THE EFFECTS OF HEAD-UP DISPLAY CLUTTER AND IN-VEHICLE DISPLAY SEPARATION ON CONCURRENT DRIVING PERFORMANCE

William J. Horrey, Christopher D. Wickens, & Amy L. Alexander
University of Illinois at Urbana-Champaign

The introduction of new in-vehicle technologies (IVTs) in automobiles may have important implications for driver safety, especially to the extent that these devices interfere with the primary driving task. Two experiments explored the effects of IVTs on vehicle control and hazard awareness: specifically, we were interested in the impact of visual clutter from head-up display (HUD) overlay as well as the impact of display separation. In experiment 1, twenty-five drivers in a wrap-around simulator drove urban and rural routes while performing a phone number read-back task. Visual displays were located either in a HUD overlaid on the horizon, a HUD positioned 7° below the horizon, or on a head-down display (HDD) located near the mid-console. Experiment 2 attempted to replicate some of the key findings in Experiment 1 with more challenging driving conditions (i.e., curved roads, varying fog densities). In general, the results suggested that drivers protected the vehicle control task, however there were costs in hazard response time and side task performance with the HDD. We suggest that effective hazard detection requires more focal visual resources whereas vehicle control may utilize ambient resources. The practical and theoretical significance of these findings are discussed.

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 added 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. A number of studies have demonstrated benefits of reduced scanning using head-up displays (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., 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, Wickens, & Ververs, 2000). This degradation may be attributable to the increased visual clutter inherent in the overlay of multiple displays. That is, while superimposing display information effectively reduces the information access costs associated with spatial separation, it creates different costs associated with visual clutter.

Other research has shown that safe vehicle control can be reasonably maintained using peripheral and ambient vision alone, though this ability degrades with increased eccentricity (Summala, Nieminen, & Punto, 1996). (Detection of critical events and hazards, however, may be seriously impaired when using peripheral vision alone, especially for larger separations (Summala, Lamble, & Laakso, 1998).) These findings offer some support for the notion of separate focal and ambient visual channels (Previc, 1998). This distinction comprises part of the resources within the visual modality of the multiple resource model of task performance (Wickens, 2002). In this model, focal visual channel relies heavily (though not exclusively) on foveal vision in order to complete tasks that require the discrimination of fine details (e.g., reading and classification of objects). In contrast, ambient vision utilizes peripheral vision to large degree for tasks involving perception of orientation, optic flow, and ego-motion.

Multiple resource models posit that tasks which share common resources along a given dimension (e.g., processing stage, perceptual modality, visual channel, processing code) will be time-shared less effectively than tasks which utilize separate resources (Wickens, 2002). For example, a driver may use focal vision to read information on a road sign while at the same time use ambient vision to keep the vehicle within their lane, however would be unable to read speedometer information, as this would require focal vision. As Summala et al. (1996) demonstrated, ambient vision does have its limitations, with performance becoming degraded at greater eccentricities. The introduction of visual in-vehicle information creates a new source of competition for focal resources which will impact not only the availability of these resources for the detection and identification of road hazards but, depending on the location of the display, may also affect the quality of ambient vision for vehicle control. As such, the information access costs associated with display separation become an important consideration for both focal and ambient driving tasks.

In general, few studies have reported performance measures for a continuous vehicle control task and discrete hazard detection as well as a secondary in-vehicle task, in order to examine performance tradeoffs that may occur across different locations. Such comprehensive examination is necessary in order that the joint contributions of ambient vision (vehicle control) and focal vision (hazard 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. As noted previously, information access costs increase with display separation however there are costs from information overlay (i.e., 0° separation) arising from display clutter. The current research seeks to address these issues by examining different display separations in a high fidelity driving simulator.

METHODS: EXPERIMENT 1

Participants & Materials

Twenty-five younger drivers (M = 22 yrs, SD = 2.5) volunteered for this study. Participants drove through various dynamic traffic environments in the Beckman Institute Driving Simulator—a fixed-based simulator consisting of a 210° forward wrap-around field of view and a 45° rear field. Traffic environments varied in difficulty and complexity, including straight urban, straight rural, and curved rural stretches of roadway. Critical hazard events were inserted into the driving scenarios at random, infrequent intervals. These events varied in nature, though typically involved some form of lane incursion (e.g., pedestrian, cyclist, vehicle; see Horrey & Wickens, 2002, for full details).

