

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

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In-vehicle technologies (IVTs) create additional tasks for the driver. To the extent that these devices degrade driving performance, there will be safety concerns. This study examines the effects of display clutter from overlay, display separation, and modality on driving and IVT task performance. In a fixed-base simulator, 22 drivers drove different routes and responded to infrequent, unexpected road hazards while engaging in a phone number task presented by different displays. Visual displays were located on a head-up (overlaid on the visual horizon or adjacently, just above the vehicle hood) or head-down display (HDD) located near the midconsole. Alternatively, digits were presented auditorily. In general, there were no differences in performance for the adjacent and overlay displays; however, there were costs associated with the HDD and auditory display for some measures. In particular, responses to hazard events were slowed when drivers used the HDD. Overall, the adjacent display best supported performance on all relevant tasks. Potential applications of this research include the design of IVTs with respect to location and modality.

INTRODUCTION

The introduction of new in-vehicle technologies (IVTs), telematics, and “infotainment” into the automobile creates additional tasks that drivers may perform concurrently (Ashley, 2001). Drivers will need to access and process information from multiple sources in order to complete these tasks while maintaining safe vehicle control and guidance. The costs associated with accessing this information and 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). As they relate to display location (relative to the outside world) and presentation modality (visual or auditory), these costs and their impact on driver safety and performance provide the framework for the present research.

Performance of multiple tasks depends on a number of mechanisms. As represented in the

multiple resource theory, these include resource demands (i.e., task difficulty) and task structure (i.e., which resources), which affect the time-sharing interference between tasks, and resource allocation policy, which dictates which task bears the brunt of the interference (Wickens, 2002). The multiple resource model characterizes task structure along four dimensions: processing stage, processing code, perceptual modality, and visual channel. To the extent that concurrent tasks share common resources along each dimension, there will be increased task interference (Wickens, 2002). With particular relevance to driving, two visual tasks will compete for visual attention, which often can be allocated to only one place at a time, thereby disrupting task performance. The qualification of this constraint is the added distinction within the multiple resource model, which differentiates between the focal and ambient visual channels (Leibowitz & Post, 1982; Previc, 1998; Weinstein & Wickens, 1992).

Focal vision, which generally refers to the foveal region, is used in tasks requiring the discrimination of fine details (e.g., reading and object recognition). Ambient vision, in contrast, is employed for tasks involving the 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. Information from these different channels may be used in support of different aspects of the driving task. For example, peripheral ambient vision may be used for vehicle control (lane keeping; Summala, Nieminen, & Punto, 1996), whereas foveal focal vision may be required for the effective detection and identification of hazards (Lamble, Laakso, & Summala, 1999), although neither task relies exclusively on one type of vision or the other. To the extent that tasks compete for a common resource-defining channel (e.g., two focal tasks), there will be degraded performance for one or both tasks (depending on resource allocation policy), and this task interference is related to access and perceptual processing costs associated with task-relevant information.

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; Wickens, 1992). A number of studies have demonstrated benefits of reduced scanning using head-up displays (HUDs), as compared with 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., Sojourner & Antin, 1990; Wickens & Long, 1995). These benefits, however, may be reduced or even reversed in conditions of high workload (Gish & Staplin, 1995) or in response to unexpected events (Fadden, Wickens, & Ververs, 2000; Tufano, 1997; Weintraub & Ensing, 1992). This degradation may be attributable to the increased visual clutter inherent in the overlay of multiple displays.

Information may also be presented auditorily. Because visual and auditory information share different perceptual resources, they may be time-shared more effectively than would two visual inputs (Wickens, 2002). Numerous studies have

supported this performance advantage (see Wickens, 1980, and Wickens & Liu, 1988, for reviews). However, other studies have suggested that auditory inputs may sometimes preempt performance of a visually displayed primary task by virtue of both the intrinsic alerting characteristics of an auditory onset (Spence & Driver, 1997; Wickens, Dixon, & Seppelt, 2002; Wickens & Liu, 1988) and the need for operators to deal immediately with longer strings of auditory material before they are lost from working memory (Helleberg & Wickens, 2003; Latorella, 1998). In either case, the effect of preemption may be described as pulling full attention away and temporarily neglecting the primary visual task; this diversion, because of the onset or the need to rehearse, would be more serious than that for a visual presentation of equivalent information.

Past research on IVT displays in the driving context has employed a wide variety of different methodologies, task demands, and performance measures (e.g., Gellatly & Kleiss, 2000; Gish & Staplin, 1995; Gish, Staplin, Stewart, & Perel, 1999). In general, most have demonstrated a performance advantage for HUDs (reduced information access costs) for one or both tasks relative to head-down presentation. Additionally, there has been evidence that better performance is obtained when using an auditory presentation of side task information (e.g., Gish et al., 1999; Parkes & Coleman, 1990); however, these findings have been less robust, given the offsetting influences of resource separation and auditory preemption (e.g., Lee, Gore, & Campbell, 1999; Matthews, Sparkes, & Bygrave, 1996; see Seppelt & Wickens, 2003, for a recent review).

