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Human Factors Aspects of Using Head Up Displays in Automobiles:

A Review of the Literature

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16. Abstract

This document provides an overview of studies investigating the use of HUDs by aviators and drivers, including a summary of HUD research variables, test procedures and study results. The predicted performance advantages of automotive HUDs include increased eyes-on-the-road time and reduced reaccommodation time, particularly for the older driver. To date, the research does not provide robust evidence for operationally significant performance advantages due to HUDs. However, conclusions are equivocal due to the interaction of independent variables such as workload, display complexity and age. Studies indicate that key operator performance issues with HUDs include contrast *interference,* where HUD symbology masks safety-critical targets in the forward driving scene, and *cognitive capture,* or degradation of responses to external targets due to the processing of information from a HUD image. In general, the review supports and extends earlier findings that HUD information cannot be processed separately from external roadway information. Countermeasures reviewed in this paper include the use of conformal symbology, and auditory HUDs. The review identifies a number of implementation issues for automotive HUDs: (1) reliable measures of the effect of HUD use on responses to priority external targets must be obtained, under realistic operating conditions; (2) practical considerations of cost, size, and adaptability to a range of driver eye heights figure prominently if the use of HUDs in the private vehicle fleet in the U.S. is to become routine; and (3) driver age and associated visual/cognitive performance differences which are commonly linked to safe vehicle operation must be taken into account during product design, development, and testing.

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Glossary

The following terms are used throughout this literature review. The definitions reflect common usage where possible. In some instances, distinctions are made between terms that are not typically made in the literature (for example, between attentional tunneling and cognitive capture). In these instances, the rationale/justification for a defmition is provided.

Accommodation: Adjustment of the thickness of the crystalline lens in the eye to bring the images of objects into focus at the retina.

Accommodative convergence: Convergence response of extraocular muscles induced by an accommodative shift to nearer objects in the absence of binocular depth cues (i.e., accommodation-induced convergence).

Analog symbology: Symbology format in which information is conveyed by changing the position of an indicator along some scale. For example, a standard analog speedometer moves a dial to point to the current speed (cf. digital symbology).

Anti-reflection coating: An optical coating that increases the transmittance at air-substrate interfaces. This coating is used to minimize double images created by reflections off the front and back surfaces of the combiner.

Attentional tunneling: Degradation in peripheral performance attributable to a narrowing of the focus of attention. In the literature, this term is used interchangeably with "cognitive capture" and "cognitive tunneling". Attentional tunneling is only manifested when performance decrements are demonstrated as a function of eccentricity (see Ward & Parkes, 1994 for review).

Backward masking: A type of masking in which the masking stimulus is presented after the test stimulus. Thus, the mask interference is retroactive.

Binocular mirrored HUD: Similar to a fully-functional HUD except that there are no optics between the image source and the combiner (only a large piece of plate glass). Thus, the virtual image distance is equivalent to the source-to-eye distance. To obtain a minimum virtual image distance of 2.5 m, the image source would **need** to be located outside the simulator cab.

Binocular misalignment: This occurs when the images of objects are not aligned vertically or horizontally (or some combination of both) for the two eyes due to optical distortions and improper alignment of optical components.

Binocular rivalry: A phenomenon occurring when the two eyes are presented with different stimuli. Under these viewing conditions, the stimuli appear to compete with each other rather than combine. Perceptually, the observer sees a temporal alternation between left and right eye views.

Cognitive capture: Typically used to refer to the inefficient attentional switching (from HUD, to primary task) when using HUDs This may result in missing external targets, delayed responses to external events, and/or asymmetrical transition times (longer to switch from HUD-to-external visual processing than vice versa). In effect, the HUD acts as an attentional 'trap' that draws information processing resources to the HUD and slows/degrades processing of external events. Although cognitive capture can also work in the reverse direction (i.e., longer to switch from external-to-HUD visual processing than vice versa), the safety relevance of this manifestation of cognitive capture is questionable.

Collimated imagery: Any optical system that produces images whose rays are parallel (i.e., planar wavefronts). When viewing such a system, the best-focus is obtained when the observer is accommodated to optical infinity (i.e., greater than about 20 feet).

Conformal (or contact analogue) symbology: This simulates the visual transformations of external objects to give observers the perception that the symbology is genuinely part of the external scene. For example, the forward driving scene might be overlaid with a perspective outline of the road ahead to guide motorists when driving in fog or at night.

Contrast interference: The reduction of luminance contrast in an image resulting **from** optical superimposition and spatial overlap of other images. In particular, if there are large differences in contrast (and/or average luminance) between two or more images, the higher contrast image(s) can reduce the detectability of the lower contrast image(s). The interference can be explained optically in terms of the interaction of light in the image (cf. visual masking).

Contrast masking: The preferred term is contrast interference.

Convergence accommodation: Accommodation induced by a convergence response in the absence of retinal image blur (i.e., convergence-induced accommodation).

Convergence eye **movements:** Movement of the visual axes nasally (toward the nose) for viewing near objects.

Depth-of-focus (DOF): The dioptric range of focus errors over which performance is not significantly degraded. DOF is dependent on pupil size, target size and target contrast. When specified in terms of the range of object distances over which performance is not significantly degraded, the term depth-of-field should be used

Digital symbology: Symbology in which the information is displayed using a digital format. For example, a digital speedometer displays the number corresponding to the speed (cf. analog symbology).

Diopter (D): The inverse of the focal length (f specified in meters) of a lens: $D = 1/f$.

Diplopia: A disorder that causes objects to appear double. This occurs when the visual axes of the two eyes are not directed toward the same object.