Procedure

At the start of the session, participants completed a demographic and simulator sickness questionnaire and were tested for visual acuity. Drivers were then given a short 5-minute training session to familiarize themselves with the dynamics of the simulator, followed by the experimental instructions.

Drivers were instructed to drive and to respond to traffic as they normally would, while staying within their respective lane and as close to the posted speed limit as possible. As participants navigated through the different routes, they were asked to complete, as best they could, a periodic phone number read-back task. This task was presented through one of three visual displays and varied in length (4-, 7-, or 10-digits). As shown in Figure 1, one visual display (Overlay) was presented in a simulated HUD superimposed on the horizon line (0° separation; to assess the impact of clutter on task performance). A second location (Adjacent) was in a HUD superimposed on the roadway just above the hood of the simulator vehicle (approximately 7° below the horizon line; consistent with many HUD locations, e.g., Kiefer, 1995). A third visual display (head-down display; HDD) was located on an LCD positioned near the mid-console of the vehicle (approximately 38° offset from the center of the horizon line; to assess the impact of display separation). (Data from an additional auditory condition is not reported here.) The digits were presented approximately every 10 to 20 seconds. Upon presentation, participants were instructed to read the numbers aloud, responding to them as quickly as possible, however not to compromise safe driving in doing so. The digits remained visible until the response was complete.

Driving performance measures of lane position were measured during the response intervals, as well as during baseline conditions. Performance for the secondary task was assessed by the time to initiate (response time) and the time to complete (response duration).

Drivers completed a block for each display configuration. Each experimental block lasted approximately 20 minutes, with the exception of the baseline block for the IVT task, which lasted 5 minutes. Participants were offered a short break in between each block.

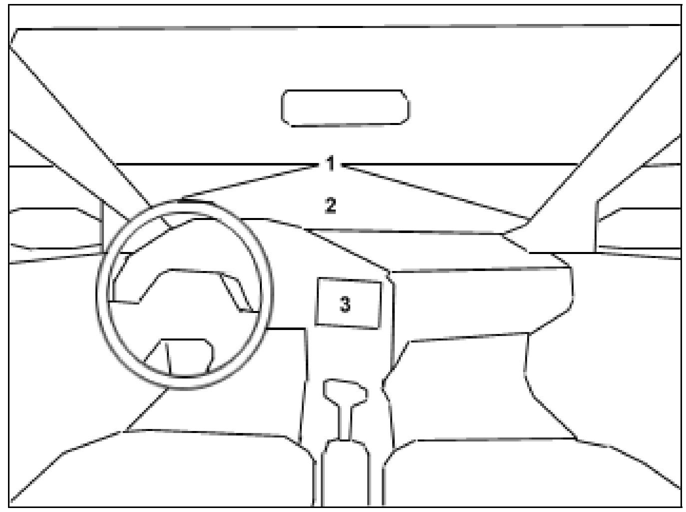

Figure 1. Display configuration for the (1) overlay, (2) adjacent and (3) head-down conditions. Adapted from Summala, et al. (1998).

At random locations throughout the driving blocks, the IVT presentation coincided with a discrete hazard event (e.g., lane incursion; 2-3 events per block). The events required a maneuver response (i.e., braking or steering) from drivers in order to avoid a collision. The number of events was minimized and the events were varied in order to reduce the likelihood of drivers anticipating them. It is unlikely that any association was made between the occurrence of the IVT side task and critical hazards (they co-occurred for less than 4% of the IVT presentations). Obviously, the effective detection and response to these hazards was critical for safe vehicle control. Response times to these hazard events were measured.

The experiment involved a 4 x 3 x 3 within subjects design, with the variables of display type (overlay HUD; adjacent HUD; HDD; baseline—no display), road type (urban, rural-straight, rural-curved), and side task load (4-, 7-, or 10-digits).

RESULTS & DISCUSSION: EXPERIMENT 1

A series of conditionalized planned comparisons was employed to investigate specific hypotheses, rather than omnibus analyses (Keppel, 1982). Several comparisons examined the effects of clutter (overlay vs. adjacent HUDs), display separation (adjacent HUD vs. HDD), and dual-task interference (dual- vs. single-task conditions).

Unfortunately, there were missing data points for a few drivers in some conditions. This is reflected by the different degrees of freedom across some comparisons. A more detailed account of these results can be found in Horrey and Wickens (2002).