In general, few (if any) studies have concurrently measured lane keeping (ambient vision), hazard response (focal vision), and IVT task performance (to examine performance trade-offs); manipulated both primary and secondary task demands; and compared multiple visual locations with auditory presentation of the same IVT information within the structured context of the multiple resource space. Such a comprehensive examination is necessary in order to assess the joint contributions of ambient vision and focal vision, as these are influenced by the attentional mechanisms of clutter filtering (from

HUD overlay), information access (from separation), auditory preemption, 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 (rural curved, straight, urban) while engaged in a secondary phone number voice dialing (IVT) task of varying difficulty. At various times throughout the drive, strings of 4, 7, or 10 digits were presented either visually (head up or head down) or auditorily to the driver and were subsequently recalled vocally. Digit length was manipulated, thereby varying working memory load, in order to better address the influence of preemption in the auditory condition. Driving performance was measured by lane keeping and speed control (ambient vision) and also by the response to eight critical hazard events (focal vision) that required an emergency control response (e.g., pedestrian incursion). Except in the control conditions, these events coincided with the onset of an IVT task.

We chose a relatively demanding IVT task that we knew would compete for resources with driving. We hypothesized that participants would choose an allocation policy such that driving would be more protected from interference than would the IVT task. However, we were particularly interested in the extent to which drivers could protect the two different aspects of driving (vehicle control and hazard detection) from the increasing resource competition attributable to task structure (i.e., shared visual resources [vs. auditory] and shared focal resources [head up vs. head down]) and from the increasing demand attributable to changes in overall task difficulty (driving and IVT load).

METHODS

Participants

Twenty-two drivers (14 men, 8 women) 18 to 29 years of age ($M = 22$ years) volunteered for this study. All had valid driver's licenses and, on average, drove 4750 miles (7643 km) per year. All participants were screened for normal or corrected-to-normal visual acuity. An additional 3 drivers were recruited, but their data were omitted from analysis because of system malfunctions.

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° wraparound forward screen and a 45° rear field. Auditory messages were presented through a 3-D surround sound system. The head-down (in-vehicle) display (HDD) was an AEI 6.4-inch (16.3-cm) LCD monitor with 640 × 480 pixels of resolution.

The simulator environments were created and coordinated with DriveSafety's HyperDrive Authoring Suite™ and Vection Simulation Software™ Version 1.4.2. A more detailed account of the simulator hardware and software can be found in Horrey and Wickens (2002).

Side task displays. Side task information was presented aurally or at three different visual display locations. One visual display (overlay) was presented in a simulated head-up display superimposed on the horizon line (0° separation). A 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). This location is 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). A third visual display (HDD) was located on an LCD 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). A fourth display was auditory, which presented the digit strings through the simulator vehicle's speaker system via synthesized voice, speaking at a rate of approximately 4 digits/s.

Driving environment overview. Each route consisted of two-lane bidirectional rural roads (both straight and curved sections) and four-lane bidirectional urban roadways. As such, there were three road types: urban straight, rural straight, and rural curved (curve radius = 210 m), with total driving time divided roughly equally across these types. Moderate levels of ambient traffic were present on each of the road types (at a rate

of approximately 9–10 vehicles/km of roadway). No parked vehicles were present on the rural stretches; however, many were present in the urban setting.

Critical events. Eight hazard events occurred at random locations throughout the drives. In an attempt to reduce driver expectancy and anticipation, we varied the events in terms of obstacle type and configuration, but all events required a maneuver to avoid a collision. For each event, time-based triggers allowed drivers approximately 2.5 to 3.0 s to make their response. For nonbaseline conditions, the events occurred in conjunction with the secondary side task (approximately 0.75 s after the onset of the side task). Five different events involved object incursions (a pedestrian, an animal, a bicycle, and two vehicle incursions) that originated from behind an occluding object on the right side of the lane. Additionally, three events involved oncoming vehicles that drifted into the driver's lane from the left side.

Procedure

Prior to participating, the recruits responded to an E-mail or phone simulator sickness questionnaire. At the start of the 120-min session, participants completed an informed consent form and a brief demographic questionnaire and were screened for visual acuity.

After participants sat in the simulator, adjustments to the seat were made, and then an introduction to the various components of the driving simulator was presented. Participants were then given a 5-min training session to familiarize them with the simulator control dynamics. 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 and 30 mph (88.5 and 48.3 kph), respectively.

As participants navigated through the routes, they were asked to complete, as best they could, a secondary IVT phone number entry task characterized by voice entry of a phone number that contained 4, 7, or 10 digits. In different blocks of trials, this task was presented through one of the four different displays. The interstimulus interval for the side task varied between 10 and

30 s. Participants were instructed to respond to the digits as quickly as possible but not to compromise safe driving in doing so. Upon noticing the digits, participants pressed a button mounted on the steering wheel, read out the digits contained in the string, and then pressed the button a second time when they finished their response. This system is analogous to voice-entry systems that require the user to cue the system when a command is being issued.

Driving performance measures of absolute lane position, variability in lane keeping (which is an index of steering activity), and variability in speed control were recorded during completion of this secondary task as well as throughout the trial when no secondary task was present (i.e., baseline conditions; these periods were, on average, the same duration as the response intervals). Also, performance for the IVT task was assessed by the time to initiate, time to complete, and accuracy of the read back.

Additionally, during each block participants were exposed to two or three critical hazard events, coincident with the presentation of a 7- or 10-digit IVT task (except for baseline). Perception-response times were recorded from the onset of each event until a steering or brake response was initiated (whichever was first).

Drivers completed five experimental blocks, which were counterbalanced across participants. Each participant completed a 20-min block with each of the four different display conditions (overlay, adjacent, HDD, and auditory) and a 5-min baseline block for the IVT task. This block included the auditory and head-up (horizon) visual displays of numerical digits but no driving task. Participants were offered a short break between blocks.