Divergence eye movements: Movement of the visual axes temporally (away from **the nose) for viewing** distant objects.

Divided attention: An attention allocation strategy in which the observer attends and responds to two or more inputs that are active simultaneously.

Dynamic range: The operating range of a device. For example, the dynamic range of a HUD display is the range of background luminance over which optimal contrast may be obtained. See schematic in Figure 1 for details.

Eye-box: The range of vertical and horizontal pupil positions over which HUD symbology is clearly visible (i.e., visible without contrast reduction or distortion). For binocular systems, the eye-box is wider than it is high due to the interpupillary distance. For monocular systems, the horizontal/vertical eye-box dimensions are roughly the same.

Forward masking: A type of masking in which the masking stimulus is presented before the test stimulus. Thus, the interference caused by the mask is proactive.

Graphic I-IUD: A simulated HUD that electronically superimposes HUD symbology as part of the same signal that generates the image for the background. Therefore, the HUD symbology is a real image and the focus distance is identical to that for the background imagery. Graphic HUDs have been used by some researchers to control for accommodative effects.

Head-Down Display (HDD): The conventional displays used in automobiles. This includes any display viewed directly (i.e., no intervening refractive or reflective optics) from a distance of about 3 1 inches (or .8 m), and is located down 15 degrees or more relative to the observer's forward line of sight.

Head-Down Instrument Panel (HDIP): Used interchangeably with HDD.

Head-Up Diipiay (HUD): Displays which project a virtual image that is usually optically superimposed on the forward field of view of drivers using either the windshield or a separate optical element as the combiner. The three components common to all fully operational HUDs are: (1) display device (includes a source and fixed/variable display matrix elements), (2) refractive and/or reflective optical elements and (3) combiner. In refractive HUD designs, the focusing is done by a large diameter lens. In diffractive (or reflective) HUDs, the virtual image is collimated and reflected by the curved combiner.

Instrument Flight Rule (IFR): Flying an airplane by instruments during low visibility conditions.

Interpupiilary distance (IPD): Distance between the centers of the pupils.

Luminance contrast: With respect to HUDs, defined as the luminance of the HUD plus luminance of the background (i.e., area adjacent to HUD symbology), divided by the luminance of the background.

Mental workload: The amount of mental effort directed toward the production or accomplishment of a task in a given period of time. Operationally defined in terms of performance on secondary or subsidiary tasks in a dual-task paradigm.

Monocular mirrored HUD: A type of experimental-use-only HUD in which the symbology is optically superimposed using a mirror positioned so that only one eye can view the HUD symbology. Combiner can be 100% reflecting (preferably front-surface) mirror placed close to the observer's eye. Due to the differences between the left and right eye images, binocular rivalry can result.

Partial overlap mirrored HUD: Similar to the binocular mirrored HUD except that the combiner is too small to allow maximum binocular overlap. Specifically, the right eye views the left half of the HUD symbology and the left eye views the right half of the HUD symbology. The amount of overlap depends on mirror width, interpupillary distance and distance to the mirror.

Projected HUD: A type of experimental-use-only HUD in which the symbology is optically superimposed via a direct projection onto the surface displaying the external scene. Similar to the graphic HUD in that the external scene and the HUD symbology are at identical distances.

Raster display: Images created by drawing horizontal lines on the display device and turning the light on or off as required to produce segments of images. The collection of horizontal scan lines is called the raster (cf. stroke display).

Reflective optics: Light rays are bent via reflection in which the angle of incidence of the light rays is the same as the angle of reflection. One advantage of reflective optics is that transmission losses are reduced since light does not propagate through the mirror substrate (cf. refractive optics).

Refractive optics: Light rays are bent via refraction in which the amount of bending depends on the refractive index of the lens, the thickness of the lens and the angle of incidence of the light rays. Not preferred as optical elements in HUDs because of the light losses that result as light propagates through the lens (cf. reflective optics).

Root mean square error: The square-root of the mean square deviation of the response from the target. More commonly termed standard deviation.

Selective attention: An attention allocation strategy in which the observer attends and responds to some inputs while ignoring others presented simultaneously.

Spatial Disorientation (SDO): A breakdown of veridical perception of orientation in space, Orientation perception is subserved by the combined inputs from visual (cortical and subcortical visual modes of processing), proprioceptive and vestibular sensory mechanisms. The cause of SDO is believed to be a mismatch among the sensory signals that can occur during high-G maneuvers or any unusual force vector while flying.

Stroke display: Image-s created by drawing continuous lines on the display. When a character/image is completed, the light is turned off, moved to a new location and then turned on to begin drawing another character/image. The term stroke comes from the fact that this type of display is similar to handwritten text (cf. raster display).

Vergence (or disjunctive) eye movements: Movement of the visual axes in opposite directions for viewing objects at either nearer (i.e., convergence which is left eye visual axis moving to the right and the right eye visual axis moving left) or farther (i.e., ***divergence*** involves left eye visual axis moving left and right eye visual axis moving right) distances.

Version (or conjugate) eye movements: Movement of the visual axes horizontally or vertically with no change in convergence.

Virtual image: Any image for which there is no measurable energy at the ***perceived*** three-dimensional location of the object. For example, when looking at a planar mirror, the ***perceived*** location of the object (i.e., observer) is behind the mirror but there is no energy at that location (i.e., behind the mirror). Virtual images can also be created using negative lenses, convex mirrors and prisms.