Lane Keeping

Lane position was determined by measuring the absolute deviation of the vehicle (in meters) relative to the center of the vehicle's lane. These deviation data are shown in Figure 2, which reveals a significant main effect of road type for all display conditions ($p < 0.001$ to $p = 0.004$), with higher rural velocities and more difficult curved sections each contributing to increased lane deviations.

A repeated measures ANOVA comparing the overlay and adjacent HUD conditions did not reveal a significant effect of display type ($F(1,17) = 0.23$, $p = 0.64$), nor a significant Display x Road interaction ($F(2,23) = 0.52$, $p = 0.60$), suggesting that the increased clutter with the information overlay did not disrupt tracking performance any more than the adjacent display (see Figure 2). The lack of interference from clutter may be because the vehicle control task relies upon ambient vision, and therefore is less susceptible to clutter effects.

There were also no differences between the adjacent and HDD conditions for lane keeping ($F(1,19) = 0.01$, $p = 0.93$). The Display x Road interaction was not significant ($F(2,38) = 0.02$, $p = 0.98$). These results suggest that drivers may have been able to use ambient vision to control the vehicle while engaged in the HDD task. That is, the IVT task uses focal visual resources to discriminate the digits whereas lane keeping can be largely accomplished through the use of ambient vision, which is well supported by peripheral vision (Previc, 1998). 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). Interestingly, these null 'separation' effects were evident in even the most difficult driving conditions (i.e., curved roads with the highest side task load; $F(3,57) = 1.04$, $p = 0.38$). The lack of display effects, even across more difficult road types and side task loads and, with the moderate statistical power of the comparison (0.48), suggested that drivers were protecting the primary driving task in these various 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 adequate vehicle control.

While there were no apparent costs of clutter or separation for lane position, comparisons to single-task baseline conditions did suggest lane keeping costs for dual-task performance (Figure 2). That is, there were significant costs for dual-task performance of approximately 0.10 m in lane deviation, a cost that was equivalent across all display configurations ($F(1,17) = 35.37$, $p < .001$).

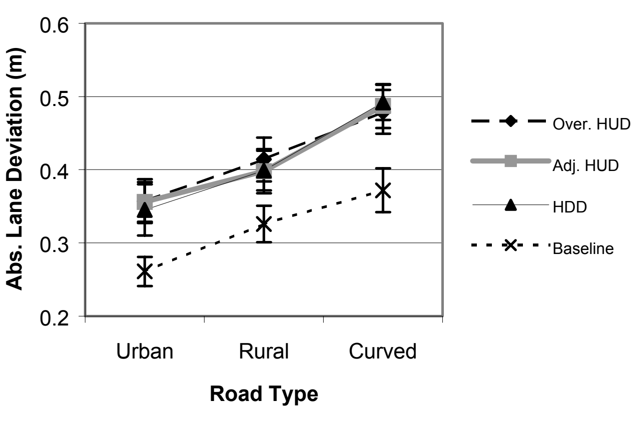

Figure 2. Absolute lane deviations by road and display type.

Hazard Detection

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 7- or 10-digit (higher load) IVT task. The response times (RTs) to the critical hazard events are shown in Figure 3.

A two-sample t-test (1-tailed) for the overlay and adjacent HUD conditions did not yield any differences between the two displays ($t(75) = 0.86$, $p = 0.39$), suggesting that the presence of information overlap and clutter did not disrupt drivers' ability to detect and respond to the critical events (see Figure 3). However, there were some non-significant advantages for adjacent relative to overlay for responses to the first, truly unexpected event. There were no differences in the RTs to these initial events between the overlay and adjacent conditions, however there were three collisions in the overlay condition (out of a possible three) compared to no collisions (out of three) in the adjacent condition. Though this observation is strictly anecdotal (due to low N in these conditions), it may have implications for events that are truly unexpected.

As shown in Figure 3, an examination of display separation yielded increased response times for the HDD ($M = 1.68$ s) compared to the adjacent condition ($M = 1.50$ s; $t(72) = 2.49$, $p = 0.02$), suggesting that effective hazard detection requires more focal (rather than ambient) visual resources. That is, hazard awareness is largely a foveal task, requiring focal visual resources to detect and identify critical objects and events. This detection task competes with the IVT task for limited focal resources, thus resulting in task interference. This degradation in response time to discrete events at larger eccentricities is consistent with previous findings (e.g., Summala, et al., 1998).