Experimental Design

The experiment had a within-subjects design with the variables of display type (overlay, adjacent, HDD, auditory), road type (urban straight, rural straight, rural curved, no drive), and task load (no task, 4 digits, 7 digits, 10 digits). Because the critical events were encountered a single time by each participant under different display conditions, they were not examined in terms of road type or task load (because these were not manipulated for the critical events).

RESULTS

Performance on the driving task (vehicle control and hazard avoidance) and the IVT task was assessed through a number of analyses across display, road type, and task load. Whenever relevant, a series of conditionalized post hoc comparisons was employed to investigate specific hypotheses (Keppel, 1982). These comparisons were aimed at investigating display differences attributable to clutter (overlay vs. adjacent), separation (adjacent vs. HDD), or modality (adjacent vs. auditory). A modified Bonferroni test was used to control the familywise error rate (see Keppel, 1982, for a detailed explanation).

Data from 1 of the 22 participants were excluded from the overall analysis of driving and secondary task performance because of missing data values for some of the conditions. However, data from this participant are included in the analysis of the critical traffic events.

Driving Performance

Lane position was determined by measuring the absolute deviation of the vehicle (in meters) relative to the center of the vehicle’s lane. As shown in Figure 1, a three-way repeated measures analysis of variance (ANOVA) revealed a significant effect of task load, $F(3, 60) = 25.7, p < .001$, such that there were dual-task costs to lane keeping associated with the IVT (with

load, $M = 0.42$ m), as compared with single-task driving, (no load, $M = 0.32$ m), $t(20) = 6.1, p < .001$. There was also a significant effect of road, $F(2, 40) = 11.1, p < .001$, with increased error in lane keeping on curved sections of roadway ($M = 0.45$ m) as compared with straight rural ($M = 0.39$ m), $t(20) = 3.5, p = .002$, and urban stretches ($M = 0.33$ m), $t(20) = 4.5, p < .001$. There was, however, no overall effect of display, $F(3, 60) = 0.55, p = .65$, nor were the two- and three-way interactions significant ($ps = .36-.66$). The lack of any interactions suggested that given the obligatory costs for dual-task performance, there were no additional performance costs for the different displays in the more challenging road and IVT conditions.

We further explored vehicle control by examining the variability in lane keeping during IVT task intervals. A repeated-measures ANOVA revealed a significant effect of display, $F(3, 60) = 10.6, p < .001$, road, $F(2, 40) = 52.2, p < .001$, and task load, $F(3, 60) = 42.8, p < .001$. As shown in Figure 2, there was increased variability in tracking performance in the HDD ($M = 0.14$ m) and auditory conditions ($M = 0.15$ m) relative to the adjacent condition ($M = 0.13$ m), $t(20) = 3.4, p = .003$, and $t(20) = 3.8, p = .001$, respectively. There were, however, no differences between the adjacent and overlay ($M = 0.12$ m) conditions, $t(20) = 1.3, p = .22$. As shown by the significant Display \times Road interaction, $F(6, 120) = 3.5, p = .003$, there was particularly

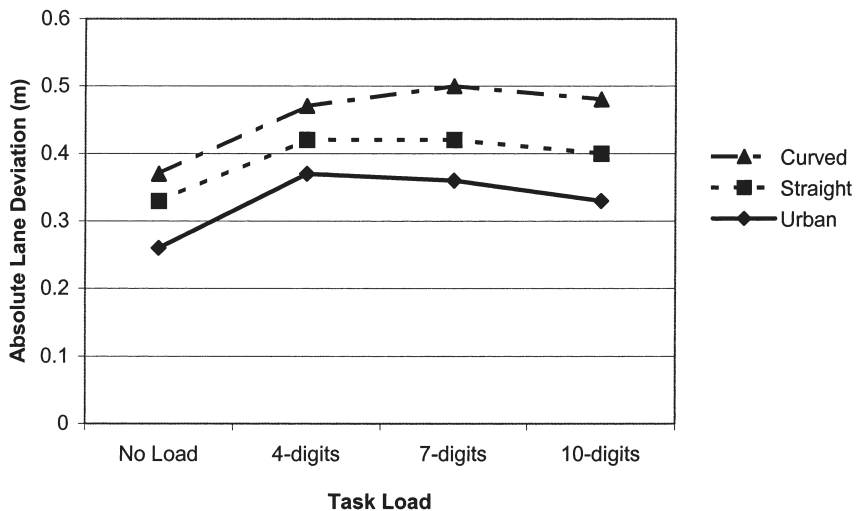


Figure 1. Absolute lane deviation by task load and road type.

