from the road to the display, which would result in degraded performance on one or both concurrent tasks. The results showed that driving performance was unaffected by the larger display separations—even in the most difficult task situations (i.e., curved stretches with a 10-digit task load). There were however slowed responses to side task information, which suggest that drivers did not invest the effort required to monitor the in-vehicle display frequently, even though they did protect the lane-keeping task.

Secondary task response durations in the HDD condition were longer than in the adjacent display condition, and these differences were amplified for the higher task loads. These findings suggest that, once they notice the onset of the secondary task, drivers invest the effort to scan back and forth from the display to the roadway, making more display fixations for the longer digit strings. It is possible that the value of monitoring the traffic environment (e.g., for safe travel) is offsetting the effort required to sample both information sources. Indeed, the model by Wierwille (1993) suggests that drivers do make multiple glances to in-vehicle displays, especially when the extraction of information requires longer than a few seconds. As noted previously, a number of research efforts have shown support for this model of sampling behavior (e.g., Gellatly & Kleiss, 2000; Dingus, Antin, Hulse, & Wierwille, 1989). The adoption of this appropriate scan strategy may allow drivers to effectively interact with an in-vehicle display, even when it is spatially separated from the traffic environment. It should be noted, however, that lane position and speed control are sluggish in nature (i.e., due to the high inertia of the vehicle) and may remain relatively unaffected during brief glances downwards to the display information, particularly when ambient vision can support some degree of lane monitoring even when the head is down. On the other hand, when precise steering or brake inputs are required, for example in response to discrete perceptual events, rather than continuous motion flow, the costs of increased display separation may be more pronounced—an issue we now address.
Hazard Awareness

The critical events reveal some important implications for display separation. In general, responses to these events were slower in the HDD condition than in the adjacent display condition. Hazard awareness is largely a foveal and focal task, requiring focal visual resources to detect and identify critical objects and events. While the vehicle control and digit tasks may be time-shared effectively due to separate focal-ambient resource demands, the same is not true for hazard detection. This detection task competes with the secondary task for focal resources, thereby degrading performance on one or both tasks when they are performed concurrently. In this case, both figure 7 and figure 12 suggest that the cost of visual resource competition in the head down location was shared by both tasks.

One key factor in the degradation of time-sharing for two focal tasks is the relative salience of events occurring in the periphery. Events that are salient near foveal vision will decrease in salience as they are moved further into peripheral vision and, as a result, may not be noticed or may be noticed later than when located centrally. Hence, drivers fixating on the in-vehicle display were less sensitive to the onset of critical (and less salient) events and would consequently have delayed responses. Similarly, Lamble, et al. (1999) found slowed responses to discrete traffic events when the drivers were fixating on more eccentric display locations. We further note that responses to the secondary task for the HDD were slower than for the adjacent display. In addition to the poor detection of traffic events while fixating in-vehicle, the detection of the (less salient peripheral) digit onset was degraded when focal attention was directed to the driving environment, resulting in increases time to notice and respond to the digit task.

While vehicle control may be time-shared effectively with separate focal-ambient visual resources or through an appropriate scanning strategy, hazard awareness and detection demands careful consideration. Discrete traffic events typically pose the greatest threat to safety and therefore should weigh heavily in any evaluation of display location. The current findings suggest that increased display separations will degrade responses to discrete, critical events and should therefore be minimized. As such, the display of information in an adjacent location (within the eye field; Wickens, 1992) would seem to support performance of both the driving tasks as well as the peripheral side task—or at least lead to reduced dual-task decrements on safety critical tasks compared to head-down console displays.

Modality

According to the multiple resource model, the presentation of secondary task information auditorily should allow drivers to time-share tasks more effectively than visual side task input because the tasks use separate perceptual resources (Wickens, 2002). This auditory presentation may however preempt performance on the visual task because of the alerting nature of auditory stimuli (Spence & Driver, in press). Alternatively, drivers may strategically decide to interrupt the visual task before the auditory information is forgotten, especially when this information is lengthy and / or complex (Helleburg & Wickens, 2002). As reviewed in the Introduction, past research on auditory-visual differences in presentation of information in a driving task has revealed mixed findings. For example, Gish, et al. (1999) found auditory side task benefits for various driving measures (brake response time and accuracy, speed monitoring). In contrast,
Matthews, et al. (1996) showed that the auditory presentation of information impaired driving performance in more difficult road conditions. There does appear to be some support of benefits for auditory side task performance (e.g., Labiale, 1990; Liu, 2001; Parkes & Coleman, 1990), though this is not a consistent finding (e.g., Lee, Gore, & Campbell, 1999).