Vision Enhancement System (VES): The use of conformal symbology displayed on a HUD to enhance the visual acquisition of safety-critical road features such as road markings, hazards/obstacles, other vehicles and traffic signs. Some systems have been developed that use infrared image intensification to enhance night driving visibility.

Visual clutter: An overall assessment (either a subjective or an objective measure) of the extent to which there are features in a visual scene (either on a HUD or in the external scene) that may interfere with some aspect of the primary task (e.g., detecting hazards).

Vii Flight Rule (VFR): Flying an airplane using external visual cues under high visibility conditions.

Visual masking: Interference that can occur between two stimuli presented ***in proximity*** (but not overlapping) in space and time. In a typical visual masking study, the mask does not spatially overlap the target. A "masking effect" usually refers to an effect that is attributable to neural interference ***rather than*** optical (i.e., pre-retinal) interference of light in the image. Although visual masking is often used to describe interference occurring for superimposition of HUD and external scenes, contrast interference is the preferred term in this instance. Although visual masking may result from viewing HUD imagery superimposed on driving scenes, the bulk of the interference can be attributed to the interaction of light from different objects in the image (cf. contrast interference).

Executive Summary

A review of existing technical literature has indicated that automotive applications of head-up displays (HUDs), using current designs, will yield mixed results. While certain performance advantages may be expected, drivers' responses to some safety-critical events may be slowed significantly. A summary of findings for each of the major topic areas addressed in this document follows. In addition, a comprehensive overview of HUD research variables, test procedures and study results may be found in a set of summary tables presented as an appendix to this report.

To begin, ***the generalizability of aviation HUD research to automotive applications is*** limited because of differences along several dimensions. First, the information content of external scenes varies dramatically between the minimal contour (clouds and open sky) for the aviator and the rapid presentation of salient--often life-threatening--targets for the everyday urban/suburban driver. While they may assume primacy for the pilot's attention, HUDs are likely to remain strictly a secondary information source for drivers. Next, HUD use in aviation has often employed conformal symbology, where the displayed information is perceived as part of the external scene (e.g., a runway outline); comparisons to research results where HUDs presenting information to drivers have used non-conformal symbology (text or graphics) are problematic. Workload differences also deserve mention: during takeoff and landing the task demands on pilots-and the associated information content of HUDs--are considerably higher than drivers can be expected to encounter, nor will users of automotive HUDs have to contend with performance degradation due to high G-forces or spatial disorientation. Finally, an important contrast between studies of aviation versus automotive HUDs lies in the relative training and capability levels of the design users. Younger individuals selected for superior vision and cognitive capability, with extensive training, are the norm in aviation HUD performance tests. This restricts the range of data obtained, and produces an inevitable bias in measures of HUD safety and useability compared to, for example, an elderly driver who is inexperienced with HUDs.

The ***predicted peformance advantages of automotive HUDs*** include a variety hypothesized benefits, particularly for the older driver. Foremost is increased eyes-on-the-road time, which intuitively reduces the probability that a driver will fail to detect a time-critical event. It is not clear the extent to which reported advantages in response time (ranging from .25 to 1.0 s) for head-up versus head-down displays may be conditional upon low workload, simple HUD displays, and/or moderate ambient light levels, however. Reduced reaccommodation demands for drivers to fixate upon external targets are also expected, due to farther virtual image distances for head-up versus head-down displays. This represents a time savings that may or may not have operational significance for the general driving population. Older drivers would be aided the most by this feature of HUDs, and their expected benefits extend to no longer having to look through the near correction (lower part) in their eyeglasses as required to view the instrument panel. At the same time, HUDs present risks of degraded operator performance, as highlighted below.

Key ***operator performance issues with HUDs*** derive from both visual and cognitive factors. In the former category, superimposing symbology on the forward driving scene may mask external objects via contrast interference. This effect depends upon the extent to which the HUD symbology fills a given viewing area, and the contrast of the HUD imagery with the visual background. Relative motion of the HUD image and the to-be-detected external targets will improve recognition of external targets, but performance will still be degraded when HUD contrast is high. The safety of nighttime operations with HUDs are called into question by this finding. In addition, the visual 'fill factor' of a head-up display is identified as an important parameter influencing driver response to external targets. The tradeoff between increased eyes-on-the-road time and increased visual clutter from HUD symbology, in terms of response effectiveness for safety-critical targets in the forward driving scene, remains to be determined. Other potentially important visual factors include misaccommodation and misconvergence effects ("Mandelbaum effects") which can result from trying to view distant objects through nearer objects or surfaces. Size perception is at issue here, with implications for distance judgments and gap acceptance. Also, binocular misalignment--i.e., when the visual system cannot fuse vertical or horizontal disparities introduced by image distortions--can result in oculomotor fatigue, binocular rivalry, and headaches. HUD designs which use the windshield as the combiner are more susceptible to this problem.

A preeminent cognitive factor in assessing driver performance with HUDs is the phenomenon termed "cognitive capture." This effect describes the degradation of responses to external targets due to the processing of information from a HUD image; as such, it principally involves the cognitive operations of selective attention, divided attention, and attention switching. Existing data suggest that cognitive interference in drivers' responses to external targets is more likely when the number of targets and distracters (in both the HUD and external scene) is large; when the spatial and temporal uncertainty of critical (external) targets is high; when the conspicuity of critical targets is low; and when the relative event rate for salient targets in the forward driving scene (i.e., those requiring "effortful" or controlled, as opposed to automatic, processing) is lower than that for HUD stimuli. A fundamental premise is that visual information conveyed via HUDs and visual information from the external driving scene are not processed on separate channels; in other words, it is impossible to process both sources of visual information simultaneously.