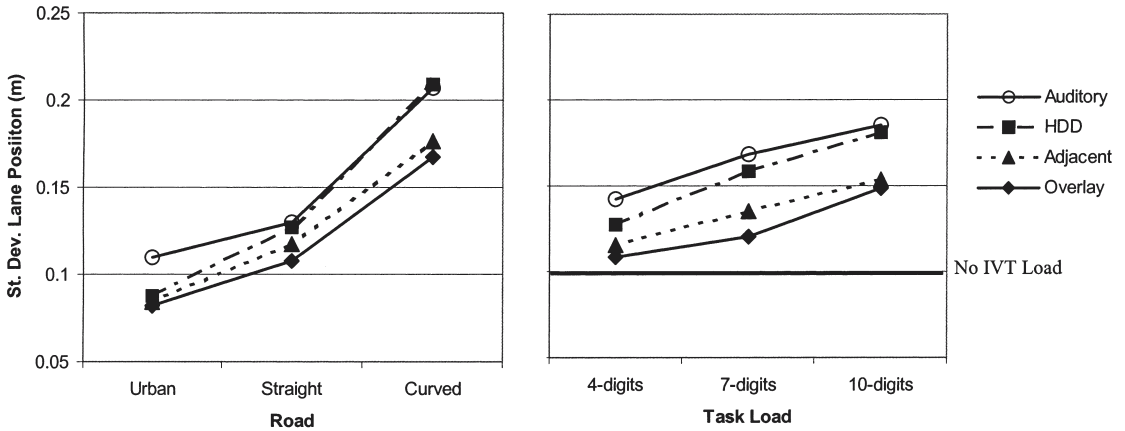


Figure 2. Variability in lane position by display type, road (left), and IVT task load (right). Thick horizontal line in right graph depicts single-task driving performance.

greater variability for the HDD and auditory conditions on curved sections of roadway, relative to straight sections, $t(20) = 4.1, p = .001$, and $t(20) = 3.2, p = .005$, respectively. Although variability increased relative to the single-task baseline, there was no Display \times Task Load interaction, $F(6, 120) = 0.7, p = .66$ (see Figure 2), for the three levels of IVT load.

Speed control was examined by measuring the standard deviation of vehicle velocity sampled during IVT task intervals and during baseline periods. These data are presented in Figure 3. A repeated measures ANOVA revealed significant main effects for display, $F(3, 60) = 11.3, p < .001$, road, $F(2, 40) = 54.7, p < .001$, and task load, $F(3, 60) = 44.8, p < .001$. In general, there was greater variability in performance in dual-

task conditions (no task load, $M = 0.13$ m/s; all task loads, $M = 0.22$ m/s), $t(20) = 7.3, p < .001$, when using the auditory display ($M = 0.29$ m/s) as compared with the visual displays ($M = 0.20$ m/s), $t(20) = 6.3, p < .001$, and with increasing task load (see Figure 3). There were no differences, however, between the adjacent ($M = 0.18$ m/s) and overlay ($M = 0.20$ m/s) conditions, $t(20) = 1.1, p = .28$, or between the adjacent and HDD conditions ($M = 0.21$ m/s), $t(20) = 1.4, p = .18$. Further examination of the significant Display \times Road interaction, $F(6, 120) = 3.4, p = .004$, suggested that the costs in speed variability for the auditory condition were amplified in urban settings relative to the visual conditions on straight and curved rural sections.

Thus, in general, there were performance

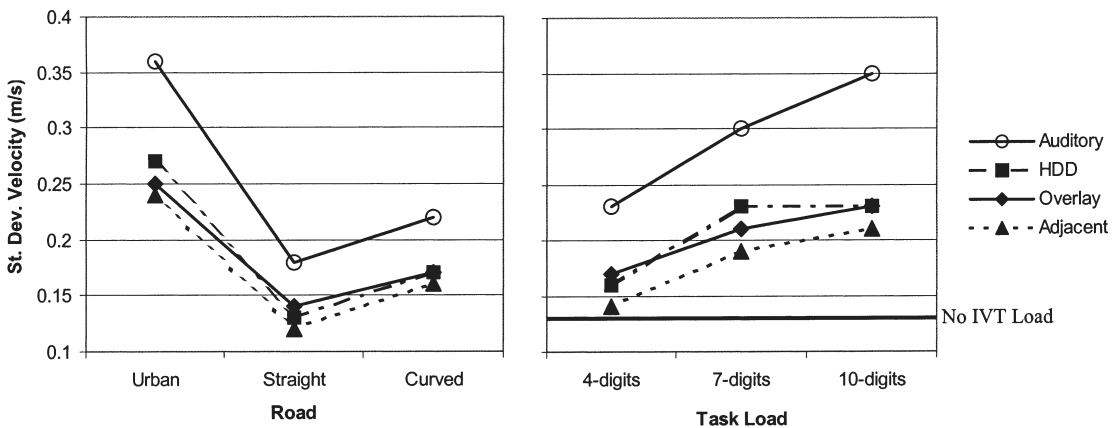


Figure 3. Variability in speed control by display type, road (left), and task load (right). Thick horizontal line in right graph depicts single-task driving performance.

costs associated with all dual-task situations for all three measures of the continuous aspects of vehicle control (absolute lane deviation, variability in lane keeping, and speed control). Given these costs, however, there were no additional costs attributable to display clutter (overlay vs. adjacent condition). Although performance with the separated HDD was equal to that with the adjacent HUD for absolute lane deviations and speed control, there was a slight increase in variability in lane keeping, especially for the more challenging conditions (e.g., curved roads and 10-digit task loads). These results suggest that drivers were generally able to protect lane keeping in the driving task from further degradation with the separated display by either (a) using peripheral vision to control the vehicle or (b) adopting a scan strategy to allow them to switch attention to and from the roadway appropriately, coupled with more substantial corrective steering wheel inputs.

Finally, there were some costs associated with the auditory presentation of IVT information (in variability in lane keeping and speed control), and these were amplified at higher levels of workload. These costs may have been attributable to task preemption and the added rehearsal and memory component of this task or, in the case of speed control, to auditory perceptual interference with the ambient road noise present in the simulator, which is in itself a salient cue for speed control.

Response Times to Critical Events

Responses to the critical hazard events were pooled across road type in the following analyses to increase statistical power, in order to reduce the likelihood of Type II statistical errors. These errors should be minimized when examining safety-critical events (Wickens, 2001). Where relevant, we include the power of the statistical test.