**Driving and Secondary Task Performance**

In the current study, there were no differences between auditory versus adjacent visual presentation of secondary task information for measures of lane position. This was also the case for the more difficult task loads and driving conditions, suggesting that drivers were protecting (i.e., not strategically preempting) the driving task to deal with the longer digit strings. An examination of speed control did however show increased variability in the auditory condition, which could indicate interference from response rehearsal in the auditory condition. Unlike the speed monitoring task employed by Gish, et al. (1999), which involved discrete speed queries at random intervals, the current study had participants in active control of the vehicle velocity—a distinction which may account for the reversed findings from both experiments.

Another plausible explanation for the current findings could be due to auditory interference at the perceptual processing stage. While speed control relies upon visual monitoring of speedometer and optic flow information, it also involves the engine noise of the simulator vehicle. Changes in the pitch and amplitude of the perception of engine noise can be readily detected and therefore accurate speed control can be attained by keeping the engine output constant—a strategy which may have been adopted by drivers in this study. Thus, the onset of the auditory digit task would interfere with this speed monitoring at the perceptual level, leading to degraded performance relative to strictly visual conditions.

It was shown that responses to the secondary task were quicker in the auditory condition compared to the visual presentation, consistent with some of the reviewed literature (e.g., Srinivasan, et al., 1995; Liu, 2001; Parkes & Coleman, 1990). This may suggest that drivers wanted to offload the information from their working memory before it was forgotten. However, it could also be a function of how auditory responses times were sampled. Responses were measured from the offset of the auditory digit presentation rather than the onset (like in visual), which may have permitted drivers to anticipate and prepare for their response, or begin responding before the completion of auditory string articulation. Such a factor cannot however totally explain the auditory advantage in the secondary task response time, since this advantage was also observed in the lack of a single-dual task decrement, a decrement which was found in the visual condition.

While auditory responses were quicker than visual for the secondary task, there was no evidence of preemption in the lane keeping task. There were also longer responses (i.e., the time required to articulate the digit string) in auditory condition compared to the visual condition, suggesting that, in the auditory condition, there was code interference between the phonetic working memory of the digit information and the speech production of the response. The interaction between task load and display type for response duration further suggested that this within-task code interference was more pronounced for the higher task loads than for smaller loads. Not surprisingly, accuracy for the auditory task was significantly degraded compared to
the visual conditions. This was expected given that the auditory display consisted of a single presentation of the digits, exceeding, in some cases, the capacity of working memory (Miller, 1956). We might expect higher levels of accuracy, albeit longer responses, if drivers could elect to have the digits repeated in the auditory condition.

**Hazard Awareness**

To the extent that hazard detection (visual) and secondary digit task (auditory) use separate perceptual modalities, there should be a performance advantage for the auditory condition over the adjacent visual condition, unless the primary task of driving is emphasized (i.e., near single-task levels of performance). Overall, we did not find any modality differences in response times to the critical, hazard detection tasks. This suggests that optimal (and proximal) placement of visual information may offset the costs of shared perceptual resources, such that performance is similar to cross-modal task combinations. As noted previously, there are practical and important implications for these findings with respect to safety. A power analysis suggests that this absence of modality difference is truly a null effect (power = .80).

The results suggest that drivers are adequately protecting the driving task, regardless of the secondary display modality, as reflected in the proper lane keeping and hazard detection data. There are however differences in secondary task performance, with an auditory presentation yielded quicker dual-task responses to the secondary task yet equally long task completion times in both single- and dual-task conditions. There was no evidence for auditory preemption of the driving task for either the vehicle control or hazard awareness tasks.