While there was a slight reduction in RTs from the first hazard to subsequent hazards, this reduction did not eliminate the time costs for the HDD. Finally, there were no differences between the two HUD conditions (which were collapsed) and baseline, single-task conditions ($t(107) = 0.82$, $p = 0.42$).

In summary, the responses to the discrete, hazard 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 (i.e., baseline,

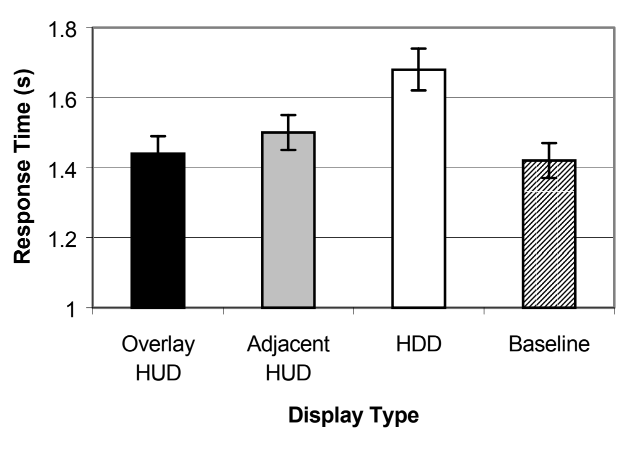

Figure 3. Response times (in seconds) to critical hazard events by display type.

adjacent, overlay). 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 more collisions in the overlay condition for the initial incursion event than in the adjacent condition, 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 conditions.

IVT Task Performance

There were no differences in response times to the IVT task for the overlay and adjacent conditions ($F(1,18) = 0.68$, $p = 0.42$), nor were there any differences in response duration (i.e., time to articulate the response) for these display conditions ($F(1,18) = 1.30$, $p = 0.27$). Clutter (as implemented with the digit strings used here) does not appear to adversely degrade performance on the secondary task, relative to a non-cluttered (adjacent) display.

There were, however, time costs in side task performance for the more spatially separated HDD, as shown by slowed response times to the task ($F(1,20) = 4.44$, $p = 0.05$) and longer response durations ($F(1,20) = 7.56$, $p = 0.01$) compared to the adjacent condition. Furthermore, these time costs for the HDD grew in magnitude with the longer phone numbers (Display x Task Load interaction; $F(2,40) = 8.15$, $p = 0.001$).

Overall, there were few effects of clutter of performance on the IVT tasks (as well as the vehicle control task). However, there were costs for the spatially separated HDD for the IVT tasks. Given that vehicle control performance was equivalent across the HUD and HDD conditions, it is possible that the control task was too easy to reflect task interference. As such, precise vehicle control could be maintained with ambient visual resources**,** or brief glances downwards to the HDD did not disrupt the trajectory of the vehicle. Experiment 2 was intended to examine these display conditions (adjacent HUD and HDD) in more challenging driving situations to determine if these control strategies would persist even when more precise steering control was required.

METHODS: EXPERIMENT 2

Twelve younger drivers (M = 22 yrs, SD = 3.7) participated in this follow-up study (these were different drivers than those in Exp.1). The driving tasks and secondary tasks were identical to those in Exp.1, however only the adjacent HUD and HDD condition were employed. Furthermore, IVT task load was not manipulated—we employed the highest task load (from Exp.1) for all conditions. For this experiment, the driving task was made more difficult by using highly curved sections of roadway as well as manipulating visibility through variable fog densities (see Horrey, Alexander, & Wickens, 2003, for more details and for a complete report of the results).

Experiment 2 involved a 3 x 2 within subjects design with the variables of display type (adjacent HUD; HDD; baseline) and visibility (high fog – 75 m visibility; low fog – 1000 m). Mental workload was assessed for each condition using the NASA-TLX workload assessment (Hart and Staveland, 1988).

RESULTS & DISCUSSION: EXPERIMENT 2

Lane Keeping

Absolute lane deviations were analyzed with a repeated-measures ANOVA for display type. Consistent with the findings from Exp.1, there were no differences in lane keeping across display type ($F(2,22) = 1.60$, $p = 0.22$), suggesting that drivers were able to protect the primary task of driving, even in highly demanding situations (see Figure 4). Furthermore, the protection of the driving task occurred in dual-task conditions (both HUD and HDD) relative to baseline (single-task) conditions (in contrast to Exp.1). This may indicate that drivers were aware of the high demands in Exp.2, and therefore allocated more resources to driving. As noted previously, the protection of the driving task may be due to the use of ambient vision or a scanning strategy. There was also a significant effect of visibility, with drivers making smaller lane deviations in the high fog conditions than in low fog ($F(1,11) = 17.7$, $p = 0.001$), suggesting that drivers may be attending to the roadway more closely when visibility is reduced.

