The Use of Head-Up Displays (HUDS) in Motor Vehicles

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A thesis submitted for examination

to the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

Master's of Arts

Carleton University

Ottawa, Ontario

September, 2005

Your file Votre référence
ISBN: 0-494-10047-8
Our file Notre référence
ISBN: 0-494-10047-8

Abstract

Motor vehicle manufacturers are installing Head-Up Displays (HUDs) in motor vehicles. HUDs are used to provide drivers with a variety of vehicle information such as vehicle speed. In theory, HUDs should assist drivers in monitoring the status of their vehicle while allowing them to spend more time looking at the external scene. However, research in the aviation literature has shown that pilots tend to cognitively tunnel on HUDs to the extent that processing of the external scene is delayed. In the present research, a driving simulator was used to examine whether cognitive tunnelling occurs with analogue and digital HUDs. This experiment showed that participants were better at maintaining the posted speed when HUD information was available. However, when the digital HUD was used for monitoring speed, lane deviations were larger and reaction times to visual and auditory probes were longer than when either of the other two displays was present.

This thesis is dedicated
to the loving memory of my mom, Marlene.
You are missed.
1940-1999

Acknowledgements

I have a number of people to thank for their support and inspiration during the writing of my thesis. First, I would like to thank my supervisor Dr. Chris Herdman for his support over the past two years. Working in your lab has provided me with many opportunities to conduct good research. The wide array of tools your lab possesses opens many doors and avenues for this research.

I am grateful to Dr. Joanne Harbluk, Dr. Rob Langois and Dr. Jo-Anne LeFevre for taking time to sit on my committee. Your questions provoked thought and new ideas for future research.

I want to thank Dan Bleichman for programming this experiment for me. I really appreciate the time you took to make this experiment successful.

Thank you Jon Wade for your help with pulling out data that was necessary for analysis. Without your wonderful programming abilities, I would still be drowning in the vast mountain of raw data.

I am grateful to Dr. Matthew Brown for all of his statistical help. Thanks to you, SPSS and statistics are no longer dirty words. I would also like to thank you for your review of previous versions of this thesis.

Thanks to Dr. Jerzy Jarmasz for his statistical help and for his feedback on this thesis.

I would like to thank my undergraduate research supervisor Dr. Steve Lindsay. You taught me a great deal about doing good, solid research.

I am eternally grateful to my family and friends for all their support during my years as an undergraduate and then a graduate student.

Charlotte, thank you for all that you have done for me since April 17, 1999. Your constant presence has filled the gap that was left on that day over six years ago.

To my sister Julie whose humour keeps me laughing and smiling.

Brenda, your love, support and friendship over the years has been invaluable. I am indebted to you.

I want to thank the Monahans (a.k.a The Clampetts) for welcoming me into their family. I am always guaranteed lots of laughs when I see you.

Finally, I have two very special people that I must thank…

I want to thank my amazing son Mat who has been my biggest supporter throughout the years. You are one-of-a-kind and I am really blessed to be your mom.

I also want to express my deep gratitude and my love to my wonderful partner Dave. Your love and support in all that I tackle in life is much appreciated. You were a great sounding board while I worked my way through certain aspects of this thesis. Are you ready for the Ph.D process?

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INTRODUCTION

Imagine driving in rush-hour traffic along a busy city street. Pedestrians are darting in and out of traffic, drivers are constantly changing lanes, a ringing cell phone begs to be answered and vehicle instrumentation is presented to the driver with a new technology called a Head-Up-Display (HUD). HUD technology allows for the projection of instrumentation onto a transparent medium located at the same level as the windscreen or onto the windscreen itself. It is assumed that this "heads-up" configuration should enhance performance by enabling drivers to access vehicle instrumentation (e.g., vehicle speed) while simultaneously monitoring information outside the vehicle. However, the assumption that HUDs will enhance driver performance may be premature: the impact of HUDs on driver performance has not been thoroughly investigated and the small body of research that does exist suggests that any benefits of HUDs (Kapstein, 1994) may be accompanied with concomitant performance costs (Ward, Parkes, & Lindsay, 1995). Similar cost/benefit tradeoffs have been reported in the aviation literature where a number of studies have shown that pilots tend to *cognitively tunnel* their attention on a HUD at the expense of missing (or being slow to detect) objects in the outside scene (see Fischer, Haines, & Price, 1980; Herdman, LeFevre, Jarmasz, Johannsdottir & Hagen, 2005; McCann & Foyle, 1995; McCann, Foyle & Johnston, 1993). Given the anticipated proliferation of HUDs technology in automobiles, it is important to determine whether drivers experience cognitive tunnelling with vehicles that are equipped with HUDs. In the present research, cognitive tunnelling was examined by assessing the attentional demands associated with driving a HUD-equipped automobile simulator.

Cognitive Tunnelling with HUDs in Aircraft

The strongest evidence that HUDs may result in cognitive tunnelling comes from the aviation literature where a number of simulator-based studies have shown that pilots attend to HUD symbology at the expense of not attending to events in the external scene (e.g., Fischer et al., 1980; Herdman et al., 2005; McCann et al., 1993; McCann & Foyle, 1995). For example, Fischer et al. found that a number of pilots failed to notice runway incursions (i.e., objects on the runway) while landing an aircraft (simulator) equipped with a HUD. In contrast, all runway incursions were detected by pilots when using a traditional Heads Down Display (HDD). In a similar study, McCann and Foyle (1995) found that the pilots flying with a HUD did notice runway incursions but were significantly slower (2.5 seconds) to respond to the incursions than the pilots in the HDD condition.

Herdman et al. (2005) provided further evidence for cognitive tunnelling in aircraft. In this experiment, pilots flew a simulated helicopter while wearing a Head Mounted Display (HMD). In the HUD condition, the HMD was equipped with HUD symbology containing primary flight, power, and navigation information. In a HDD condition, no HUD information was displayed on the HMD. Instead, pilots were required to look under the HMD to read the instrument panel. The HDD condition is similar to what pilots must do when they are using Night Vision Goggles (NVG). They must look underneath the goggles to read information on the instrument panel. Pilots were required to follow a designated flight path while maintaining assigned speed and altitude. Additionally, throughout the mission pilots were to report any air or ground activity (e.g., objects in the air or on the ground). Evidence for cognitive tunnelling was found in that pilots missed more of the ground and airborne objects in the HUD than the HDD condition (49.5% vs. 38%).

In sum, simulator-based research suggests that pilots are either more likely to miss or are slower to respond to objects/events in the external scene when a HUD is present. This suggests that pilots cognitive tunnel their attention on the HUD at the expense of not attending to information in the external environment. Despite the fact that pilots have increased "heads-up" time when using a HUD, the pilots fail (or are slow) to "see" information in the external environment.

Motor Vehicle HUD Studies

Relatively little research has examined the impact of HUDs in automobiles. It seems plausible that the inherent costs and benefits of HUD technology that have been observed with pilots would map directly onto the task of driving an automobile. In fact, cognitive tunnelling effects may be more robust and critical in driving an automobile than in piloting an aircraft. Whereas pilots are seldom required to directly use information from the environment to aviate, drivers must constantly sample the outside environment to enable precise control of their vehicle's position (e.g., within lanes and relative to other vehicles).

To date, simulator-based studies of automobile HUDs have been inconclusive. Kapstein (1994) reported a benefit whereby drivers were significantly better at monitoring speed, maintaining lane position, and reported having reduced workloads when HUD information was available relative to when it was not. In contrast, Ward et al. (1995) found that drivers had *less* longitudinal and lateral control of their vehicle under emergency braking conditions when HUD information was available relative to when it was not. Further, drivers' reaction times to a lead car braking under emergency conditions were longer when HUD information was available than when it was not. The Ward et al. findings are consistent with the hypothesis that HUDs induce a cognitive tunnelling effect in automobiles. The contrasting findings of the Kapstein versus the Ward et al. studies may reflect differences in samples (e.g., participants in the Kapstein study were much younger than in the Ward et al. study) and HUD characteristics (HUD location varied across the two studies). From an applied perspective, it is important to note that in both of these studies the HUDs were represented in analogue format. This is important because HUDs that are being implemented in most automobiles are typically in digital format. It is possible that driver performance may be influenced by whether an analogue or a digital HUD is used.

Digital versus Analogue HUDs

Digital displays are simple in their presentation and are often assumed to be easier and more efficient to read than analogue displays (Miller & Penningroth, 1997) and as such, are typically chosen over analogue format in passenger vehicles. However, Paivo (1978) found that analogue displays are processed faster than digital displays under conditions that require spatial processing. Additionally, analogue displays are processed faster when rate-of-change information is required (see Helander, 1987; Kantowitz & Sorkin, 1983; Murrell, 1965). Given these findings, it may be that when drivers (and pilots) are attempting to process rate of change information using a digital HUD (e.g., change in motor vehicle speed or altitude change in an aircraft), they may spend more time attending to the HUD than if the information was presented in an analogue format.

One of the goals of the present research is to investigate the attentional demands associated with use of a digital HUD versus an analogue HUD.

HUDs and Visual Attention

Research has shown that visual attention is both space-based and object-based. Space-based attention is typically examined using a cueing paradigm where participants are required to respond as quickly as possible to the onset of a light or other simple visual stimulus. The target stimulus is preceded by a cue whose function is to draw attention to an area of space in which a target will subsequently appear. Examples of cues include brightening the outline of an object (Posner & Cohen, 1984), the abrupt onset of a simple stimulus (Averbach & Coriell, 1961; Eriksen & Hoffman, 1973; Posner et al. 1980) or a symbol (e.g., an arrow) directing attention where a target will appear. The commonly reported finding is that responses were quicker to cued targets than to uncued ones. These findings suggest that the human visual system can actively attend to and enhance particular regions of the visual field.