**Dual- versus Single-Task Performance**

*Performance on Driving Tasks*

There were costs to lane keeping performance in dual-task (both visual and auditory) compared to single-task driving conditions, however these costs were no different across road type. This latter finding suggests that drivers are, to some extent, appropriately protecting the driving task, even in more demanding driving conditions, characterized by the urban and curved rural roads. This protection of the primary driving task is further supported by the null effect of increasing task load on lane keeping. If drivers did not protect the driving task then we would expect further degradation of driving performance in the higher task load conditions. There were also dual-task costs associated with speed control and these effects were more amplified in more difficult driving situations (i.e., urban, curved). The nature of these overall costs may be attributed to a general “cost of concurrence” (Navon and Gopher, 1979), whereby the driver, expecting the need to process secondary task events, diverts some resources from driving to handle task management. Alternatively, because the costs did not differ across displays, they might have been attributable to cross-modal, within-stage competition for response resources between steering, and vocal articulation of the secondary task. Both multiple resource models (Wickens, 2002) and single channel bottleneck models (Pashler, 1998) have articulated the particularly heavy competition for resources between response selection processes.
For the critical traffic events, there were no dual-task costs associated with response times compared to baseline (single-task) conditions. This was true for both visual and auditory modalities (with the exception of the HDD condition—an effect due to the large eccentricity, rather than dual-task load per se). As before, the power of these statistical comparisons was examined, given the relevance for traffic safety. In general, it appears as though these are truly null effects of dual-task costs (visual, power = .72; auditory, power = .76). As such, the important task of hazard awareness and detection is apparently being protected by the driver while engaging in a secondary task. It is unclear, however, whether this effect will generalize to less salient and/or more peripheral traffic events. At the same time, it should be noted that more peripheral traffic events are, with some exceptions, less intrinsically hazardous.

Secondary Task Performance

In examining dual-task costs for secondary task performance, we see that there were no costs in response time to the digit task in auditory conditions. It is likely that participants in both single- and dual-task conditions responded quickly in order to offload the digits from working memory before they were forgotten. In the visual conditions, however, there were slowed responses in dual-task conditions relative to single-task. Given that there were no rehearsal and memory demands for this visual task, drivers may have strategically delayed their responses to the secondary task in order to further protect the driving task (e.g., to scan the traffic environment or ensure proper vehicle alignment prior to engaging in secondary task). Response durations for dual- and single-task conditions did not differ for either the visual nor auditory conditions. Furthermore, there were no differences in accuracy for the visual conditions for dual- and single-task conditions, and surprisingly, there was a slight yet significant improvement in recall in the dual-task auditory condition compared to single-task.

Comparison with Controlled Laboratory Study

Given the similarity between the procedures and methods in the current study with those employed by Wickens, et al. (2002a), we now examine some of the findings reported in both experiments.

In the report by Wickens, et al. (2002a), there were primary tracking costs associated with the superimposition of digit information. In the current study, however, we did not find any such performance decrements, likely because there was more peripheral information available for drivers in support of these vehicle control tasks (rather than a fixed-point crosshair tracking target) and because the lower bandwidth, higher inertia tracking task employed here was probably more “forgiving” of brief diversions of attention. This suggests that the clutter effects in the Wickens, et al (2002a) study were more pronounced than in the current study, thus leading to degraded tracking performance.

With respect to display separation, there are notable similarities between the two studies. At wider eccentricities, it was apparent that observers required more glances to the side task in order to complete the more difficult (7- and 10-digit) task loads. This was illustrated through increased response durations for the secondary task under these conditions. There were also
slower response times to the digit task in the spatially separated displays, suggesting that the onset of the digit task was less salient or observers made fewer scans to monitor the display. In contrast to the previous study, the current results did not show a cost of increased separation on tracking error (lane keeping performance) reflecting again, either a greater robustness of driving to the brief diversion of foveal vision (because of the dynamics of the task, or the greater availability of peripheral vision), or the apparently greater intrinsic priority given to tracking in this study, compared to that given in the prior study.

Some of the reported effects of auditory presentation in Wickens, et al. (2002a) map nicely onto the current findings. First, auditory responses were faster than visual ones, though the response durations were longer, again due to code interference between digit rehearsal and the speech response—an effect that was amplified for higher task loads. The Wickens, et al. (2002a) study, however, reports an increase in tracking error in the auditory condition relative to the adjacent display, reflecting what they concluded to be an auditory onset “preemption effect”. This effect was not replicated in the current study, again suggesting the greater protection of tracking performance from attentional diversions.