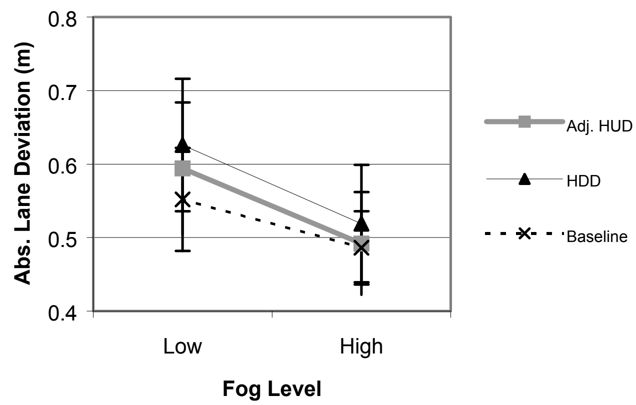

Figure 4. Absolute lane deviations by fog level and display type.

IVT Task Performance

As was the case in Exp.1, analysis of the side task performance revealed time costs for the HDD—specifically, response times were slowed compared to the adjacent HUD ($F(1,10) = 5.7$, $p = 0.04$) and response durations were longer ($F(1,11) = 4.4$, $p = 0.06$). There was however a significant Display x Visibility interaction for response duration ($F(1,11) = 6.5$, $p = 0.03$), with the performance decrements with the HDD being much larger in the high fog compared to low fog conditions. These findings support the notion that there is a trade-off in side task performance on the side task in order to protect the primary driving task (as resource theory would predict; Wickens, 2002).

Mental Workload

As shown in Figure 5, results from the NASA-TLX assessment also showed that drivers using the HDD had significantly higher workload ratings than for the adjacent HUD

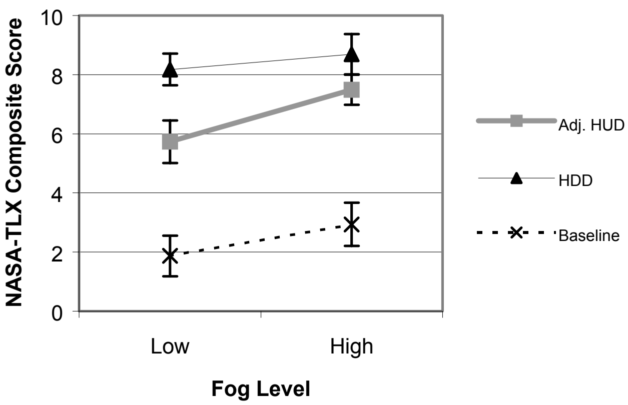

Figure 5. NASA-TLX composite scores by fog level and display type.

($F(1,11) = 23.11$, $p = 0.001$) and baseline conditions ($F(1,11) = 38.94$, $p < 0.001$). There was also increased workload in the high fog condition, compared to low fog ($F(1,11) = 6.73$, $p = 0.03$). These findings reflect the increased resource demands associated with the different display and driving conditions.

GENERAL DISCUSSION

Taken together, the results from the current experiments showed that drivers are able to protect the primary task of vehicle control when performing a concurrent side task and this protection can occur even in more challenging driving situations with a HDD. This suggests that drivers may be able to effectively time-share the vehicle control task (which relies on ambient visual resources) and the side task (which relies on focal visual resources; Previc, 1998; Wickens, 2002). However, this time-sharing may break down in situations where the driving task demands some focal visual resources, as is the case with the hazard events (Exp.1). 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. Head-up displays appear, from the current data, to provide a more effective buffer against visual competition for focal resources

Although moving the display into a position closer to the driving environment is an obvious solution, 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 (Exp.1). 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 keeping, IVT performance) 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).

Finally, we note that—although the IVT task required only limited cognitive processing—drivers in both experiments were relatively proficient at buffering primary task (lane keeping) from the higher task demands, by allocating more resources to that task, as the driving task increased (from Exp.1 to Exp.2, and from low fog to high fog), and as the secondary task became more demanding (by moving its display head down).

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