Space-based attention has been characterized as an attentional "spotlight" (Fernandez-Duque & Johnson, 1999). There are two general approaches to the spotlight model of attention. One approach is to assume that information falling outside the attentional spotlight is not processed (Posner, 1980). The other approach is to assume that the spotlight enhances the processing of information falling within the spotlight, but that some information outside the spotlight can be processed (e.g., Downing & Pinker, 1985; Jonides, 1981). In both approaches, it is assumed that all objects that fall within the spotlight will be processed in parallel. That is, features from multiple objects should be processed with the same ease as multiple features from a single object. However, a growing body of evidence from object-based attention studies does not support this claim.

The object-based theory of visual attention maintains that the perceptual organization of a scene occurs in two stages. In the first stage, the organization of a scene is believed to be preattentive and to follow Gestalt principles of organization (Kanizsa, 1979; Koffka, 1935). Through these principles of organization, elements that share continuity of contour, colour, proximity, completion, or movement are bound and attention is directed to these grouped components called objects. After a scene is organized, stage two apportions attention to one object at a time. If a person is processing attributes of one perceptual object, it is believed that this processing occurs in parallel. In other words, according to the object-based model, concurrent processing occurs when elements lie within a single object, independent of its spatial dimensions. However, if a person is processing features across two or more objects, then processing is serial and thus, will be more time-consuming.

A number of studies have provided evidence for object-based attention. For example, Duncan (1984) had participants attend to one or two objects that occupied the same location in space. The objects were a box and a line drawn diagonally through the box. Across trials, two properties of the objects varied. The box was either large or small and a gap was located on either the right or left edge of the border. The line was either dotted or dashed or tilted to the left or right. Participants were required to identify two attributes at once. In one condition, they had to report on two attributes from a single object (either box or line) and in the other condition, they had to report on one attribute from two objects (both box and line). The results showed that participants were more accurate when the two attributes were located on a single object than when the two attributes were located on two objects. Behrmann, Zemel, & Mozer (1998) were able to successfully replicate Duncan's (1984) study.

In sum, object-based attention studies have provided evidence that people are quicker and more accurate when responding to attributes that occur in one object as compared to attributes than occur in multiple objects. As discussed below, an object-based approach provides a possible explanation for cognitive tunnelling. On this view, when HUD symbology (one object) is processed, processing of the external environment (second object) is delayed and this leads to missed or delayed responses to objects in the external environment.

Object-Based Attention and Cognitive tunnelling

Jarmasz, Herdman and Johannsdottir (2005) suggested that (a) HUD symbology and the external environment are grouped into two separate objects and (b) this grouping is sufficient enough to capture visual attention onto a HUD for an extended period of time. On this view, there are two Gestalt principles of grouping that separate HUD symbology from the external scene. First, HUD symbology is typically monochromatic (usually green) and therefore will be perceptually grouped based on similarity. Second, HUD symbols move as one object and the external scene moves as another, thereby providing perceptual grouping based on common fate. According to McLeod, Driver, Dienes, and Crisp (1991), common fate is a dominant grouping factor.

Jarmasz et al. (2005) examined (a) whether perceptual grouping through common fate can sustain object-based attention over an extended period of time and (b) the impact of endogenously focusing strategies on object-based attention. Jarmasz et al. displayed 7 dots, 3 of which moved in unison and 4 dots that remained stationary. The moving dots moved for 2-6 seconds along an elliptical trajectory. The 3 moving dots were called the 'moving' object and the 4 stationary dots were called the 'static' object. In Experiment 1, the goal was to determine if participants would perceive the moving dots as one object and the static dots as another by the principle of common fate. During each trial, 2 of the 7 dots changed from grey to either red or green. These changes occurred in one of two ways: the object colour change could occur in either one object (2 of the moving dots or 2 or the stationary dots) or in two objects (one moving dot and one stationary dot). Participants had to indicate whether the two dots changed to the same colour (i.e., both red or green) or to different colours (i.e., one red and one green). Participants were instructed to attend to the entire display and to not focus solely on either the moving or static dots. The results showed that responses were significantly faster when the colour change occurred in the same object. These findings are consistent with the claim that (1) visual stimuli are grouped into objects based on common fate and (2) stimuli that are grouped by common fate received object-based attention.

Experiment 2 of Jarmasz et al. (2005) was identical to Experiment 1 except that participants were instructed to endogenously focus their attention on either the moving or the stationary dots. The results showed that reaction times were significantly faster when the colour change occurred on the same attended object (either the moving dots or the static dots) than when colour change occurred across objects. This finding further supports the assertion that grouping by common fate can result in viewers focusing and maintaining their attention on moving versus stationary objects. By extension, common fate could result in the grouping of HUD symbology into one object and the external scene into a second object. In accord with object-based attention theory, a pilot or driver would have to serially switch attention between the HUD and the external environment. The implications of attentional switching are discussed in the following section.

Divided Attention: Multiple Resource Theory

A common approach in the attention literature is to view attention as a limited quantity or resource. On this view, divided attention represented the allocation of attentional resources across two or more tasks. When the combined task demands exceed the available capacity, then performance decrements are observed. During the 1960s and 1970s, a number of studies examined performance decrements in dual-task situations (for a review see Pashler, 1998). The majority of this research was performed using tightly controlled laboratory experiments where participants were given specific instructions regarding attentional allocation. Although this research has certainly provided a great deal of information about human attention, one limitation of this work is that humans do not operate in such controlled, sterile environments. Rather, they are bombarded with a myriad of visual, auditory and tactile stimuli that either get ignored or processed. For example, the operator of an automobile must monitor the car's speed and lane position, as well as attend to other vehicles, pedestrians, and traffic signs and signals. Having to simultaneously attend to all of this information may exceed the driver's limited capacity. This can result in task shedding, such as pausing a conversation on a cell phone in order to perform a difficult driving manoeuvre. Alternatively, there may be performance decrements on critical tasks, such as increased deviations in speed or lane positioning caused by attending to a conversation on a cell phone while driving.

Wickens (1980, 2002) developed a multiple-resource model of attention to address patterns of interference in a multi-task environment (e.g., driving a motor vehicle). Wickens identified the structural dimensions of human information processing that met the shared criteria of "accounting for changes in time-sharing efficiency, and being associated with neurophysiological mechanisms which might define resources" (p. 162-3). As shown in Figure 1, Wickens postulates four categorical and dichotomous dimensions to account for variance in performance when time-sharing between tasks is required. These four dimensions are stages, perceptual modalities, visual channels, and processing codes.

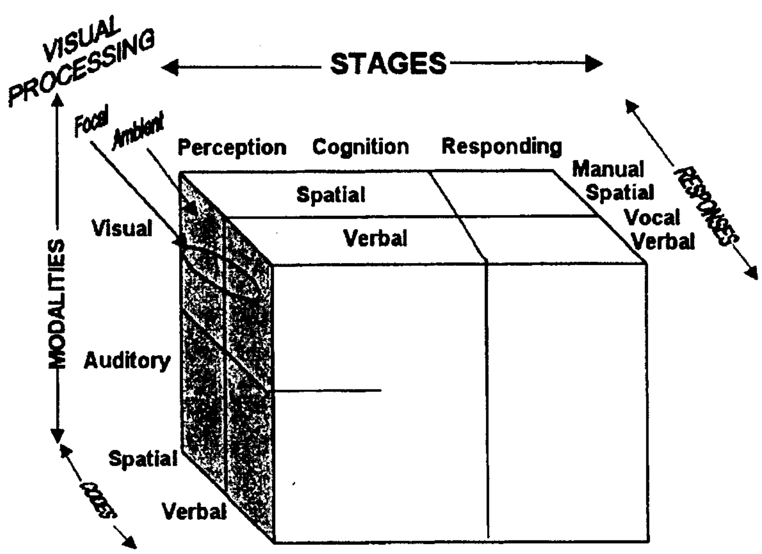

Figure 1. Three-dimensional representation of the structure of multiple resources. The fourth dimension (visual processing) is nested within visual resources.[1]

[1] From "Multiple Resources and Performance Prediction," by C. D. Wickens, 2002, *Theoretical Issues in Ergonomics Science, 3(2),* p. 163.

Stages. The stage dimension is separated into perceptual/cognitive activities and response execution. Perceptual/cognitive activity ranges from early components of speech recognition to higher-level cognitive processes such as those associated with maintaining an accurate mental picture of an object. Examples of a response task would be speech production or a key press (Wickens, 2002). Evidence that perceptual/cognitive activities are functionally separate from response activities is provided by the event-related potential (ERP) data (Israel, Chesney, Wickens, & Donchin, 1980; Osterhout & Holcomb, 1992). ERPs are patterned voltage changes in ongoing electrical brain activity. When a cognitive or sensory stimulus is presented, a series of positive and negative voltage peaks are distributed across time. The presence of the P300 (a positive potential that occurs 300 ms. after onset of stimulus) ERP is generally considered to indicate that perceptual/cognitive activity is occurring. Further, this activity is assumed to occur independently from response-related potentials (Duncan-Johnson & Donchin, 1982; Kutas, McCarthy, & Donchin, 1977). Israel, Chesney, Wickens and Donchin (1980a, b) found that when participants were asked to discriminate between two auditory tones and keep a mental count of the number of times one of the tones was presented (perceptual/cognitive task), the P300 component of an ERP was elicited. However, when participants were asked to do a tracking task (motor task) instead of the perceptual/cognitive task, the P300 was not educed.

Wicken's (1980, 2002) assumes that if two perceptual/cognitive tasks are performed concurrently, then performance decrements on one or both tasks will occur. The grouping of perceptual and cognitive activities into demands for a common set of resources predicts that interference will occur across a broad range of tasks. For example, a visual search task will presumably interfere with a concurrent mental rotation task.

Perceptual Modalities. Research has shown that when visual and auditory information processing occurs at the same time, very little interference occurs (e.g., see Eijkman & Vendrik, 1965; Shiffrin & Grantham, 1974; Treisman & Davies, 1973; Tulving & Lindsay, 1967; Wickens, Sandry, & Vidulich, 1983). However, Wickens (2002) argued that this lack of interference may not be due to separate visual and auditory resources. He suggests that there may be "peripheral factors" that cause inter-modal (two visual or two auditory) interference. If two visual stimuli are spatially disparate, scanning will be required and this may lead to impaired performance in one of the two tasks. Further, having two stimuli spatially or temporally proximate may cause masking effects and subsequently lead to interference. However, Wickens does state that in most real world settings, there is a substantial amount of visual scanning and that dual-task interference than can be reduced by moving a visual task to the auditory channel.