Figure 4 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). A one-way ANOVA revealed a significant effect of display type, $F(4, 177) = 3.7, p = .006$. Post hoc comparisons (two-sample, one-tailed t tests) examined the impact of display separation, modality, dual-task interference, and clutter. There were increased response times for the HDD ($M = 1.68$ s) as compared with the adjacent condition ($M = 1.50$ s), $t(72) = -2.49, p = .02$, indicating performance costs for the separated display in recognizing and responding to hazards. This degradation in response time to discrete events at larger eccentricities is consistent with previous findings (e.g., Lamble et al., 1999). There were, however, no differences in response times across modality (adjacent visual vs. auditory),

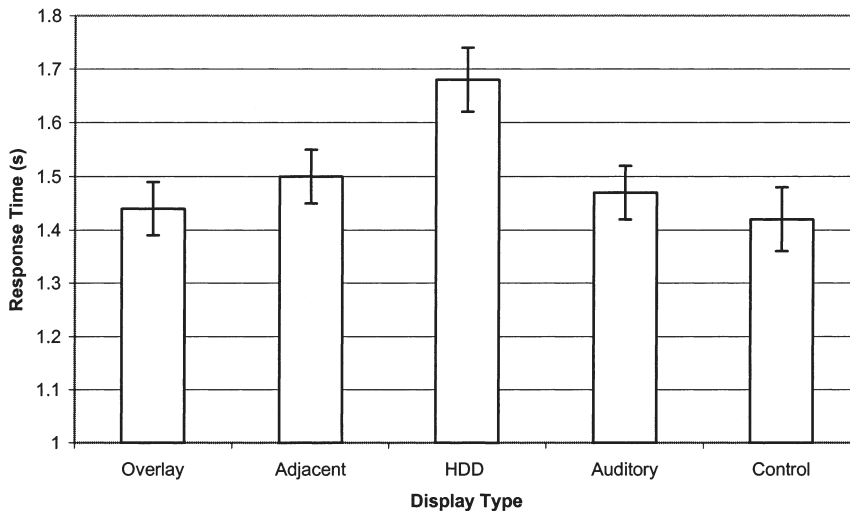


Figure 4. Average response time to critical events by display type.

$t(77) = 0.45, p = .65, \text{power} = .80$, nor was there any suggestion of dual-task costs associated with these discrete events: control $M = 1.42$ s; dual-task visual $M = 1.50$ s, $t(70) = 1.1, p = .27, \text{power} = .72$; dual-task auditory $M = 1.47$ s, $t(69) = 0.65, p = .52, \text{power} = .76$.

A two-sample t test (one tailed) for overlay and adjacent HUD conditions did not yield any differences between the two display locations, $t(75) = -0.86, p = .39, \text{power} = .72$, suggesting that the presence of information overlap and clutter did not disrupt drivers' ability to detect and respond to the critical events. However, given that previous research has reliably demonstrated costs associated with superimposed (i.e., cluttered) head-up information and responses to truly surprising, unexpected events (e.g., Fadden et al., 2000), we examined the first occurrence of an incursion event for the overlay and adjacent conditions. It is assumed that the first occurrence of such events was truly surprising and unexpected, whereas subsequent ones were just temporally uncertain. Although there were no differences in the response times for this subset of 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) as compared with no collisions (out of three) in the adjacent condition. Because of the low N , any meaningful statistical analysis was precluded; however, the collision frequencies for the overlay display may offer some support for the notion that cluttered displays interfere with the effective response to truly unexpected events.

In summary, the responses to the discrete, critical events revealed three important findings. First, there was a 0.2-s time cost in responding to critical events with increased display eccentricity (HDD), a time during which a car traveling at 55 mph (88.5 kph) could travel an additional 20 feet (6.1 m). Second, there were no dual-task costs in response times for display conditions that did not involve peripheral vision (i.e., all conditions except the HDD), nor were there costs or benefits of auditory presentation of IVT information. Third, there did not appear to be any time costs of clutter (overlay) in detecting and responding to the critical events; however, there were increased collisions in overlay conditions for the initial, and therefore more surprising, incursion event.

Secondary Task Performance

For the three visual display conditions, IVT task response time (RT) was measured from the onset of the digit string until the verbal response was initiated. In contrast, RT 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. Because of this potential artifact, we highlight comparisons of visual and auditory RTs with their respective baseline (single-task) performance demands (i.e., dual-task decrement), as opposed to direct comparisons between the two modalities.

A repeated measures ANOVA for the variables of display, road type, and task load revealed no significant effect of task load on IVT response time, $F(2, 40) = 0.4, p = .66$. Although there were significant effects of display, $F(3, 60) = 52.1, p < .001$, and road type, $F(3, 60) = 20.2, p < .001$, these are best interpreted in terms of their significant two-way interaction, $F(9, 180) = 2.9, p = .003$. As shown by the bottom set of four lines in each panel of Figure 5 depicting RT, dual-task auditory RT ($M = 0.4$ s) did not differ from that of the single-task auditory (no-drive) condition ($M = 0.3$ s), $t(20) = 0.5, p = .64$, whereas in the visual conditions response times were slowed down substantially (by approximately 0.25 s) by the presence of the concurrent driving task (visual baseline $M = 0.8$ s, adjacent $M = 1.1$ s), $t(20) = 5.1, p < .001$, even in the overlay condition, in which the visual onset of the secondary task would probably be in foveal vision.