Even earlier processing inefficiencies than those manifested in cognitive capture--i.e., problems at the stage of stimulus transduction and preprocessing--are described by studies of interference at the encoding stage of information processing. Multiple targets, targets near the threshold of detection, and/or targets embedded in "noisy" backgrounds may suffer from such interference. Common examples include HUD symbology that is spatially superimposed on an external target, producing contrast interference, or which is presented adjacent to an external target, producing spatial masking; in either case, it is likely that the efficiency with which the external target is encoded will be reduced. Encoding interference can be mitigated by separating inputs along one or more stimulus dimensions (e.g., spatial separation, use of color) or sensory modalities (e.g., using the auditory channel for selected message elements). However, while auditory HUD elements may reduce interference at the encoding stage, this practice does not preclude interference at the cognitive level of processing, and the potential for encoding interference with other auditory inputs (e.g., collision warning signals) is introduced.

Current ***HUD design issues*** center on these sources of interference Inefficiencies at the cognitive stage of processing have implications for the amount and format of information displayed on HUDs, while inefficiencies at the earlier, stimulus encoding stage have implications for the spatial location and luminance contrast of HUDs. Often, design choices must take both sources of interference into account. A typical apparent image distance for HUD symbology, roughly two meters, reflects an attempt to reduce cognitive-level interference by linking the HUD information spatially to the end of the hood of the driver's own vehicle, as opposed to farther distances at which the HUD information is embedded in the visual clutter of the external scene. This design choice also reduces the possibility of spatial superimposition or spatial masking of safety-critical targets, and thus improves HUD processing efficiency at the encoding stage as well. Additional design issues which deserve attention in automotive HUD applications include display variability across models, opportunities for the presentation of conformal symbology, field of view limitations, and user adjustability of HUD image attributes.

The ***effect*** of ***HUDs on driving*** speed is an area of particular interest. Some studies have demonstrated subjective preferences among drivers for HUD speed indicators versus traditional head-down displays, as well as an increase in glance frequency and a decrease in glance duration with the HUD speed indicator, but multiple investigations have found no significant effect on speed choice across a variety of driving conditions. Also, hypothesized improvements in the efficiency of acquiring speed information remain open to question, because of the low workload conditions which prevail in previous research on this issue.

Finally, a number of ***implementation issues for automotive HUDs*** must be addressed before widespread acceptance of these devices can be expected, particularly for many applications envisioned in ongoing Intelligent Transportation System (ITS) program initiatives. To move beyond the presentation of vehicle status indicators, such as speed, to the display of navigational instructions, motorist advisories for road conditions, accidents, weather, and other types of information, reliable measures of the effect of HUD use on responses to priority external targets must be obtained, under realistic operating conditions, The appropriate assignment of driver information inputs to continuous, contingent, and "on-demand" categories of displays remains to be determined. Practical considerations of cost, size, and adaptability to a range of driver eye heights also figure prominently if the use of HUDs in the private vehicle fleet in the U.S. is to become routine. And of course, driver age and related differences in visual acuity, contrast sensitivity, and the efficiency of attentional and other cognitive processes strongly implicated in safe vehicle operation define critical parameters for product design, development, and testing.

Driver Age and Visual Interference Concerns in the Use of Automotive HUDs
Part I: Literature Review

Introduction

This review establishes the framework for the development of a testing protocol for automotive HUDs that generalizes to a broad cross-section of everyday driving conditions. The idea to display instruments as virtual images superimposed on external images was first proposed by Paul Fitts in 1946. It was not until 1960 that head-up displays (HUDs) were first manufactured for military aircraft (Weintraub and Ensing, 1992). Although HUDs are now widely used between military and commercial aviators, they have only been considered for widespread automotive use since approximately 1985 (Enderby and Wood, 1992). Since then, the extent to which HUDs will benefit drivers has been investigated and is still largely unresolved. If research can be directed toward clearly defining the safety and design issues, this could facilitate progress toward mature applications -- and widespread use of -- automotive HUDs.

This document covers the following major topic areas: (1) aviation versus automotive HUDs, comparing and contrasting the two major HUD applications to determine the limits of generalizability of aviation HUD research; (2) expected performance advantages of automotive HUDs, addressing commonly cited and potential advantages of HUDs; (3) current HUD design issues, identifying currently unresolved design issues and limitations for HUDs that impact driver performance; (4) operator performance issues, emphasizing the impact of HUDs on vision and cognition; (5) the effect of HUDs on driving speed; and (6) implementation issues for HUDs in automobiles. An overview of current knowledge in this area and discussion of key methodological issues is then presented. This report concludes with two appendices that contain, respectively, a comprehensive summary table of HUD research findings, and a condensed description of current and proposed automobile HUD design features.

Aviation Versus Automotive HUDs

This document presents an overview of current findings in human factors research on HUDs. Whenever possible, study results are discussed in terms of implications for the design of automotive HUDs and potential safety benefits. In some instances the researchers have designed the experiment to address aviator HUD design issues. For these studies, there may be limitations in the extent to which the findings generalize to the design and effectiveness of automotive HUDs. This is due to the differences between proximal (i.e., instrument panel) and distal (i.e., external scene) stimuli, characteristics of the tasks, operator skill levels and age ranges. These differences are defined below and are used throughout the review to compare and contrast aviation and automotive HUD applications.