Visual channels. In addition to separate resources for processing visual and auditory stimuli, the multiple resource model postulates that visual processing is broken down into two parts; foveal and ambient vision. Foveal vision is used for fine detail and pattern recognition such as reading text. Ambient vision is peripheral vision and is used for tasks involving the perception of orientation and ego motion. According to Wickens, this separation within the visual system is what allows us to walk through our environment (ambient vision) while reading (foveal vision).

Processing Codes. This element of Wickens' (1980, 2002) model accounts for how manual and verbal responses can be effectively time-shared. A manual response is spatial in nature while vocal responses are verbal. When a manual and a verbal task are done concurrently, time-sharing of these two tasks is very efficient. Conversely, when two manual or two verbal tasks are processed simultaneously, performance on one or both of the tasks suffers (Sarno & Wickens, 1995; Wickens, 1980). Performance decrements on one or both tasks are affected by task priority (Wickens, 2002). If one task has higher priority, performance on the second task will suffer. If both tasks have equal priority, performance will be equally compromised on both tasks. Wickens has suggested that response performance in a multi-task environment (such as a motor vehicle or aircraft) can be improved if both a verbal and a manual response are done concurrently.

Wickens (2002) cautions that even though two concurrently performed tasks may rely on different resources (e.g., a visual & auditory task or a verbal & manual response), phenomena called 'preemption' and 'engagement' may make it impossible for efficient time-sharing. This occurs when one task requires so much attention that any of the benefits gained by distributing its resource demands are eliminated. The result is the other task is completely ignored. For example, Strayer and Johnson (2002) conducted a simulator study where participants were asked to have a cellular phone conversation while driving. They found that the cell phone conversation was so engaging that it disrupted the task of driving. This occurred even though the two tasks are quite separate in their resource demands. Therefore, it is important to understand that preemption or engagement may take place even though concurrent tasks depend on separate resources.

Summary. Wickens' (1980, 2002) model can be used to make predictions about performance in a multitask environment. The model provides a framework to help understand why performance suffers when people are required to perform two tasks that use the same pool of resources. It also describes how these performance breakdowns in multitask environments can be offset by shifting one of the tasks to a different structure. For example, when two visual tasks are performed concurrently, changing one of the visual tasks to an auditory task will likely lead to better performance on both tasks. This can help reduce the probability of human error when task demands are high.

Present Research

In the present research, the impact of a digital display versus an analogue display (to monitor speed) on driving performance was investigated. Based on the Wickens' (1980, 2002) model, it is hypothesized that the presence of a digital HUD versus an analogue HUD or a traditional analogue Head-Down Display will require more central cognitive processing resources. In turn, this increased resource demand will lead drivers to cognitively tunnel on the digital HUD leading to degraded performance across a number of measures. These measures may include speed monitoring, lane maintenance and object detection. Further, it is expected that as the number and difficulty of manual tasks increase (e.g., driving around curves, driving at higher speeds), performance across a number of measures will suffer. These measures may include speed monitoring and lane deviations maintenance.

In this experiment, two different kinds of HUDs (i.e., digital and analogue) as well as the in-dash speedometer (HDD) were used to monitor vehicle speed. The ability to (a) maintain speed and (b) maintain lane position was used as an index of driving performance. Additionally, reaction times and response accuracy to auditory and visual probes were collected.

METHOD

Participants

Twenty-eight people (17 male, 11 female) participated in the study for either course credit (Introductory Psychology) or $25.00 remuneration. The data from four participants were eliminated: two participants were unable to complete the experiment due to simulator sickness and two misunderstood task instructions. The remaining 24 (16 men, 8 women) participants all had valid driver's licenses and, on average, drove an estimated 18,290 km. per year. All participants had normal or corrected-to-normal vision. The average age of the 24 participants was 30 years.

Apparatus

The experiment was conducted using a high fidelity, fully configured, DriveSafetyTM 500c driving simulator.[2] A cut-down passenger vehicle consisting of only the driver's seat and controls was located in front of five projection screens providing 21.8° of vertical and 150° degrees horizontal field of view. Imagery from the rear-view mirror and both side mirrors was superimposed on the projection screens in appropriate locations. The car simulator included computer-generated engine and external (passing traffic) noise. A single driving scenario was used. The driving scenario was constructed using Tool Command Language (TCL) scripting language that was executed under a PC-based Linux platform. The scenario simulated a two-lane highway passing through rural farming areas with incoming traffic.

Vehicle speed was displayed using either: (1) a digital HUD, (2) an analogue HUD, (3) a standard vehicle instrument panel (hereafter, HDD in reference to the typical

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[2] I would like to thank Transport Canada for use of their driving simulator.

Head-Down Display configuration). The digital HUD (see Figure 2) was located 5° below the horizon and 10° to the left of centre on the front screen. HUD digits were green and subtended a viewing angle of 4° vertically and 2° horizontally. The analogue HUD (see Figure 3) was centred relative to the location of the digital HUD and subtended 10° both vertically and horizontally. The analogue HUD was the same green colour as the digital HUD. The HDD can be seen in Figure 4. The visual displays of the scenario were updated at a rate of 60 Hz. and data were collected at 60 Hz.

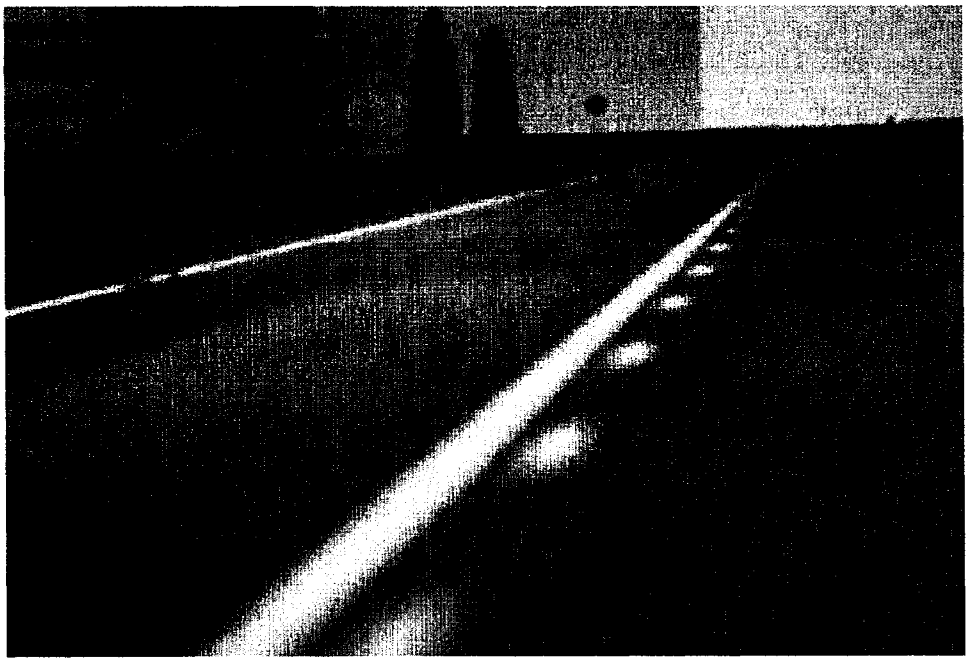

Figure 2. Digital HUD used in the experiment.

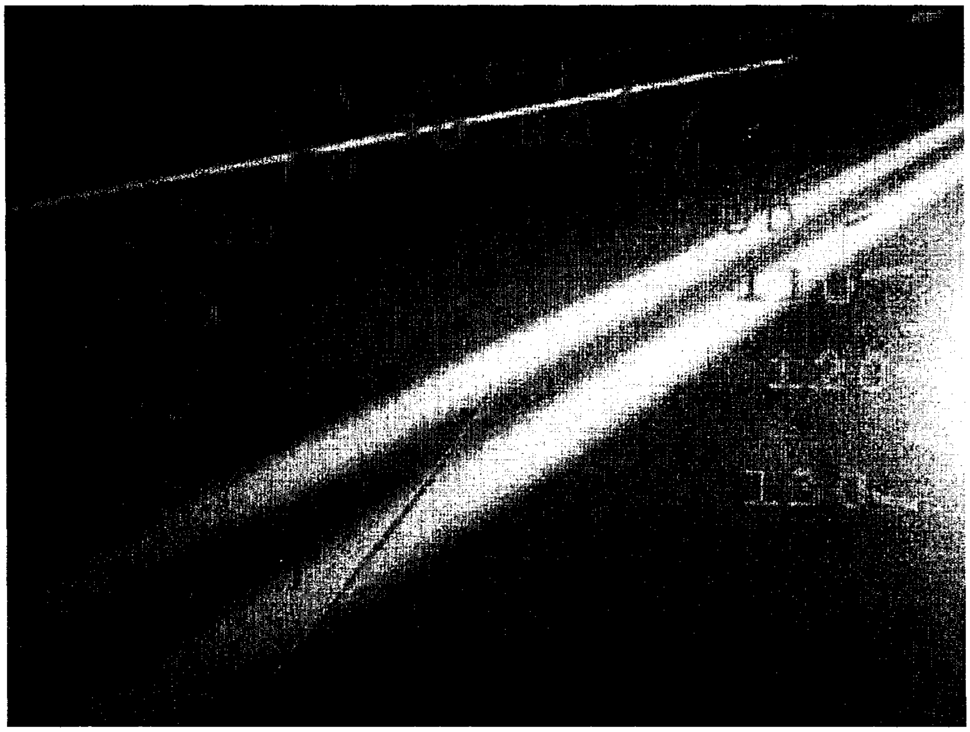

Figure 3. Analogue HUD used in the experiment.