Additionally, RT performance with the HDD was slower ($M = 1.2$ s) than with the adjacent display ($M = 1.1$ s), $t(20) = 2.3, p = .03$, suggesting increased information access costs associated with the more eccentric display. Performance with the overlay ($M = 1.1$ s) and adjacent HUDs ($M = 1.1$ s) was equivalent, $t(20) = 1.4, p = .17$. The Display \times Task Load interaction was not significant, $F(6, 120) = 0.8, p = .54$.

Response duration was measured from the moment participants indicated the start of their verbal response to when they finished speaking (indicated by button push). A repeated-measures

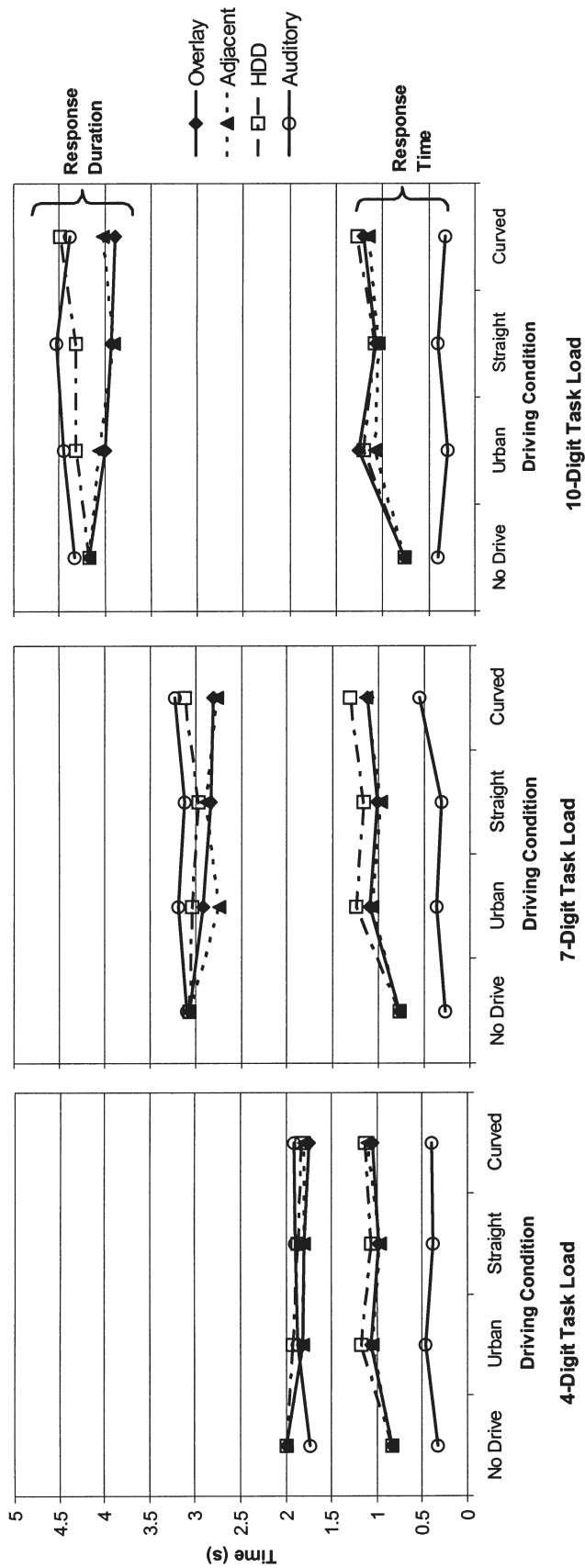


Figure 5. Response times and response durations for the IVT task by task load, road, and display type. The lower clusters of lines represent IVT response time, and the upper clusters of lines represent response duration.

ANOVA on response duration data, shown in the upper cluster of lines in Figure 5, revealed a significant effect of task load, $F(2, 40) = 412.2$, $p < .001$ (not surprising, given that it takes progressively longer to read back more digits), and a marginal effect of display, $F(3, 60) = 2.6$, $p = .06$. In general, performance was equivalent in the overlay ($M = 2.9$ s) and adjacent conditions ($M = 2.9$ s), $t(20) = 0.2$, $p = .84$, but poorer in the HDD ($M = 3.1$ s) and auditory conditions ($M = 3.2$ s) relative to the adjacent condition, $t(20) = 2.8$, $p = .01$, and $t(20) = 1.8$, $p = .09$, respectively. The main effect of road type was not significant, $F(3, 60) = 0.6$, $p = .64$.

As shown in Figure 5 (upper portion), there was a significant Display \times Road Type interaction, $F(9, 180) = 3.5$, $p = .001$, such that the duration of auditory and HDD responses was slightly longer in dual-task than in single-task conditions, whereas response duration was marginally shorter in the overlay and adjacent HUD dual-task conditions as compared with single-task conditions. This pattern is most evident for the 10-digit task load, as evidenced by the significant interaction of Display \times Task Load, $F(6, 120) = 3.6$, $p = .002$. As shown in Figure 5 (upper portion), the display differences in response duration were more pronounced for the 10-digit strings than for the shorter strings: At 10-digit load, HDD $M = 4.4$ s and auditory $M = 4.5$ s, as compared with adjacent $M = 4.0$ s, $t(20) = 3.0$, $p = .007$, and $t(20) = 2.1$, $p = .05$, respectively.