Information content of external scenes: Typically, the external scene of aviators consists of minimal contour such as clouds and open sky. Potential external targets include other aircraft and runways. Compared to driving, little information is acquired directly from the external scene. In other words, HUDs and other information sources inside the cockpit are typically primary information sources whereas external information sources are secondary. In contrast, drivers are exposed to much more contour and the total number of potential targets in the external scene is higher. Also, this information is presented to drivers at much higher information rates (i.e., number of potential targets per minute of driving is higher for drivers than for pilots). In light of these differences between automotive and aviation tasks, it is unlikely that automotive HUDs will replace the external driving scene as the primary information source.

Visual clutter intolerance: Because of the high priority given to direct visual information acquisition, drivers typically prefer to locate HUD symbology outside of central vision (Inuzuka, Osumi and Shinkai, 1991; Sojourner and Antin, 1990; Okabayashi, Sakata, Fukano, Daidoji, Hashimoto and Ishikawa, 1989; Weihrauch, Meloeny and Goesch, 1989). In fact, the results of the Inuzuka et al. (1991) study suggest that any symbology placed within a 5 degree radius of the fovea would be "annoying" to drivers. It is possible that these preferences can be attributed to the fact that the HUDs used in these studies displayed speed information. Therefore, the preference for locating symbology in peripheral vision may be due to the lower priority given to speed monitoring. To date, there are no studies that rate the tolerance of drivers for other types of symbology that present high priority information.

One type of symbology that drivers might be more tolerant of is conformal symbology. Conformal symbology simulates the visual transformations of external objects to give observers the perception that the symbology is actually part of the external scene. Although this type of symbology is common among HUDS used by pilots, on-going research is investigating automotive applications of conformal symbology. For example, vision enhancement systems (VES) would help drivers locate external targets when driving at night using symbology that overlays the actual external target. Conformal symbology has been shown to minimize detrimental effects of visual clutter and cognitive workload typical of non-conformal symbology (Naish, 1964; McCann and Foyle, 1994). Even though there are no studies that compare the preferences of drivers for conformal versus non-conformal symbology location, a strong recommendation from previous research is that non-conformal symbology should not be displayed head-up. Any benefit attributable to the display of information head-up is either non-existent or reversed (i.e., HUD worse than HDD) when displaying non-conformal symbology.

An approach that would maximize the overall HUD advantage is to display both conformal and non-conformal symbology using two HUDs: a lower HUD placed below central vision for the display of non-conformal and conformal symbology and an upper HUD superimposed on the forward field of view for the display of conformal symbology only. This display, termed the DUET display, was proposed by Weintraub and Ensing (1992, pp. 150-154) to (1) solve the problem of visual clutter and the negative consequences this can have and ***(2)*** maximize the benefits of HUDs, particularly the unique advantages of conformal symbology. Two HUDs are required since the typical HUD field-of-view is less than 5 degrees vertically and 7 degrees horizontally.

Age differences Demographics show that the average age of the driving population is increasing. In an attempt to take a proactive role in the design of future information displays, human factors researchers typically incorporate age as an independent variable in HUD studies. The "design driver" for automotive HUDs must incorporate the oculomotor, perceptual and cognitive limitations of older drivers. In contrast, HUD studies using pilots typically do not include age as an independent variable in their analyses. This is one area where automotive HUD designers may be faced with new and more demanding challenges that cannot be anticipated from previous experience with HUD use within aviation settings.

Workload and task differences Typically, pilot workload is heaviest during takeoff and landing. During these relatively brief periods, the demands on pilots are higher than during the most demanding driving conditions. For military aviators, task demands can be dangerously high. For example, landing a fighter jet on a carrier deck has been described by pilots as a controlled crash. Military pilots are also susceptible to spatial disorientation (SDO) and are exposed to high G-forces. HUDs may play a role in SDO since there have been some reports that HUDs impair a pilot's ability to cope with SDO (Biberman and Alluisi, 1992). The implication for automotive HUD use is that high task demands may contribute to misinterpretation of HUD information.

If automotive HUDs ever approach the level of information content that currently exists on aviator's HUDs, acceptance among drivers is expected to be low. There are at least two reasons for this: (1) acquiring information directly from external stimuli will always be primary for drivers and (2) drivers are not accustomed to acquiring and processing information from external as well as in-vehicle displays without making head/eye movements. Pilots are trained to fly by instruments alone (instrument flight rule or IFR) under low visibility conditions. Given the high demands for direct visual information processing, it is difficult to imagine safe driving using instruments only (even with significant advances in technology). If it is assumed that the external visual scene will always be the primary information source, secondary information sources must enhance the driver's ability to extract information from external sources.

Standardization and training issues: Another potential limitation to the widespread acceptance and safety of automotive HUDs is the extent to which training is required to use HUDs. This is currently a low-priority issue since automotive HUDs are still under development. However, one lesson learned from the use of HUDs among aviators is that training and standardization issues need to be addressed prior to widespread implementation. This is particularly important when familiarity with one HUD does not transfer to the use of other HUDs; for example, when using an unfamiliar HUD in a rental car. Older drivers may find it particularly difficult adapting to this situation. To some extent, problems with transfer of training can be minimized by (1) incorporating the capabilities and limitations of drivers into the design of the HUD and (2) standardization of symbology and hardware. An example of how proper de-sign of HUD symbology impacts training was demonstrated by Naish (1964). In this study, pilots receiving no training in the use of conformal symbology performed as well as pilots receiving training (Naish, 1964). Training will be required for combiner adjustments, contrast adjustment' and other physical adjustment procedures. As various HUDs reach final development stages, HUD evaluation criteria should include training time based on objective performance measures.