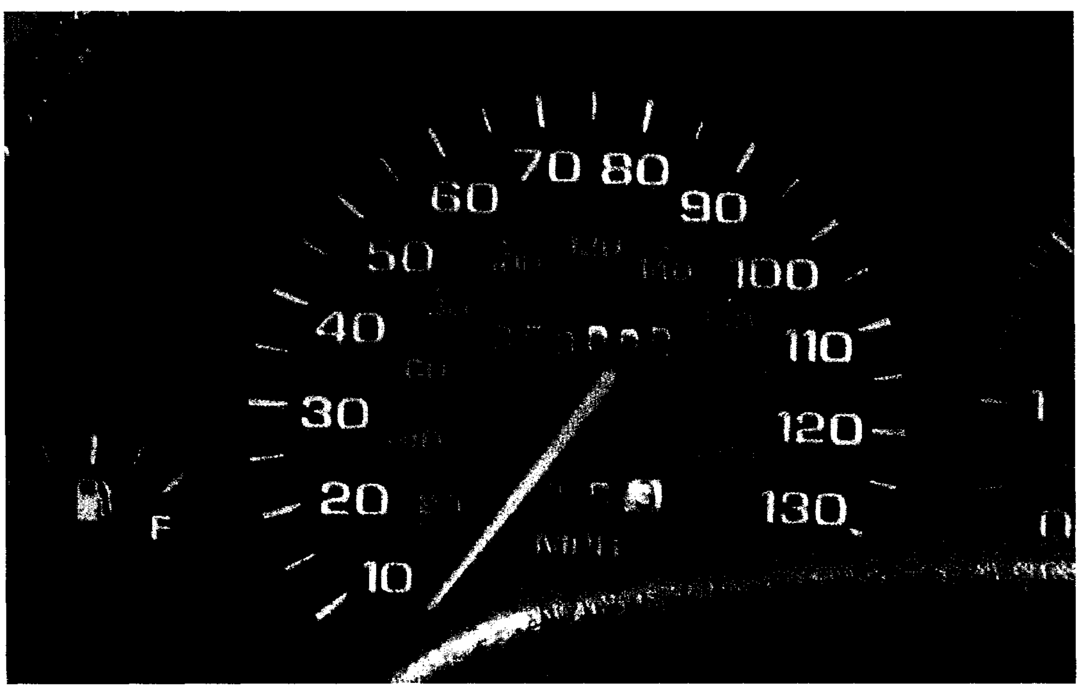

Figure 4. Portion of the HDD used in the experiment.

While driving, the participants were required to respond to visual and auditory probes (in separate experimental conditions) by pressing a button attached to their right index finger. The auditory and visual probes were presented randomly every 3 to 5 seconds throughout the scenario. The visual probe was a small red square that covered an area of 0.45° vertical x 0.5° horizontal. The visual probes were presented on the front screen in 6 pseudo-random locations as shown in Figure 5. The auditory probe was a tone that was heard through a speaker located directly behind the participants' head. Both auditory and visual probes were presented for 300ms. Failures to respond to a probe within 2000 ms of the probe's onset were logged as misses.

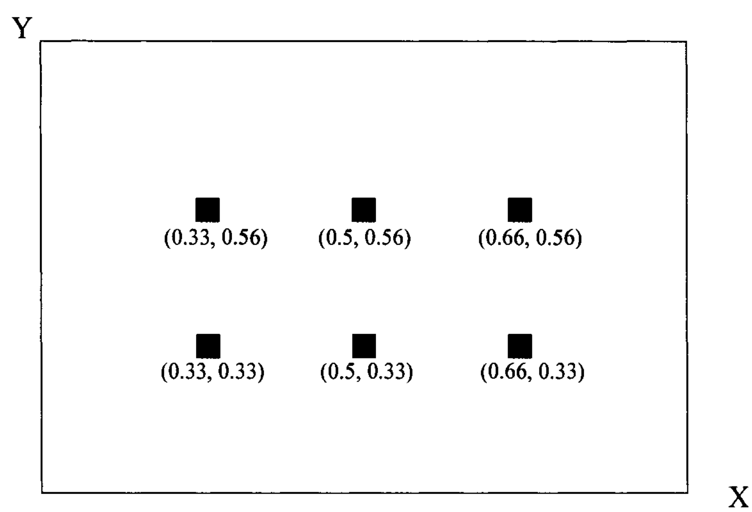

Figure 5. X and Y coordinates of the visual probes.

Design and Procedure

The study was a 3 (Display: HDD vs. analogue HUD vs. digital HUD) x 3 (Probe: no probe vs. auditory probe vs. visual probe) x 2 (Speed: 35 MPH vs. 65 MPH) x 2 (Road Type: straight vs. curved) repeated-measures design. The experimental session consisted of three 30-minute scenarios with each scenario consisting of two speed limits (35 MPH

& 65 MPH), three probe conditions (none, auditory & visual) and two road types (straight & curved). Display condition (HDD, analogue HUD, digital HUD) was varied across the three scenarios. The speedometer on the instrument panel was covered for both the analogue and digital HUD conditions to ensure that participants used the HUD to monitor speed.

Counterbalancing was accomplished using a Latin Squares design such that each HUD condition appeared either first, second or third for an equal number of participants. Probe condition was crossed with Display condition and counterbalanced with the constraint that the no-probe condition was always presented first. Speed was crossed with both Display and Probe conditions and counterbalanced. Road condition was crossed with all three of the above factors with straight sections always appearing before curved sections.

Each participant familiarized themselves with the controls and operation of the driving simulator during a ten-minute practice session. The digital HUD was displayed during this practice session to minimize novelty effects associated with the presence of a HUD that could occur during the experimental trials. Participants were instructed to (a) obey all posted speed limits and general rules of the road, (b) keep the vehicle centred in the traffic lane and (c) respond to auditory and visual probes as quickly as possible. Participants were told that their primary task was safe operation of the vehicle.

RESULTS

All data sets were trimmed in two ways. First, data was eliminated at the speed limit transition areas (transitioning from either 35 to 65 MPH or from 65 to 35 MPH) were eliminated. Transition areas were the first 20-seconds of driving time immediately following a change in the speed limit. Second, due to properties of the driving simulator, lane deviations greater than 1.8 m from centre are not logged in the data file. Accordingly, data in which the participant's lane position deviated 1.8 m or more from centre were eliminated from all subsequent analyses.

An alpha level of .05 was adopted throughout this research. Comparisons between conditions were made using 95% confidence intervals (see Loftus & Masson, 1994). Confidence intervals allow for a simple (visual) heuristic where a difference between two conditions is judged to be significant when the confidence intervals of two conditions overlaps by ¼ or less of the total interval. A significant difference between two conditions is also referred to as a critical difference and can be calculated by multiplying the confidence interval by $\sqrt{2}$.

Responses to Visual and Auditory Probes

The visual and auditory probe tasks were used to index the attentional demands associated with drivers' use of the Displays (HDD, analogue HUD, digital HUD) as well as the demands associated with different Road type (straight vs. curved) and Speed conditions (35 MPH vs. 65 MPH). Although different patterns of data associated with the visual and auditory probe tasks could be expected, a direct comparison of the two tasks across the various conditions was not of theoretical interest. Accordingly, the visual and auditory probe data were analyzed separately.

Visual Probe Data

Three one-way ANOVAs showed no effects of counterbalancing order for Display condition, Probe condition, or Speed condition on reaction times (RTs) or hit rates. Data across these counterbalancing orders were therefore collapsed.

Visual Probe Reaction Times

Reaction times to visual probes are shown in Figure 6 and were analyzed in a 2 (Road Type: straight vs. curved) x 2 (Speed: 35 MPH vs. 65 MPH) x 3 (Display: HDD vs. analogue HUD vs. digital HUD) repeated-measures ANOVA. A main effect of Road type, $F(1, 23) = 9.5$, MSE = 7402, $p < .01$, showed that responses to visual probes were significantly slower while participants were driving on the curved (499 ms) versus the straight (485 ms) sections of the road. As expected, this shows that participants were required to allocate more attention to driving in the curved than in the straight sections of the road. In general, this finding is consistent with Wicken's (1980, 2002) claim that the ability to share manual (output) resources depends on the difficulty of the concurrent manual tasks. On this view, two easy manual tasks such as driving on a straight road and executing a simple button press can be time-share effectively. When one (or more) of the manual tasks is difficult (e.g., such as steering through a curve), performance on this or another concurrently performed task (e.g., button press) will decrement.

Of primary interest was a significant main effect of Display, $F(2, 46) = 3.15$, MSE = 2352, $p < .05$, where responses to visual probes were slower overall in the digital HUD (502 ms) condition relative to both the analogue HUD (488 ms) and the HDD (485 ms) conditions. Although Display did not interact significantly with Speed, a comparison based on the confidence intervals (see Figure 6) shows that the disadvantage of the digital versus the analogue HUD occurred only in the 65 MPH condition. In the 35 MPH zones of the scenario, participants' responses to visual probes were slower in both the digital and the analogue HUD conditions relative to the HDD display condition. Considered together, these results suggest that while cognitive tunnelling occurred to some extent with both the digital and the analogue HUD (see 35 MPH condition), cognitive tunnelling was greater with the digital HUD.