Finally, in general, all the visual display conditions yielded near-perfect recall accuracy. There were significant costs, however, for accuracy in the auditory condition ($M = 0.86$) as compared with that in the visual conditions ($M = 1.0$), $t(20) = -13.29$, $p < .001$. The auditory costs were primarily associated with the highest (10-digit) task load, which well exceeds the assumed capacity of working memory (Miller, 1956).

Table 1 summarizes the various findings for measures of vehicle control, hazard detection, and performance on the IVT. These are presented in terms of the impact of dual-task performance (vs. single task), clutter from overlay, display separation, and modality.

DISCUSSION

The purpose of the current study was to assess the relative costs to driving performance associated with display clutter and overlay, spatial separation, and shared modality of an in-vehicle task. In this section, we discuss these costs in terms of performance trade-offs between the various driving and IVT tasks.

In general, there were costs associated with the performance of multiple concurrent tasks, as evidenced by degraded performance on the continuous aspects of vehicle control (lane keeping and speed control). However, there were no dual-task costs in responding to critical hazard events, as compared with control conditions. As such, the drivers were apparently able to protect

TABLE 1: Summary of Findings for Driving Measures and IVT Task Performance

	Multiple Tasks: Single \rightarrow Dual Task	Overlay: Adjacent \rightarrow Overlay	Separation: Adjacent \rightarrow HDD	Modality: Adjacent \rightarrow Auditory
MAE lane keeping	Loss	0	0	0
Variability in lane keeping	Loss	0	Loss (\uparrow DL)	Loss (\uparrow TL)
Variability in speed	Loss	0	0	Loss (\uparrow DL)
Hazard RT	0	0	Loss	0
Initial hazard collisions	n.a.	Loss	n.a.	n.a.
IVT RT	0 (auditory)	0	Loss	n.a.
IVT response duration	Loss (auditory) Gain (visual)	0	Loss (\uparrow TL)	Loss (\uparrow TL)

Notes. Data are presented along the dimensions of multiple task performance (going from single- to dual-task conditions), clutter (adjacent to overlay conditions), display separation (adjacent to HDD), and display modality (adjacent to auditory). MAE = mean absolute error; 0 = no loss or gain in performance between the two conditions; loss = a loss in performance in the second condition, relative to the first condition; gain = a gain in performance in the latter condition; \uparrow DL = a loss in performance that increases with driving load (i.e., driving difficulty; e.g., curved roads); \uparrow TL = a loss in performance that increases with task load; n.a. = not applicable.

the important tasks of hazard awareness and detection while engaging in a secondary task (except in the HDD dual-task condition). Performance on the IVT task in dual-task situations was somewhat mixed, depending on the modality, and will be discussed further. Given the “default” costs for dual-task performance, we will now explore the potential additional costs associated with the various display and workload conditions.

Display Clutter from Overlay

The results of the current research revealed no differences between a spatially superimposed display (overlay) and an adjacent HUD for the measures of lane keeping, position variability, or speed control, nor were there any differences or performance trade-offs in IVT task performance (response time and response duration). This finding held even for the overlay of the longest digit strings, which did not degrade driving performance relative to shorter strings, even in the most challenging (curved) driving situations. We infer that the clutter imposed by the overlaid display did not interfere with vehicle control because this task relies, to a large degree, on peripheral and/or ambient vision (Previc, 1998) and is therefore less susceptible to clutter effects.

Additionally, there was no increase in response times to the critical hazard events for the overlaid information. In contrast, a meta-analysis of the HUD literature carried out by Fadden et al. (2000) showed that responses to unexpected events tend to be longer in overlay HUD conditions relative to HDD conditions. In the current study the events were all highly salient and occurred in close proximity to the superimposed display, and this may have afforded drivers the ability to detect and respond quickly, despite the clutter of the overlaid digits. The use of hazard events that are less perceptually salient (e.g., in dim illumination) or presented more peripherally might demonstrate overlay costs. We also note that the superimposition of HUDs containing more complex, continuously displayed information, as compared with that used in this experiment, could also reveal penalties not seen here (e.g., Yeh, Merlo, Wickens, & Brandenburg, 2003).

There was, however, some evidence of de-

gradations in the effectiveness of the response to the initial, truly surprising event, with more collisions in the overlay condition than in the adjacent condition, although response times were comparable. Although strictly observational, this may have implications for a head-up display cost for events that are truly unexpected, especially in light of previous findings in support of this effect (e.g., Fadden, Ververs, & Wickens, 2001; Fischer, Haines, & Price, 1980).

Display Separation

Because of the information access costs associated with more peripheral display, greater performance losses would be expected in the HDD condition, relative to the more proximally located adjacent display. In general, however, there was similar performance on measures of absolute lane deviations and speed control for both display types, although there was more variability in lane keeping for the separated display (HDD).

One plausible explanation is that the vehicle control and IVT tasks utilize separate visual channels (ambient and focal, respectively) and therefore, according to multiple resource models, can be time-shared relatively effectively (Previc, 1998; Wickens, 2002). The maintenance of accurate lane position using the upper peripheral visual field has been supported by previous research (e.g., Summala et al., 1996), although this ability declines as separation increases and is moderated by driver experience. These limitations in time-sharing at the wide (38°) separation used here is indicated by the increased variability in lane keeping: Although the drivers could keep their vehicle in roughly the same location as in the other display conditions, they required more inputs and possibly more scans upward to do so. As such, drivers may be adopting an appropriate scanning strategy that allows them to briefly access HDD information while properly monitoring the driving environment when the need arises. 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 would decrease the likelihood of scanning from the road to the display, which would result in degraded performance on one or both concurrent tasks.