**Theoretical Implications**

Several findings in the current study have implications for the model of visual attention and scanning presented in the Introduction (i.e., SEEV model; Wickens, 2001) as well as multiple resources models of time-sharing (e.g., Wickens, 2002). The SEEV model posits that visual scanning will be influenced by the interaction of the four factors of salience, effort, expectancy, and value. As noted in the Introduction, salience is driven by bottom-up processes while expectancy and value are driven by top-down processes. Effort, on the other hand, modulates the impact of the other variables in determining where visual attention will be allocated.

The current findings regarding spatial separation have implications for effort and saliency, and to a lesser degree, value. First, drivers took longer to respond to traffic events when using the (more separated) HDD, suggesting that the event was less salient because it fell in driver’s peripheral vision. Responses were faster in other conditions because the event occurred closer to the fovea—resulting in higher salience within the visual field. Likewise, responses to the secondary task were slower because of the degraded salience of the digit onset in the periphery. These slowed responses may have also been due to a decrease in the number of scans to the display to check for the digits. Because of the wide separation, such scanning required effort, which typically reduces the likelihood of accessing the separated information.

There was no loss in vehicle control performance, however, for the separated display. We can speculate that drivers were either able to use peripheral vision to adequately control their vehicle while engaged in the digit task or they adopted scan strategies to continue monitoring the traffic environment. While the former suggests that the vehicle control tasks can be accomplished with degraded peripheral vision (as other have shown; e.g., Summala, et al., 1996), the latter suggests that drivers are investing the effort to make multiple distant scans to support both the driving task as well as the in-vehicle task (e.g., Wierwille, 1993). The results would seem to support this strategy of making multiple scans, given the increased secondary response
durations for higher task loads. We might reason that the inherent value of the driving task, in terms of safe travel, is offsetting the costs of effort, such that drivers are willing to invest the extra effort so as to reduce the likelihood of making critical errors in the driving task.

In addition to the relevance to models of visual attention, the results of the current study show some support for models of multiple resources. Specifically, there is evidence to suggest that concurrent visual tasks can be time-shared when they rely upon separate visual channels. Vehicle control (lane keeping and speed control) can be maintained (to a certain degree) using the ambient visual channel while being performed concurrently with a secondary, focal visual task. However, this does not extend to two focal visual tasks (i.e., hazard awareness and the secondary digit task).

**Practical Implications**

As with previous studies, the current research highlights many important factors in assessing display location and modality. Ideally, drivers will be able to interact efficiently and, more importantly, safely with in-vehicle systems and telematic devices. Efficient display interaction involves the timely response to display information, as well as the rapid extraction of the relevant information. Safety, on the other hand, will be influenced by drivers’ ability to maintain proper vehicle control, as well as monitor the traffic environment for hazards and potentially dangerous situations. Obviously, safety is of critical importance—for both the users of in-vehicle technology as well as other road users.

Displaying information in a head-up location has the benefit of reducing the information access (i.e., time) costs associated with spatially separated displays. Indeed, the costs associated with the console-mounted head-down condition in the current study are clear. While drivers are able to maintain adequate lane and speed control, they have slowed responses to discrete traffic events, as well as degraded performance on in-vehicle tasks (i.e., slower response times and longer response durations). Moving the display into a position closer to the eye field (Previc, 1998) is an obvious solution. However, positioning the information too close to the driver’s line of sight (overlay), the source of most of the relevant driving information, may degrade driver’s ability to respond to truly unexpected, surprise traffic events. Although the current study can offer only mild support for this degradation (in terms of the accident frequency for initial incursion events), the lack of any discernable differences between the overlay and adjacent for any of the other performance measures (lane and speed control, secondary response time, duration, and accuracy) would seem to suggest that the adjacent presentation would be the better candidate. From a technical perspective, it would also seem to be the more technologically feasible (e.g., Gish & Staplin, 1995; Ward & Parkes, 1994).

The auditory presentation of side task information did not impact vehicle control and safety differently than adjacent visual presentation. Drivers were able to respond to the auditory side task quicker, however took longer to complete the task. There were also costs in accuracy for the auditory side task compared to visual. Given the speed-accuracy tradeoffs in secondary task performance, the appropriate modality for a given display may be assessed on a task-by-task basis. For instance, a task requiring accuracy (e.g., obtaining a correct phone number) may be
better represented visually whereas a task that may require more speeded responses (e.g., response to navigation instructions) may benefit from an auditory display—assuming, of course, that the presentation of navigation information would consist of lower task loads, so as not to impair accuracy, an important part of way-finding.