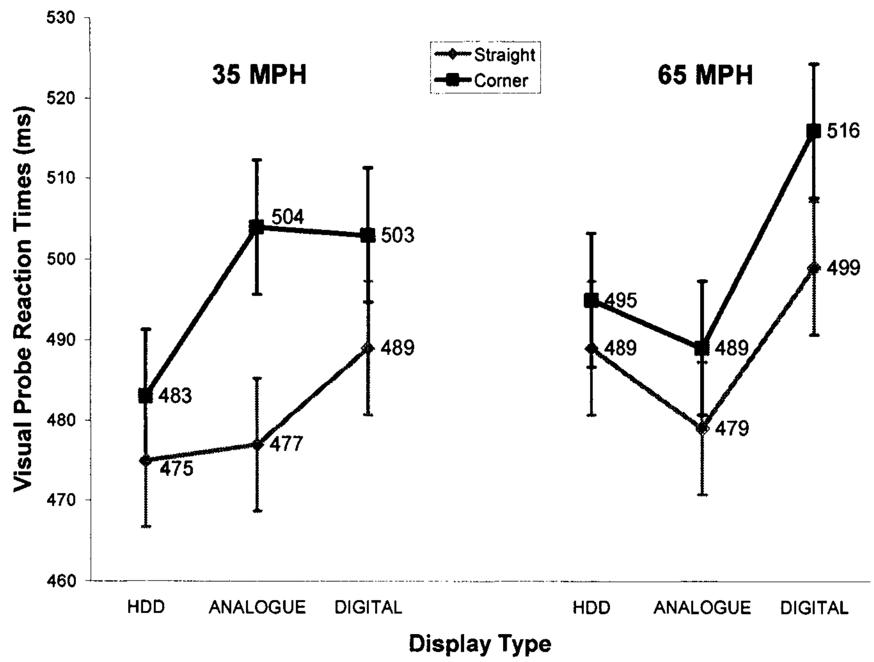

Figure 6. Reaction times (ms) for visual probes as a function of Road Type, Speed and Display.

Visual Probe Hit Rates

Hit rates to visual probes are shown in Figure 7. Hit rates to visual probes were generally high (90% or higher across all conditions). As with the RT data, a 2 (Road Type: straight vs. curved) x 2 (Speed: 35 MPH vs. 65 MPH) x 3 (Display: HDD vs. analogue HUD vs. digital HUD) repeated-measures ANOVA showed a main effect of Road Type, $F(1, 23) = 26.8$, MSE = 22.06, $p < .001$. As shown in Figure 7, hit rates were generally lower while participants were driving on the curved (93%) versus the straight road (96%) sections of the road. This finding is consistent with the reaction time data in showing that participants were required to allocate more attention while steering through curves than when driving on a straight road.

A main effect of Display, $F(2, 46) = 14$, MSE = 29.27, $p < .001$, showed that hit rates were overall significantly higher in the analogue (96%) and digital HUD (95%) conditions than in the HDD (92%) condition. The difference in hit rates between the analogue and digital HUD conditions was not significant. Although the difference in hit rates between the HDD versus the analogue and digital HUD conditions is not large (average difference of 3.5%), this finding shows that driver's likelihood of missing an expected event (i.e., visual probe) is greater when they are required to look away from the external scene to monitor vehicle speed.

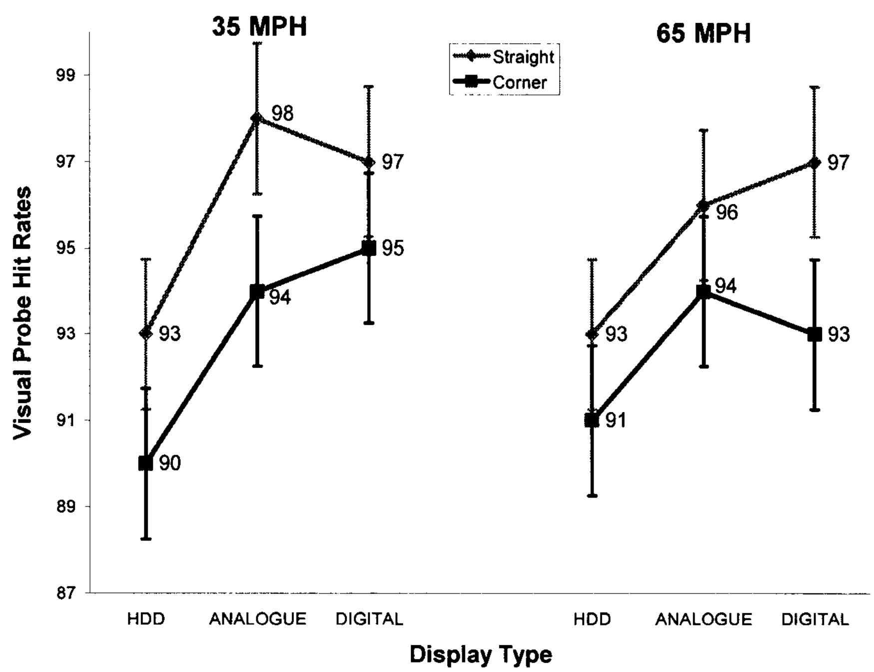

Figure 7. Hit rates for visual probes as a function of Road Type, Speed and Display.

Auditory Probe Data

Three one-way ANOVAs revealed that there was no effect of counterbalancing order for Display condition, Probe condition, or Speed condition on reaction times (RTs) or hit rates. Data across these counterbalancing orders were therefore collapsed.

Auditory Probe Reaction Times

Reaction times to auditory probes are shown in Figure 8. A 2 (Road Type: straight vs. curved) x 2 (Speed: 35 MPH vs. 65 MPH) x 3 (Display: HDD vs. analogue HUD vs. digital HUD) repeated-measures ANOVA showed a significant main effect of Road Type, $F(1, 23) = 9.5$, MSE = 7402, $p < .01$. As with the visual probe data, responses to auditory probes were significantly slower on the curved sections of the road (400 ms) than on the straight (384 ms) sections of the road. This finding provides further support to the notion that participants were required to allocate more attention while steering through curves than when driving on a straight road.

Of primary interest was a main effect of Display, $F(2, 46) = 7.7$, MSE = 3450, $p < .01$. Overall, responses to auditory probes were significantly slower in the digital HUD (409 ms) condition as compared to the analogue HUD (376 ms) and the HDD (391 ms) conditions. As with the visual probe RT data, this pattern suggests a cognitive tunnelling effect with the digital HUD whereby monitoring vehicle speed required more attention when using the digital HUD as compared to the analogue or the HDD.

Although Display did not significantly interact with Road Type and Speed, the pattern of results in Figure 8 shows that the responses to auditory probes were consistently slower in the digital HUD versus the analogue HUD and the HDD conditions when participants were driving in the 35 MPH zones of the road. In the 65 MPH zones, there was a disadvantage for the digital HUD only in the straight sections of the road.

It is also important to note that responses to auditory probes were generally faster in the analogue HUD than the digital HUD condition. In fact, there was no evidence for cognitive tunnelling with the analogue HUD in that responses to auditory probes were undifferentiated from those in the HDD display condition.

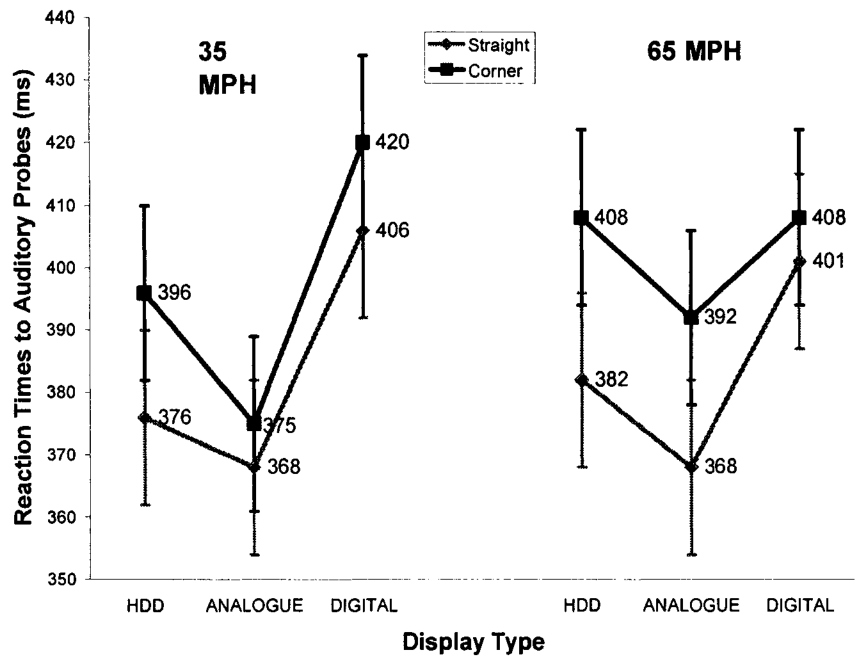

Figure 8. Reaction times (ms) for auditory probes as a function of Road Type, Speed and Display.

Auditory Probe Hit Rates

As shown in Figure 9, hit rates to auditory probes were generally very high (98% or higher across all conditions). A 2 (Road Type: straight vs. curved) x 2 (Speed: 35

MPH vs. 65 MPH) x 3 (Display: HDD vs. analogue HUD vs. digital HUD) repeated-measures ANOVA revealed no significant main effects or interactions.

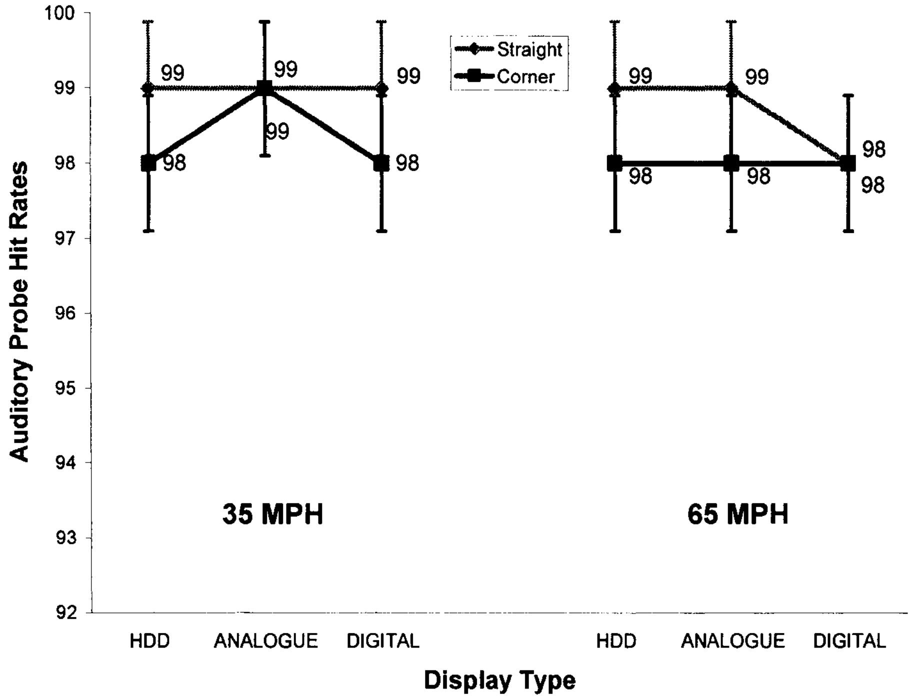

Figure 9. Hit rates for auditory probes as a function of Road Type, Speed and Display.