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[1] Most HUDs have a manual brightness control. However, some HUDs have an automatic brightness control that is based on illumination on the dashboard. Even in HUDs with automatic adjustments, there is a manual adjustment to fine-tune the brightness (i.e., contrast).

Expected Performance Advantages of Automotive HUDs

The following benefits of HUDs are the most commonly-stated advantages of automotive HUDs which underlie predicted performance gains for various dependent measures. In later sections these advantages will be discussed in more detail. Also, the following discussion of the benefits to older drivers presumes that automotive HUDs are designed to incorporate their needs with respect to virtual image distances, minimal visual clutter, minimal distraction, luminance contrast, ease of use and display location.

Increased eyes-on-the-road time: Intuitively, the more time a driver spends looking at the road the less likely he or she is to miss time-critical events. Studies attempting to quantify this advantage (HDD vs. HUD response times) have demonstrated more efficient processing. Specifically, the HUD advantage ranges from .25 to 1 second. Although this may not seem like a significant advantage, this represents 22 to 88 feet more stopping distance, respectively, in an emergency situation (traveling 60 mph). Unfortunately, it is likely that HUDs may not always improve the safety of driving. Research suggests that the HUD advantage may only manifest itself under limited circumstances such as low workload (Larish and Wickens, 1991), simple HUD displays (Okabayashi, Sakata and Hatada, 1991) and under moderate ambient light levels (Weintraub and Ensing, 1992).

Shortcomings of previous studies include, first, test situations in which scanning behavior is constrained by the experimental protocol. In other words, subjects initiate a scan after being prompted. Kiefer (1991) assessed scanning behavior under naturalistic conditions. In this study, he measured the time that drivers spent in speedometer scanning cycles (SSC) which included: (1) scanning from roadway to speedometer, (2) speedometer fixation time and (3) scanning from speedometer to roadway. Three dependent measures were reported: (1) mean time in SSC, (2) glance frequency per minute and (3) total time in SSC. Although total time in SSC was higher for the HUD in session 1, successive sessions were no different head-up or head-down. This was attributed to a novelty effect of the HUD speedometer. An alternative explanation that cannot be ruled out is that drivers may have been involuntarily distracted by the head-up speedometer. The only consistent advantage of the head-up speedometer across 4 sessions was in terms of mean time per glance; overall, drivers spent 144 milliseconds less time in SSCs viewing the HUD speedometer. Similar conclusions were reached in a more recent study by Sprenger (1993). The results of this study also showed more frequent sampling of the HUD (143 glances to the HUD versus 88 to the in-dash speedometer) and shorter periods of fixation on the HUD (median fixation time for HUD was 619 msec vs. 711 msec HDD). Unfortunately, the Sprenger study confounded display format and location. In the Sprenger study, the HDD used a conventional analog display whereas the HUD used digital format. Kiefer and Angel1 (1993) recently compared these two formats for HDD display locations and found the analog format to be superior in terms of minimizing eyes-off-road time (obtained by multiplying mean eyes-off-road time per glance by the glances per minute). Thus, it may be the case that the HUD advantage found by Sprenger is actually attenuated via the use of digital speed information. Finally, a limitation of both the Kiefer and Sprenger studies is that they were conducted under low workload conditions. Under high workload conditions, it is likely that the frequency of glances to both displays would be reduced and that the difference between the displays in terms of glance frequency would also be reduced. This suggests that the "novelty" effect may be an artifact of the low demand situation.

Evidence that HUDs reduce the number of head/eye movements under high workload conditions was reported by Haines, Fischer and Price (1980). Using a flight simulator, they demonstrated that pilots make fewer transitions between the external scene and cockpit displays when using HUDs. This is contrary to the findings of Kiefer (1991). However, the results are not directly comparable because of (1) differences in workload and (2) task differences (namely, pilots are trained to fly IFR or VFR). To date, there are no studies of driver eye scanning behavior under high workload conditions. Assuming that the results do generalize to driving tasks, there are some implications of these findings for HUD use. First, if head/eye movements are lower under high task demand conditions, HUDs may have some benefit for alleviating fatigue. Secondly, fewer external targets would be missed. Unfortunately, research suggests that unexpected targets are more likely to be missed when using HUDs This effect has been termed cognitive capture, and will be discussed below.

Reduced reaccommodation demands: The benefits here include time to reaccommodate and the amount of accommodation. Since the virtual image is typically located further away than head-down instrument panels (HDIPs), less accommodation is required when switching from external viewing to HUD viewing. Reducing accommodative demands has clear advantages for older drivers due the progressive loss of accommodative range with age. For example, by about age 60 the average amplitude of accommodation is 1 dioptcr. Thus, for the average 60-year-old, viewing the instrument panel (about .75 meter or 1.33 diopters) may require them to look through the near correction (or lower part) in their eyeglasses.

Reducing the accommodation demands should also increase the HUD advantage by reducing reaccommodation time. For younger subjects (mean age 21.9 years), the savings in reaccommodation time is not pronounced because subjects can make responses prior to completing the accommodative response (Weintraub, Haines and Randle, 1984; 1985). Older observers were not tested in this experiment. However, other researchers have shown that virtual image distances nearer than 2.5 m increase the recognition times of older (50 to 70 years) drivers (Inuzuka, Osumi, Shinkai, 1991). This effect is attributed to diminished accommodative range of older subjects.