It is apparent that the inferred head-down scans had negative implications for the important driving performance measure assessed here, the response to critical events. In general, responses to these events were slower in the HDD condition than in the adjacent display condition. Detection and identification of hazards is largely a foveal and focal task. Although the vehicle control (ambient vision) and digit tasks may be time-shared effectively because of their separate (focal vs. 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. Similarly, Lamble et al. (1999) found slowed responses to discrete traffic events when drivers were fixating on more peripheral display locations.

There were, however, separation-induced performance trade-offs with the IVT task. In general, it took longer for drivers to initiate the IVT task with the HDD, and it took them longer to articulate the digits, an effect that was more pronounced for the longer digit strings. Furthermore, it is these longer digit strings (when coupled with the more challenging curved road sections) that contributed to the increased variability in lane keeping, suggesting that longer task durations and increased bandwidth of road information result in drivers being less able to rely on ambient resources for vehicle control.

Display Modality

Models of multiple resources would predict that the presentation of auditory information in addition to a concurrent visual task would not interfere as much as another visual task would (Navon & Gopher, 1979; Wickens, 2002). However, some evidence suggests that auditory presentation, in some cases, can result in the preemption of a primary task (e.g., Helleburg & Wickens, 2003; Latorella, 1998; Spence & Driver, 1997; Wickens & Liu, 1988). Some evidence for the contribution of preemption to the current data comes from three sources, none of which is conclusive in itself, but which are all suggestive when considered in combination. First, auditory RT to the IVT was faster than visual RT (when each was compared with its single-task baseline), as if a more immediate

response was undertaken when the IVT was auditory in order to avoid the loss of information from working memory. Such an effect would also be predicted from a multiple resource interpretation, which would also favor auditory delivery for the secondary task. Hence we turn to two aspects of the primary (driving) task that were disrupted more, rather than less, by auditory presentation of the IVT, contrary to what models of multiple resources would predict.

Specifically, lane position was more variable during auditory IVT task intervals than during the visual IVT delivery, as if the auditory onsets and possible need for rehearsal of the digit strings led to a temporary neglect in monitoring lane position. In this regard the auditory effect mimicked the effect of head-down visual presentation, suggesting a common mechanism of tracking neglect. The third source of evidence consistent with preemption and neglect is the increase in speed control variability associated with auditory IVT presentation. However, this evidence is weaker because the head-down condition did not mimic it, and an alternative interpretation can be provided – that is, the speed control variability may be a function of perceptual interference of the auditory IVT information with the simulator vehicle's engine noises. (The pitch of engine noise is a strong indicator of fluctuations in speed.) Notably, there were no performance costs in the auditory condition for the hazard events, suggesting that the auditory presentation did not affect these discrete aspects of the driving task. Rather, the observed preemption of driving was limited to the continuous aspects of vehicle control.

Not surprisingly, accuracy for the auditory task was significantly degraded as compared with the visual conditions, especially for the longer digit strings. 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 even longer responses, if drivers could elect to have the digits repeated in the auditory condition.

Implications

From a theoretical perspective, the results of the current study show some support for

models of multiple resources (Wickens, 2002). Specifically, there is evidence to suggest that concurrent visual tasks can be time-shared, to a certain degree, when they rely on separate ambient and focal visual channels. That is, drivers can maintain vehicle control (lane keeping and speed control) using the ambient visual channel while performing a concurrent focal visual task, although this ability declines slightly in situations of increased driving or task load. In contrast, this success is not realized when two visual tasks compete for focal resources (e.g., hazard monitoring and the IVT task).

With respect to the IVT modality, the current results suggest that auditory presentation of IVT information may have resulted in the preemption of some aspects of the primary task of driving – specifically, lane keeping and speed control – rather than resulting in the effective time-sharing predicted by models of multiple resources. Hazard detection, however, was generally buffered from the effects of preemption. We speculate that the nature of the auditory presentation (abrupt and alerting, requiring mental rehearsal) contributed to the observed preemption. Resolving the contrasting effects of preemption cost and multiple resource advantage when auditory presentation is employed remains an important research issue.

From a practical standpoint, the current research highlights many important factors for the assessment of display location and modality in terms of efficient interaction and safe and proper vehicle control. 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. Although drivers were able to maintain adequate lane control, they had 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 a driver's ability to respond to truly unexpected, surprise traffic events. Although

this study offers only mild support for this degradation (in terms of accident frequency for initial incursion events), the lack of discernable differences between the overlay and adjacent conditions for any of the other performance measures seems to suggest that the adjacent presentation is the better candidate.

The auditory display, as implemented here, seemed to have adverse effects associated with preemption for certain measures of driving performance (variability in lane keeping and speed control). As such, there were no overall performance losses on the IVT task for the auditory display in dual- versus single-task conditions. Given the difficulty of the digit task, especially for the higher task loads, preemption may have been a strategy adopted by drivers to alleviate some of the working memory demands of this task. Other tasks, however, that do not place such high cognitive demands on a driver may not induce this preemptive effect. Thus the overall implication of these findings may be that auditory messages should be kept short so as to avoid promoting preemption strategies.

Drivers in the current study did an adequate job of protecting the primary task of driving from increased degradation caused by the higher resource demands and increases in resource competition. However, overall, there were dual-task costs associated with vehicle control. It is not clear from the current findings whether this decrement could be reduced or mitigated through long-term exposure to the secondary task or through training. Given the benefits yielded by the adjacent display 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.

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