Summary of Visual Probe and Auditory Probe Results

The visual and auditory probe data show a general disadvantage for the digital HUD display. Relative to the HDD and the analogue HUD displays, the use of a digital HUD slowed participants' responses to visual probes and to auditory probes. This is consistent with a cognitive tunnelling hypothesis whereby a driver's attention is required to process the digital HUD information, therefore resulting in slower processing of the visual and auditory probes.

The slower response times to visual and auditory probes in the digital HUD as compared to the analogue HUD condition provides some insight into cognitive tunnelling. This finding suggests that more central attention is required when speed information is presented in digital format as compared to analogue format. It is interesting to note that there was no evidence for cognitive tunnelling in the analogue HUD condition. In fact, hit rates to both visual and auditory probes were higher in the analogue than the HDD condition and response times to probes were generally undifferentiated across these two display conditions.

Speed Monitoring Data

Speed monitoring performance was calculated by subtracting vehicle speed from the posted speed limit and taking the absolute value of this difference. Three one-way ANOVAs revealed that there was no effect of counterbalancing order for Display condition, Probe condition, or Speed condition on speed monitoring performance. Data across these counterbalancing orders were therefore collapsed.

The speed monitoring data was analyzed with a 3 (Display: HDD vs. analogue HUD vs. digital HUD) x 3 (Probe Type: no probes vs. auditory probes vs. visual probes) x 2 (Road Type: straight vs. curved) x 2 (Speed: 35 MPH vs. 65 MPH) repeated-measures ANOVA. All main effects and several two-way interactions were significant.

There was a significant main effect of Display, $F(2, 46) = 19.4$, MSE = .4, $p < .001$, a significant main effect of Speed, $F(1, 23) = 11.2$, MSE = 1.4, $p < .01$ a significant two-way interaction between Display and Speed, $F(2, 46) = 33.2$, MSE = .2, $p < .001$. As shown in Figure 10, deviations from the posted speed limit were on average significantly higher in the HDD (2.57 MPH) condition relative to the analogue HUD (1.93 MPH) or the digital HUD (1.91 MPH) condition. When collapsed across the posted-speed conditions, there was no significant difference in speed deviations between the analogue and digital HUD conditions. Overall, departures from the posted-speed limits were significantly larger in the 65 MPH zones (2.44 MPH) than in the 35 MPH zones (1.84 MPH). However, when the HDD was used for speed monitoring, speed deviations undifferentiated across the 35 MPH versus the 65 MPH zones. In contrast, speed maintenance was significantly better in the 35 MPH than the 65 MPH speed zone when either the analogue HUD or the digital HUD was being used. In general, the pattern of results shows an advantage for speed monitoring with HUDs over a traditional HDD. The one exception is in the 65 MPH condition where speed deviations did not differ between the digital HUD versus the HDD condition.

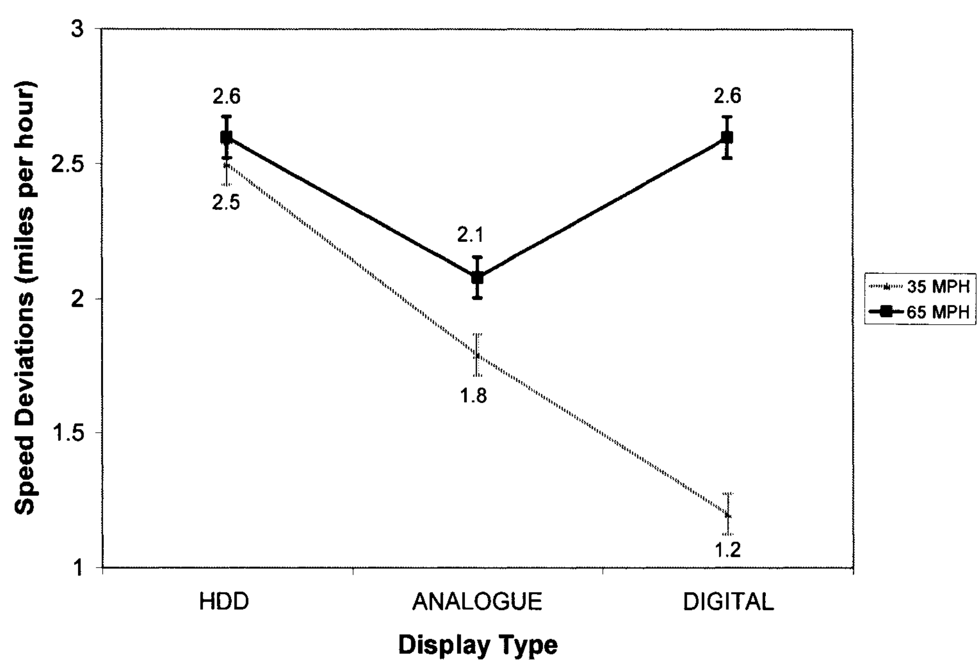

Figure 10. Mean absolute value of speed differences between vehicle speed and the posted speed limit across Display and Speed.

Figure 11 shows a significant main effect of Road Type, $F(1, 23) = 6.5$, MSE = .6, $p < .05$, and a significant two-way interaction between Speed and Road Type, $F(1, 23)$

= 5.8, MSE = .4, $p < .05$. Speed deviations were significantly larger on curved sections of the road (2.29 MPH) than on straight sections (1.97) and as noted above, deviations were greater in the 65 MPH (2.44 MPH) than the 35 MPH (1.84 MPH) zones. As shown in Figure 11, where the ability to monitor speed in the 35 MPH zones was not affected by road type, speed deviations in the 65 MPH zones were greater when steering through a curved section of the road.

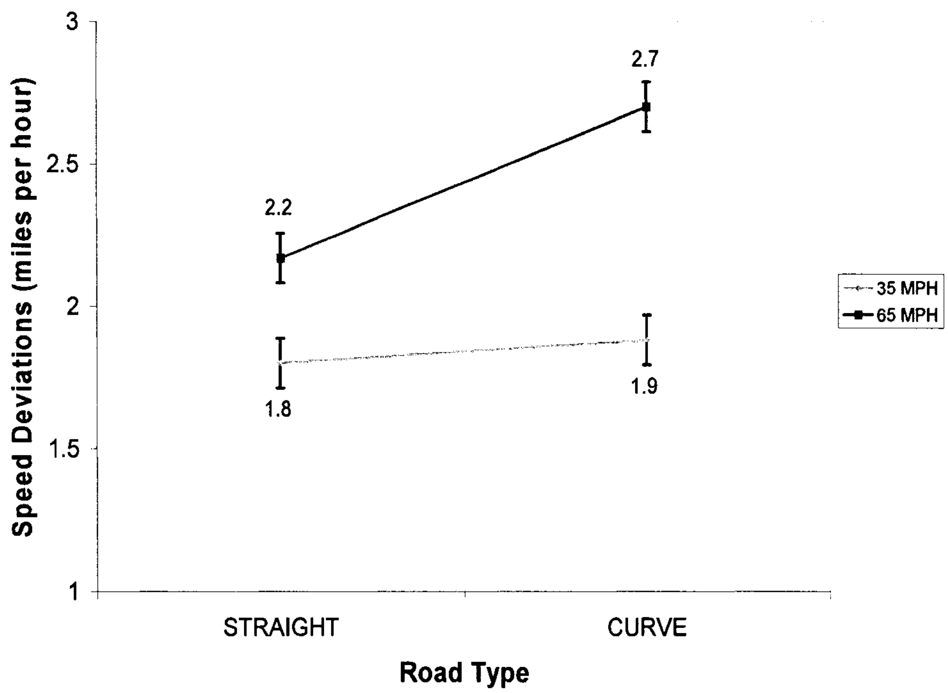

Figure 11. Mean absolute value of speed differences between vehicle speed and the posted speed limit across Road Type and Speed.

Figure 12 shows a significant main effect of Probe Type, $F(2, 46) = 4.7$, MSE = .2, $p <.05$. Speed deviations were largest in the visual probe condition (2.30 MPH), smaller in the auditory probe condition (2.10 MPH) and smallest in the no-probe condition (2.00 MPH). This shows that participants experienced most difficulty time-sharing speed monitoring with the visual probe task. As shown in Figure 12, speed deviations were significantly greater in the visual probe condition than in either the auditory or the no-probe conditions. Speed monitoring performance was not significantly different in the auditory versus the no-probe conditions.

Although the two-way interaction between Display and Probe Type was not significant, it is clear from Figure 12 that speed deviations were larger in the HDD condition relative to either the digital HUD or the analogue HUD condition. Further, speed deviations when visual probes were present were smallest in the digital HUD condition.