The lack of a significant reaccommodation time-saved in the Weintraub et al. studies may be attributable to the depth-of-focus (DOF) in the experiment. The DOF is the range of focus errors over which performance is unaffected. DOF is dependent on pupil size (large pupil size produces low DOF) and the blur criterion (i.e., when does target appear "blurred"). DOF was not assessed in the Weintraub study. However, the target luminances (1 cd/m^2 for the runway scene and 2.6 cd/m^2 for the HUD symbology) suggest that DOF would have been low (less than .125 D) due to the large pupil size (roughly 6 mm; maximum pupil size is about 8 mm). However, DOF is also dependent on the target used in determining whether a target is "blurred"; namely, large, coarse targets (low spatial frequencies) are less affected by defocus than small targets (high spatial frequencies). It is estimated that the critical features in the symbology used by Weintraub et al. subtended about 7.5 minutes of arc (or 4 cycles/degree) which is well above a critical gap for 20/20 resolution (Le., 1 minute of arc). Based on data from Westheimer and McKee (1980), it is believed that the targets were at or slightly above threshold in the 1% diopter condition ***before*** reaccommodation was initiated. In short, the lack of a significant reaccommodation time-saved with HUDs in the Weintraub et al. (1985) study may be attributable to the high DOF for the targets used. If these target sizes (and contrasts) are representative of targets in actual automotive HUDs, then these results can be generalized to automotive HUDs. If not, further research is needed to assess reaccommodation time-saved under conditions representative of driving (particularly night driving) while using an automotive HUD.

Considerations for older drivers: All benefits expected from HUDs (i.e., reduced rcaccommodation, fewer eye/head movements, increased eyes-on-the-road time) are expected to be higher for older drivers. However, possible disadvantages of HUDs (such as cognitive capture and visual clutter) are expected to be more problematic for older drivers. The implication is that older subjects should be routinely used in HUD research as they represent a much larger range of visual and cognitive abilities. To obtain widespread acceptance, automotive HUDs should incorporate the limitations of older drivers.

There has been surprisingly little research into aging effects with HUDs The research to date suggests that while there are no clear benefits to older drivers, they do not perform more poorly with HUDs. Kiefer (1990) found no interaction of location (HDD vs. HUD) by age on speedometer scanning or average speed. This lack of an interaction suggests that there is a HUD advantage for the older subjects as well as the younger subjects but that it is not more pronounced for either age group. Using a driving simulator, Marin-Lamellet, Dejeammes and Kerihuel (1994) found significant main effects of age. For both HUD and forward screen presentation, older subjects were slower in reacting to displayed turn arrows and stop signs and they took longer to complete the trial runs. In agreement with Kiefer, the interaction of age with method of display was not statistically significant on any dependent measure. The authors point out that the workload was low in this experiment which would not be expected to generalize to more complex driving tasks. This would also apply to the Kiefer study as subjects drove along a closed 6 mile loop through a park in Washington, Michigan. None of the studies included in this review investigate the effects of HUDs on different age groups when confronted with varying levels of workload.

With respect to cognitive issues, HUDs may be potentially more distracting to older drivers which might lead to an increased propensity for cognitive capture. Research shows that one of the best predictors of accident involvement is the ability to switch attention (Avolio, Kroeck and Panek, 1985). Parasuraman and Nestor (1991) demonstrated that the ability to switch attention is predictive of accident involvement among elderly drivers. Unfortunately, most of the studies investigating cognitive/attentional issues with HUDs have not included older subjects. This may be attributable to the fact that researchers investigating cognitive issues have been primarily in the aviation community where age effects do not take precedence.

Although statistically significant HUD advantages have been repeatedly demonstrated, the small HUD advantages that are typical may be of little operational significance. In fact, it is difficult to reconcile the lack of large measured HUD advantages (and in some situations, HUDs have no effect or can degrade performance) with the fact that HUDs are so widely accepted among aviators. Many researchers believe that the primary advantage of HUDs, which many dependent measures are insensitive to, is the design of the symbology (Weintraub and Ensing, 1992). Research extends this contention to suggest that HUDs are only beneficial for the display of conformal (or partially conformal) symbology. Specifically, non-conformal symbology displayed head-up has been shown to degrade performance. In view of this finding, displaying head-up speed information would not be expected to enhance driver safety relative to a head-down display because it is a nonconformal information source. Incidentally, head-up speed information is provided on all automotive HUDs and is also the single most widely studied HUD dependent (i.e., speed variability) and independent (i.e., digital speedometer display) variable.

Current HUD Design Issues

The following discussion deals with design issues and technological limitations that directly impact the overall utility of automotive HUDs. The first subtopic deals with a "lesson learned" during the process of widespread deployment of aviator HUDs from which automotive , HUD designers can benefit.

Display variability: Cockpit display design/layout is perhaps one of the oldest problems in human factors; namely, how to convey information to pilots that is consistent across aircraft. Instrumentation advances are a continuous, on-going process which leads to differences in the layout and type of displays for the same plane (Biberman and Alluisi, 1992). This leads to variability even within an aircraft type which can, to some extent, be overcome by training. However, routine training in the use of different automotive HUDs (e.g., driving a HUD-equipped rental car) may not be feasible. Automotive HUDs are more likely to be widely accepted if there is a high degree of consistency in the way information is conveyed to drivers. This is due to at least 3 factors: 1) a wider range of skill levels among current driving population, 2) potential for new types of information (i.e., non-redundant information display) to be displayed on automotive HUDs with ITS/ATIS advances and 3) processing information from HUDs may already add to a driver's workload, even where practice on a specific HUD is not required.