The side task employed in the current study required only limited cognitive processing on the part of the driver and did not involve much interaction (i.e., seeking specific display-related information) or decision-making. While more comprehensive, interactive tasks may not reveal any different findings for visual display location, modality differences in such tasks should also be explored, to expand the generalizability of the current findings.

Drivers in the current study did an adequate job of protecting the primary task of driving under different display and task load conditions. However overall, there were dual-task costs associated with vehicle control, though not for hazard detection. It is not clear from the current findings whether this decrement could be reduced of mitigated through long-term exposure to the secondary task or through training. Given the benefits yielded by adjacent and/or auditory presentations relative to the other conditions, targeted dual-task training for these displays may be an important, safety-related consideration, prior to widespread automotive application of in-vehicle systems.

ACKNOWLEDGEMENTS

Thanks to Nicholas Cassavaugh and Braden Kowitz (Integrated Systems Laboratory, Beckman Institute) for their help in programming and coordinating various components of the simulation and software. Thanks to Hank Kaczmarski (ISL) for his input and work in installing various pieces of hardware. We also thank Art Kramer for his comments and suggestions and Roger Marsh, for his input on computer equipment. Thanks to General Motors for funding the grant which allowed the current research to take place.

REFERENCES


Hancock, P.A., Lesch, M., & Simmons, L. (in press). The distraction effects of phone use during a crucial driving maneuver. *Accident Analysis and Prevention*.


## APPENDIX A. SELECT DETAILS FOR PARTICIPANTS

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age</th>
<th>Gender</th>
<th>Annual mileage (miles)</th>
<th>Questionnaire Self-Reports†</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cell phones¹</td>
</tr>
<tr>
<td>1</td>
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<tr>
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<td>21</td>
<td>M</td>
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<tr>
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<td>F</td>
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<td>F</td>
<td>3,000</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
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<tr>
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<td>F</td>
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<td>M</td>
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</tr>
<tr>
<td>25*</td>
<td>21</td>
<td>F</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Ceased participation after experiencing symptoms of motion sickness.
† 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. URBAN AND RURAL ROADWAYS
APPENDIX D. HYPERDRIVE TILES USED FOR DRIVING SCENARIOS

<table>
<thead>
<tr>
<th>Zone</th>
<th>Tile Description</th>
<th>Tile Name(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>2-lane straight</td>
<td>rur2p001-005</td>
</tr>
<tr>
<td></td>
<td>90-degree turn</td>
<td>rur290n001-002</td>
</tr>
<tr>
<td></td>
<td>Extended curve</td>
<td>rur2n001-002</td>
</tr>
<tr>
<td>Urban</td>
<td>4-lane straight</td>
<td>urb4n001-003</td>
</tr>
<tr>
<td></td>
<td>T-intersections (minor)</td>
<td>urb4c2urb2</td>
</tr>
<tr>
<td></td>
<td>Major 4-way intersections</td>
<td>urb4xb001-003, 005-007</td>
</tr>
<tr>
<td>Transition</td>
<td>Rural (w/ center lane) to rural (2-lane)</td>
<td>rurc2rur</td>
</tr>
<tr>
<td></td>
<td>Residential to rural</td>
<td>res2rur</td>
</tr>
<tr>
<td></td>
<td>Suburban to residential</td>
<td>sub2res</td>
</tr>
<tr>
<td></td>
<td>Urban to suburban</td>
<td>urb2sub</td>
</tr>
</tbody>
</table>
APPENDIX E. CRITICAL EVENT SPECIFICATIONS