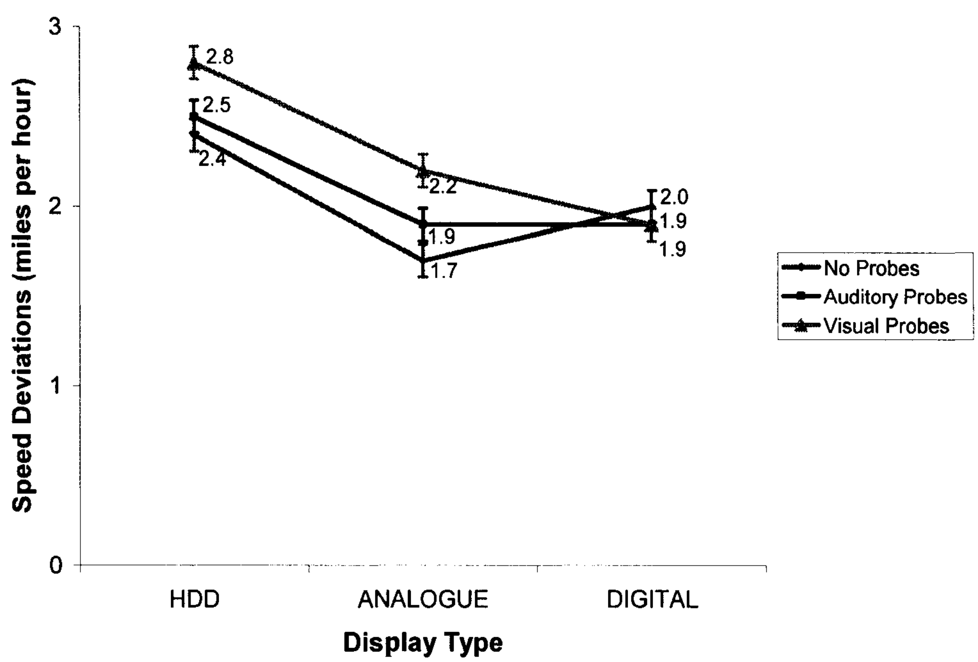

Figure 12. Mean absolute value of speed differences between vehicle speed and the posted speed limit across Speed and Display.

Summary of Speed Monitoring Results

The speed monitoring data show a clear advantage for the digital and analogue HUD display over a traditional HDD. Relative to the HDD, the use of the analogue or digital HUD displays allowed participants to drive closer to the posted speed limit. This result is consistent with the claim that speed monitoring is better when a HUD is present. The HUD allows the driver constant access to the vehicle speed leading to better speed maintenance.

Departures from the speed limit were significantly larger when visual probes were present relative to when either auditory or no probes were present. When participants were watching for and responding to visual probes, they were less able to divide their attention between the visual probes and the speed monitoring display.

Recall that reaction times to visual probes were slowest in the digital HUD condition. Further, there was a trend for smaller speed deviations in the digital HUD condition when visual probes were present. Considered together, these results suggest a cognitive tunnelling effect. That is, attention was captured and held by the digital HUD (as seen by smaller speed deviations) resulting in slower processing of visual probes.

The results of the speed monitoring data in combination with the visual and auditory probe response times and hit rate data shows an advantage for the analogue HUD compared to the HDD and the digital HUD. Response times and hit rates were generally superior in the analogue HUD condition. Further, the analogue HUD allows for excellent speed maintenance without the apparent cognitive tunnelling effects seen with the digital HUD.

Lane Position Data

The ability to monitor lane position is a critical aspect of safe driving. Failing to maintain a proper lane position can have serious consequences (e.g., crossing into oncoming traffic, hitting the road shoulder). Indeed, lane position is arguably more important that speed monitoring in terms of the driving safety.

In the present study, participants were instructed to maintain a centre lane position. Accordingly, the centre-most position of the lane was assigned a value of zero and any deviation left of centre was recorded as a negative value (in meters [m.]), whereas any deviation to the right was recorded as a positive value (in meters [m.]). Although knowing about possible tendencies to drift systematically in one direction relative to the other may be of some interest, it is beyond the scope of this study. For this reason, only the absolute value of all lane deviations, regardless of direction, are examined. Absolute lane deviation measures are commonly used to assess drivers' ability to maintain lane integrity (e.g., see Kapstein, 1994; Horrey & Wickens, 2004).

Order Effects

Three one-way ANOVAs revealed that there was no effect of counterbalancing order for Display condition, Probe condition, or Speed condition on lane maintenance. Data across these counterbalancing orders were therefore collapsed.

The lane deviation data were analyzed with a 3 (Display: HDD vs. analogue HUD vs. digital HUD) x 3 (Probe Type: no probes vs. auditory probes vs. visual probes) x 2 (Road Type: straight vs. curved) x 2 (Speed: 35 MPH vs. 65 MPH) repeated-measures ANOVA. This analysis revealed three main effects and several interactions.

There were significant main effects of Display, $F(2, 46) = 5.323$, MSE = .020, $p < .01$, and Road Type, $F(1, 23) = 34.690$, MSE = .049, $p < .001$, as well as a significant Display by Road Type interaction, $F(2, 46) = 7.726$, MSE = .007, $p < .01$. As shown in Figure 13, lane deviations were largest in the digital HUD condition (0.38 m.) and significantly smaller in the analogue HUD (0.35 m.) and HDD conditions (0.35 m.). There were no significant differences in lane position monitoring between the HDD and the analogue HUD conditions. Further, lane deviations were significantly smaller on straight sections than on curved sections (0.32 vs. 0.42 m., respectively). The two-way interaction between Display and Road Type shows that lane deviations on a curved road were large but not significantly different across the three HUD conditions. Lane deviations on a straight road are smaller than on the curved sections and undifferentiated across the HDD versus the analogue HUD condition. However, lane deviations on a straight road were significantly larger in the digital HUD condition relative to the HDD or the analogue HUD conditions.

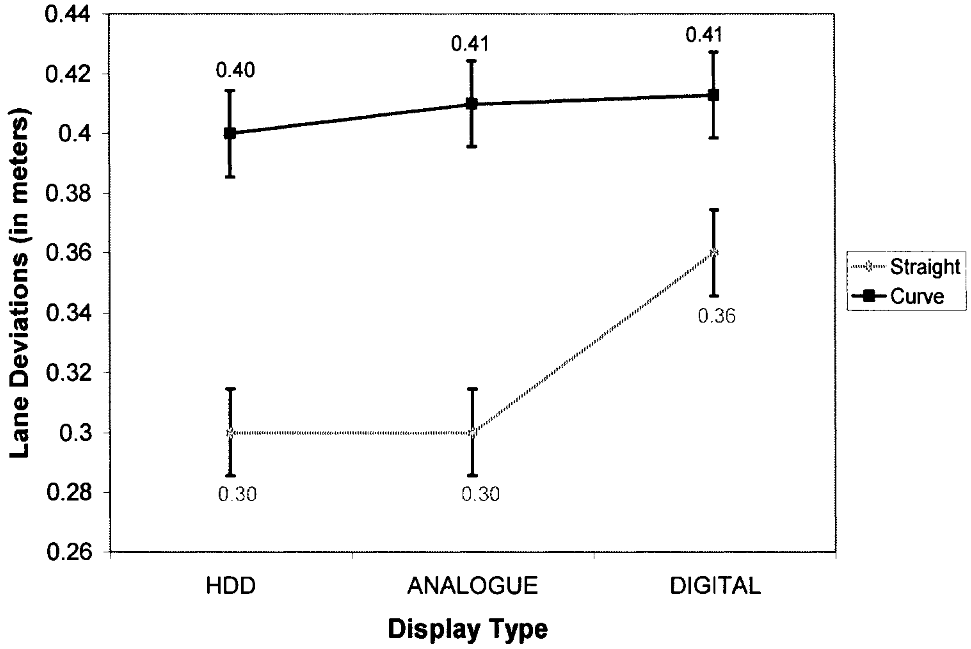

Figure 13. Mean absolute value of difference between vehicle position and centre of lane across Display and Road Type.

Figure 14 shows a significant main effect of Speed, $F(1, 23) = 43.033$, MSE = .026, $p < .001$, and the significant two-way interaction between Speed and Road Type, $F(1, 23) = 16.404$, MSE = .011, $p < .001$. Lane deviations were larger in the 65 MPH zone (0.33 m.) than in the 35 MPH zone (0.40 m.). The difference in ability to maintain lane position in the two speed zones was greater for curves than for straight sections.

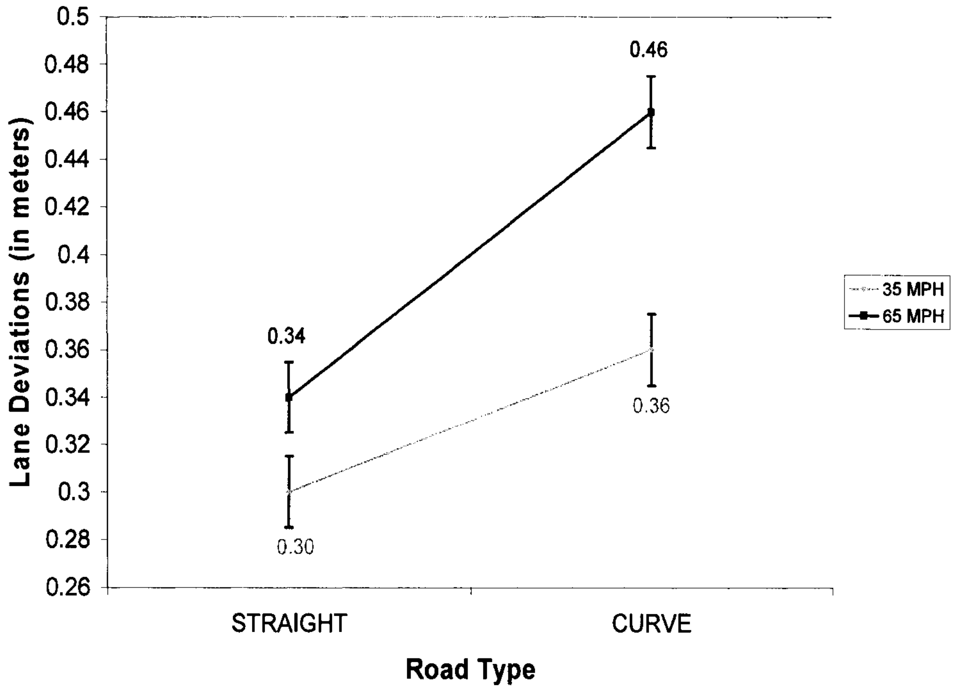

Figure 14. Mean absolute value of difference between vehicle position and centre of lane across Road Type and Speed.