<table>
<thead>
<tr>
<th>Event</th>
<th>Zone</th>
<th>Entity Name</th>
<th>Initial θ (in °)†</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian Incursion</td>
<td>Urban</td>
<td>&quot;Caucasian Male&quot;</td>
<td>5.2 x .9</td>
<td>Emerges from behind a delivery truck</td>
</tr>
<tr>
<td>Bike Incursion</td>
<td>Urban</td>
<td>&quot;Bicycle&quot;</td>
<td>1.8 x 2.9</td>
<td>Emerges from behind a delivery truck</td>
</tr>
<tr>
<td>Dog Incursion</td>
<td>Urban</td>
<td>&quot;Dog, Running&quot;</td>
<td>3.5 x 4</td>
<td>Emerges from behind an SUV</td>
</tr>
<tr>
<td>Vehicle Incursion</td>
<td>Rural</td>
<td>&quot;Grand Prix Blue&quot;</td>
<td>3 x 6.9</td>
<td>Initially hidden by hedgerow</td>
</tr>
<tr>
<td>Parked Car Pullout</td>
<td>Urban</td>
<td>&quot;Grand Prix Red&quot;</td>
<td>1.6 x 4.6</td>
<td>Initially parked in front of a delivery truck</td>
</tr>
<tr>
<td>Lane Drift</td>
<td>Rural Straight</td>
<td>&quot;Montero Dark Blue&quot;</td>
<td>.9 x 1</td>
<td>-</td>
</tr>
<tr>
<td>Lane Drift (Turn)</td>
<td>Rural Curved</td>
<td>&quot;Lexus Gray&quot;</td>
<td>1.2 x 2.8</td>
<td>-</td>
</tr>
<tr>
<td>LTAP</td>
<td>Urban</td>
<td>&quot;Tacoma White&quot;</td>
<td>2.3 x 6</td>
<td>-</td>
</tr>
<tr>
<td>Wide Right Turn</td>
<td>Rural</td>
<td>&quot;Grand Prix Green&quot;</td>
<td>1.6 x 2.5</td>
<td>Initially parked in rural driveway</td>
</tr>
<tr>
<td>Light Change</td>
<td>Urban</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

† Approximate initial visual angle (height x width) of the entity at the onset of the event.
APPENDIX F. SIMULATOR SICKNESS PRE-SCREENING 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 G. INFORMED CONSENT

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 H. PRE-EXPERIMENTAL QUESTIONNAIRE

Age: ______  Sex:  M  F  Handedness:  R  L  Health:  1  2  3  4  5

Do you wear Glasses/Contacts on a regular basis?  N  Y

How many years of school have you completed?  ________________

Phone Number: __________________  E-mail: __________________

Can we call you to participate in additional experiments?  Yes  No

Where did you hear about us?  ________________________________

Signature of Participant: ____________________________________ Date: __________________

Name: ________________________________  (Please Print)

Social Security Number _______ - ______ - _______

************************************************************************

For Office Use Only

Far Vision: _______  Near Vision: _______  Color-Blindness: _______

Time IN: _______  Time OUT: _______  Total Time: _______

Pay for Exp: _______  Parking: _______  Total Pay: _______
APPENDIX I. EXPERIMENTAL PROTOCOL

Begin with informed consent form, pre-experiment questionnaire, and test for visual acuity.

Minimum visual functioning: acuity 20/30.

Today you will be driving through four different scenarios. Each drive lasts roughly 17 to 20 minutes and will consist of both 2-lane rural roads as well as more complex urban roads. 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 (5 minute) scenario in which you will not be required to drive. You will be given rest periods in between in 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. During urban stretches, you will be required to make some turns. These turns will be indicated by route signs. You’ll see examples of these in the practice trial. In addition, we ask that you observe the following (emphasize these points):

- On rural roads, the speed limit is 55 mph. We ask that you keep you velocity within 5 mph of this value. If you deviate too much, you will be notified.

- On urban roads, the speed limit is 30 mph. Again, we ask that you stay within 5 mph of this value.

- In addition, we ask that, on urban stretches, you stay in the right-hand lane unless required to make a left hand turn (as indicated by the route signs).

- On all roads, try to keep your vehicle positioned in the center of your respective 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. Show samples of route signs.
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.
3. (In urban setting), decelerate to 30 mph and maintain. Note sound and flow.
4. Make a right hand turn.

(If necessary), while making right and left hand turns in the urban setting, it may help if you fixate on a single location though the turn. This tends to decrease symptoms of motion sickness. For instance, fixate on a parked vehicle around the corner in the direction of the turn.

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 either 4, 7, or 10 digits long and will appear in one of three places: superimposed on the horizon line of the road (these will be shifted to the left or right when turning), superimposed on the road right above the hood of your vehicle, or on this display located down near your center console. Alternatively, they may be presented aurally through the car speakers. You will always know beforehand how these digits will be presented (it will be constant for each given scenario).