Figure 15 shows a significant two-way interaction between Display and Probe Type, $F(2, 46) = 3.525$, MSE = .032, $p < .05$. When using either the HDD or the analogue HUD display, participants' lane deviations were similar and not differentially affected by the probe condition. When participants were using the digital HUD display, however, lane deviations were relatively large and greater in the visual and auditory probe conditions versus the no-probe condition. This pattern of results shows that time-sharing lane positioning requirements with a secondary probe task is difficult when the driver is presented with speed information in a digital HUD format.

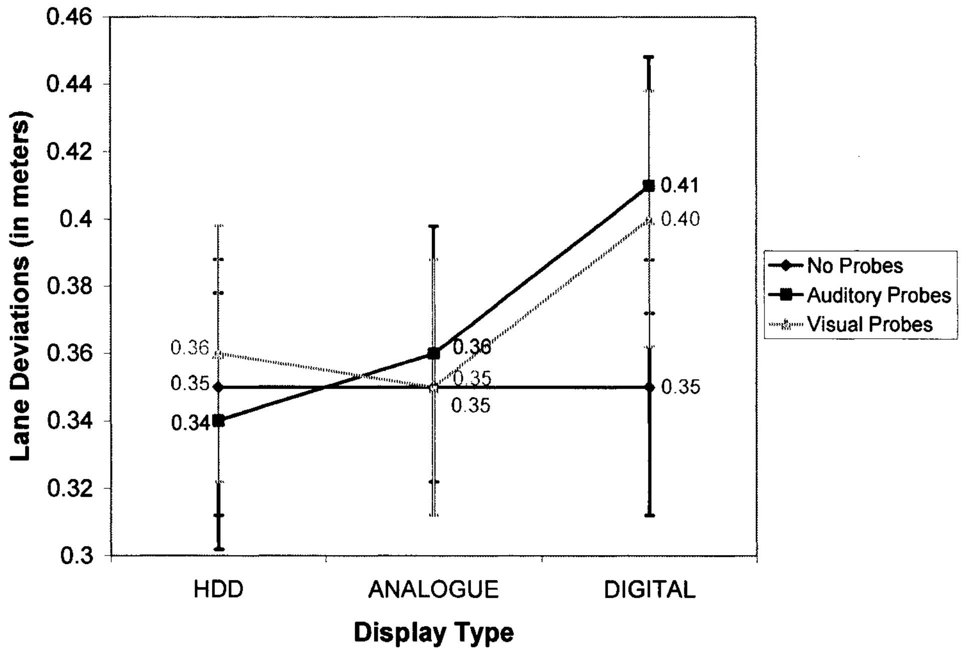

Figure 15. Mean absolute value of difference between vehicle position and centre of lane across Display and Probe Type.

Summary of Lane Deviation Results

The results of these lane deviation data are straightforward: lane deviations were larger in the digital HUD condition than in either the analogue HUD or HDD condition. These results are consistent with previous findings that HUDs cause cognitive tunnelling. Specifically, these data are consistent with the claim that more attention was required to process the digital HUD information than the analogue HUD or HDD information, thereby resulting in fewer attentional resources for use in maintaining lane position. However, there is no evidence that cognitive tunnelling occurred in the analogue HUD condition.

Further, when auditory or visual probes were present, lane deviations were larger in the digital HUD condition relative to the analogue or the HDD conditions. These results are consistent with the claim that HUDs with digital speed readouts (typical of most HUDs currently used in passenger automobiles) render drivers susceptible to cognitive tunnelling whereby their attention is focused on the HUD information to the extent that external environment information (e.g., lane position and expected events) is not adequately processed.

GENERAL DISCUSSION

The results from this driving simulation experiment are straightforward: when vehicle speed was available on a digital or an analogue HUD, participants were better at monitoring their speed. However, when a digital HUD was used participants were worse at maintaining their lane position compared to when they relied on an analogue HUD or a HDD to obtain vehicle speed information. These results are consistent with the claim that HUDs with digital speed readouts (typical of most HUDs currently used in passenger automobiles) render participants susceptible to cognitive tunnelling whereby their attention is focused on the HUD information to the extent that navigation environment information (e.g., lane position) is not adequately processed.

It is argued here that, despite both the digital HUD information and the external environment information occupying the same visual space, these two types of information are treated as two distinct objects because they are grouped separately based on the Gestalt principle of common fate. It is further argued that participants have difficulty dividing their attention between these two objects. That is, participants selectively attend to the digital HUD information at the cost of not attending to external environment information (i.e., the presence of digital HUD information induces cognitive tunnelling). One interpretation of cognitive tunnelling is object-based attention whereby visual attention is captured by the HUD symbology. However, the present data suggests that cognitive tunnelling may be a central cognitive resource issue. Evidence for this is seen in slower reaction times to auditory probes. If cognitive tunnelling was merely the capture of visual attention, reaction times to auditory probes would not differentiate across the three display types. Future research will be needed to investigate the central cognitive resources required for processing a digital display.

Further, the results of the current study are consistent with Wickens' (1980, 2002) multiple resource model. Specifically, there is evidence as the difficulty of manual response tasks increases, performance suffers. For example, as vehicle speed increased (from 35 to 65 MPH) and road type changed (from straight to curved sections) both lane and speed deviations were significantly larger. Additionally, reaction times to both visual and auditory probes were significantly longer when curves were negotiated relative to when straight sections were driven. In this situation, button presses and steering the car were two manual responses that were not efficiently time-shared

With respect to performance when multiple visual tasks were done concurrently, again there is some support for Wickens' (1980, 2002) model. When visual probes were present, overall deviations in vehicle speed were significantly larger than when either auditory or no probes were present. Participants found it difficult to concurrently watch for visual probes and monitor/control vehicle speed. Departures from the posted speed were significantly larger when participants were driving around curves or at the higher speed (65 MPH), suggesting that more visual-spatial resources were dedicated to the external scene (and fewer to the speed display) to ensure safe vehicle operation.

The present findings suggest that display type rather than simply having a HUD present resulted in more performance decrements (specifically lane keeping and reaction times to auditory and visual probes). It is speculated that the digital HUD requires (a) more time looking at the display to extract all of the information required to determine speed and speed changes and (b) more cognitive resources to process changes on the display. When monitoring speed with a digital HUD, the vehicle's present speed must be held in mind while further sampling of the HUD is needed to determine if the vehicle is speeding up or slowing down. If a speed change occurs and it is noted, the new vehicle speed must be subtracted from the original speed to determine if vehicle speed needs to be increased or decreased. When monitoring speed with an analogue HUD or analogue HDD, the vehicle's present speed does not need to be kept in mind. Rather, the needle on the analogue HUD points to the present speed and the movement of the arrow indicates changes in speed. In essence, the movement of the arrow signifies a change in speed and the direction of the movement (and not a mathematical calculation) informs the driver if vehicle speed needs to be increased or decreased. Arguably, assessing vehicle speed and responding to speed changes when using an analogue display requires less time looking at and processing the information on the display than when using a digital display. Understanding how a digital display is processed is an important research issue. Future research will be needed to investigate how information on digital and analogue displays is processed and when these display types should and should not be used.

From a practical standpoint, the current research highlights many important factors for the assessment of display location and display type in terms of efficient interaction and safe and proper vehicle control. Displaying information in a head-up location has the benefit of reducing the amount of time a driver's eyes are looking down (e.g., at the in-dash speedometer). Indeed, speed maintenance and hit rates for the visual probes were significantly better when either HUD type was used. However, the costs associated with a digital HUD in the current study are clear. Lane deviations were larger and reaction times to visual and auditory probes were longer than when either the analogue HUD or the HDD displays were used. Additionally, as task difficulty increased (e.g., driving faster and negotiating curves) lane deviations were significantly larger in the digital HUD condition relative to the analogue HUD and the HDD conditions. Further, performance across a number of measures (e.g., speed and lane maintenance and reaction times to auditory and visual probes) was significantly better with the analogue HUD relative to when the digital HUD was used. Given the apparent difficulty in processing the information on the digital HUD, especially for higher task loads, delaying responses to other tasks may have been the strategy participants adopted. This led to performance decrements across concurrent tasks. Finally, participants were better at maintaining the posted speed relative to when the HDD was used. Therefore, the implications of these finding may be that HUD displays in motor vehicles should be in analogue format. An analogue HUD allows drivers to better maintain the posted speed, to stay within the confines of the driving lane, and to respond quickly to expected events with no obvious costs.

Although monitoring vehicle speed is important, the consequences of failing to do so pale in comparison to the potentially disastrous outcomes of neglecting one's lane position or not being able to detect objects and/or events in the navigation environment (e.g., a child running into the roadway). As such, the present research suggests that the limited benefits of a digital speed HUD are outweighed by the potential costs associated with not adequately processing information in the external environment. It is therefore essential to refine and empirically assess how information should be presented on a HUD so as to maximize driver awareness of vehicle status while minimizing potential cognitive tunnelling effects.

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Appendix A

Task Instructions Given to Participants

Today you are going to be driving the simulator and you are going to be using three different speedometers to monitor your speed. The three types of speedometers you will be using are a digital head-up display, an analogue head-up display and the traditional in-dash speedometer. When you are using one of the head-up displays, your speed will be projected onto the middle screen located directly in front of you. You will drive through the scenario three times using only one of the speedometers each time you drive. As you drive through the scenario, I want you to obey general rules of the road. These include driving at the posted speed limit and staying within the lane markings. Further, you will also be required to drive both straight and curved sections of road. When you are driving around curves, please maintain your speed and lane position as best as you can. Finally, there are going to both visual and auditory probes presented and when you see or hear the probe, I want you press the button that is strapped on your index finger. I want you to respond to the probes as quickly as you can. The visual probes are red squares and they will be randomly presented on the centre screen located directly in front of you. The auditory probe is a tone that you will hear through a speaker located directly behind your head. You will not be exposed to both visual and auditory probes at the same time. Rather, you will respond to the visual/auditory probes first and then you will respond to the other probe (either auditory/visual) second. Your primary task in this experiment is safe vehicle operation. This means driving the posted speed limit and staying in your lane. Any questions?