When the numbers are presented visually (in one of the three locations) or when they are heard through the speakers, you will be required to read the numbers back. Note that in the auditory condition, the numbers will only be presented a single time. As soon as you notice the digits you should try to respond to them. As soon as you start to respond, you will press the horn a single time (Show use of horn). When finished reading them back (or after reading back as many as possible in the auditory condition), you will hit the button again. In the visual conditions, this second button press will make the digits disappear. Try to keep one hand near the horn, such that you can reach the horn easily.

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

The number digits will appear every 15 to 30 seconds, on average.

Do you have any questions about this secondary task?

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

General directions (adjust according to particular block):
During this drive the number digits will be presented (horizon, above hood, on display, aurally). Remember to hit the button once at the start of your response and once at the end of it. Drive as you normally would, but adhere to the requirements specified previously (*repeat if necessary*). The drive should last roughly 17 to 20 minutes.

For auditory: Remember to hit the horn when you respond in this condition!

(*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.

Following the five blocks, give participants final questionnaire, debrief, answer questions, and pay them for their participation. Try to ensure that this time exceeds 15 minutes, or that the participant is not going to be driving immediately following the session.
## APPENDIX J. EXPERIMENTAL TRIAL ORDERS

<table>
<thead>
<tr>
<th>Order #</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>A1U*</td>
<td>B2U</td>
<td>C3U</td>
<td>D4U</td>
<td>E</td>
</tr>
<tr>
<td>2</td>
<td>C2U</td>
<td>D1U</td>
<td>A4U</td>
<td>E</td>
<td>B3U</td>
</tr>
<tr>
<td>3</td>
<td>B4U</td>
<td>A3U</td>
<td>E</td>
<td>D2U</td>
<td>C1U</td>
</tr>
<tr>
<td>4</td>
<td>D3U</td>
<td>E</td>
<td>C4U</td>
<td>B1U</td>
<td>A2U</td>
</tr>
<tr>
<td>5†</td>
<td>E</td>
<td>AU</td>
<td>BU</td>
<td>CU</td>
<td>DU</td>
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<tr>
<td>6</td>
<td>A1R*</td>
<td>B2R</td>
<td>C3R</td>
<td>D4R</td>
<td>E</td>
</tr>
<tr>
<td>7</td>
<td>C2R</td>
<td>D1R</td>
<td>A4R</td>
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<td>8</td>
<td>B4R</td>
<td>A3R</td>
<td>E</td>
<td>D2R</td>
<td>C1R</td>
</tr>
<tr>
<td>9</td>
<td>D3R</td>
<td>E</td>
<td>C4R</td>
<td>B1R</td>
<td>A2R</td>
</tr>
<tr>
<td>10†</td>
<td>E</td>
<td>DR</td>
<td>CR</td>
<td>BR</td>
<td>AR</td>
</tr>
</tbody>
</table>

A-D = Driving scenarios with different event types  
E = Baseline for secondary tasks (auditory and visual). No route or events.

1 = HUD Overlay  
2 = HUD Adjacent  
3 = HDD Console  
4 = Auditory

U = Urban start point  
R = Rural start point

* U and R start points are varied to reverse the order in which the events take place within a scenario.

† Orders #5 and #10 are baseline measures for emergency events—there is no secondary task during the onset of the event.
APPENDIX K. VISUAL DISPLAYS AND ANGULAR SIZE OF DIGIT STRINGS

<table>
<thead>
<tr>
<th>HUD Overlay / Adjacent</th>
<th></th>
<th>HDD Console</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height</td>
<td>Width</td>
<td>Height</td>
</tr>
<tr>
<td>4-digits</td>
<td>0.7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>7-digits</td>
<td>0.7</td>
<td>5.6</td>
<td>1</td>
</tr>
<tr>
<td>10-digits</td>
<td>0.7</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: Units are expressed in degrees of visual angle subtended by digit strings from average driver eye point.
APPENDIX L. POST-EXPERIMENTAL QUESTIONNAIRE

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.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td>1-2 times per month</td>
<td>3-4 times per month</td>
<td>3-4 times per week</td>
<td>Everyday</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
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<tr>
<td>Never</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rarely</td>
<td></td>
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</tr>
<tr>
<td>Occasionally</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Often</td>
<td></td>
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</tr>
<tr>
<td>Always</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>Rarely</td>
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<tr>
<td>Often</td>
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<tr>
<td>Always</td>
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</tbody>
</table>

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

Thank you very much for your time and effort!