Design of display symbology: In the absence of demonstrated HUD advantages found by some researchers, it has been asserted that the primary advantage of HUDs is the effective design of the HUD symbology. Even so, there are some aspects of HUD symbology that need improving. For example, one complaint among pilots who use HUDs is that the symbology provides ambiguous information about altitude. In fact, some fatal accidents and near misses have been attributed to the fact that the altitude information on HUDs does not tell the pilot, at a glance, whether he is upright or inverted (Biberman and Alluisi, 1992, p. S-l, A-7). The implication for automotive HUD designers is that carefully designed symbology in itself can determine HUD acceptance among drivers.

As noted earlier, there are data to support the idea that conformal symbology enhances performance with HUDs. Conformal symbology elements overlay and move with outside world elements that they represent. An example of this is a virtual runway displayed via the HUD that moves with the real runway as the plane moves. Although conformal symbology may not be applicable to automotive HUDs (primarily because the virtual image will not be collimated in automotive HUDs), the research suggests that the advantage of HUDs can be maximized by careful design of the symbology. In fact, many researchers believe that the symbology design on HUDs is one of the main reasons for the widespread acceptance of HUDs among pilots. This was stated succinctly in a paper by Long and Wickens (1994) ".. .when non-conformal symbology is used, the costs of increased scanning head-down are balanced by the benefits of reduced clutter.. . " These kinds of tradeoffs can be addressed in the current project for automotive HUD applications.

Field-of-view limitations: The typical field-of-view (FOV) of an automotive HUD is only 5 by 5 degrees (see Appendix B for details). This clearly limits the utility of conformal symbology since the external scene onto which the symbology is overlayed must be contained within this small angular window. Furthermore, the small FOV limits the maximum amount of information that can be displayed at one time before visual clutter degrades visibility of external targets. One possible solution to the limited FOV problem was proposed by Swift and Freeman (1986). In their design, multiple displays are placed side-by-side (each with 5 by 5 degree FOV) to increase the horizontal field of view. This display, termed the Instrument Head Level Infinity Display (or IHLID), presents collimated imagery to the driver that is not superimposed on the forward driving scene. Instead, the virtual images are seen just above the dashboard. Thus, the driver still enjoys the benefit of increased eyes-on-the-road time and reduced reaccommodation time while eliminating visual clutter and contrast interference. One potential drawback of this approach is system cost. Although the cost will inevitably be higher than a single HUD system with a 5 by 5 degree FOV, it may be the most feasible way to increase the horizontal FOV of HUDs.

Display luminance contrast: One limitation of most HUDs is that they cannot meet the maximum luminance contrast requirements for viewing during bright daylight conditions. Weintraub and Ensing (1992) give an example of viewing symbology against sunlit snow which is roughly 34,000 cd/m^2 (10,000 ftL). To obtain a maximum recommended contrast ratio of 1.5: 1 against a background of 34,000 cd/m^2, the luminance of the HUD symbology would have to be 17,000 cd/m^2 (or about 170,000 cd/m^2 at the source assuming a typical 10% reflectance by the combiner). Current technology cannot meet this maximum requirement even with stroke symbology which is brighter than raster symbology. Even if such a display could be produced, the heat given off by the source could melt the HUD and surrounding components.

There are a number of possible solutions to the luminance contrast limitation with high background luminances. Lloyd and Reinhart (1993) report that a minimum contrast requirement of 1.15: 1 can be used for tasks involving familiar high-contrast scenes (for example, a familiar road) which is in agreement with previous recommendations (see Weintraub and Ensing, 1992, p. 29). Another possible solution is to use a combiner with a higher reflectance. Although this results in a lower transmittance of the forward driving scene, this loss is more likely to be tolerated if placed outside of the critical viewing area (5 to 10 degrees below driver's line of sight; see Inuzuka et al., 1991 for details).

It has not been demonstrated whether 34,000 cd/m^2 should be considered a reasonable worst-case for driving. If the HUD symbology is placed low in the visual field (perhaps superimposed on the road surface), anecdotal evidence suggests that the background luminance will rarely approach 34,000 cd/m^2 At any rate, the average maximum display luminance of existing automotive HUDs (from Appendix B) is 2842 cd/m^2 . Based on this and a minimum luminance contrast of 1.15, the typical maximum background luminance that HUDs can be viewed against based on currently available automotive HUDs is 18,947 cd/m^2 (or 56% of the maximum proposed by Weintraub and Ensing above).

The previous discussion deals with viewing HUD imagery against a high background luminance. At low background luminances, there is a potential for HUD luminance contrast to be too *high*. For some HUDs, the luminance simply cannot be adjusted low enough to obtain the maximum acceptable luminance contrast ratio of 4:1 (Rogers, Spiker and Cicinelli, 1986). As a result, there is a high potential for missed and/or delayed detection of external targets. Another potential source of masking and contrast interference of external targets is the background luminance of the HUD (referred to as "CRT glow"; cf. Weintraub and Ensing, 1992). We are unaware of any study that has investigated the potential for missed external targets under viewing conditions that simulate night driving with high contrast (i.e., 1.5:1 to 10:1) HUDs.

The research indicates that there is no single HUD luminance contrast that optimizes performance for all driving conditions. There is a range of HUD luminance contrasts for a given ambient light level within which the actual HUD luminance contrast should be maintained. This range is an optimal tradeoff between contrasts that are too low (i.e., poor visibility of the HUD symbology) and contrasts that are too high (i.e., poor visibility of external targets overlapping the HUD symbology and high potential for cognitive capture via the HUD). HUDs should be designed to provide contrasts in roughly the middle of this luminance contrast range for a particular ambient light level. Figure 1 is a schematic of the contrast operating function. The axes are logarithmic in units of luminance (cd/m^2) with HUD luminance on the ordinate and background luminance on the abscissa.

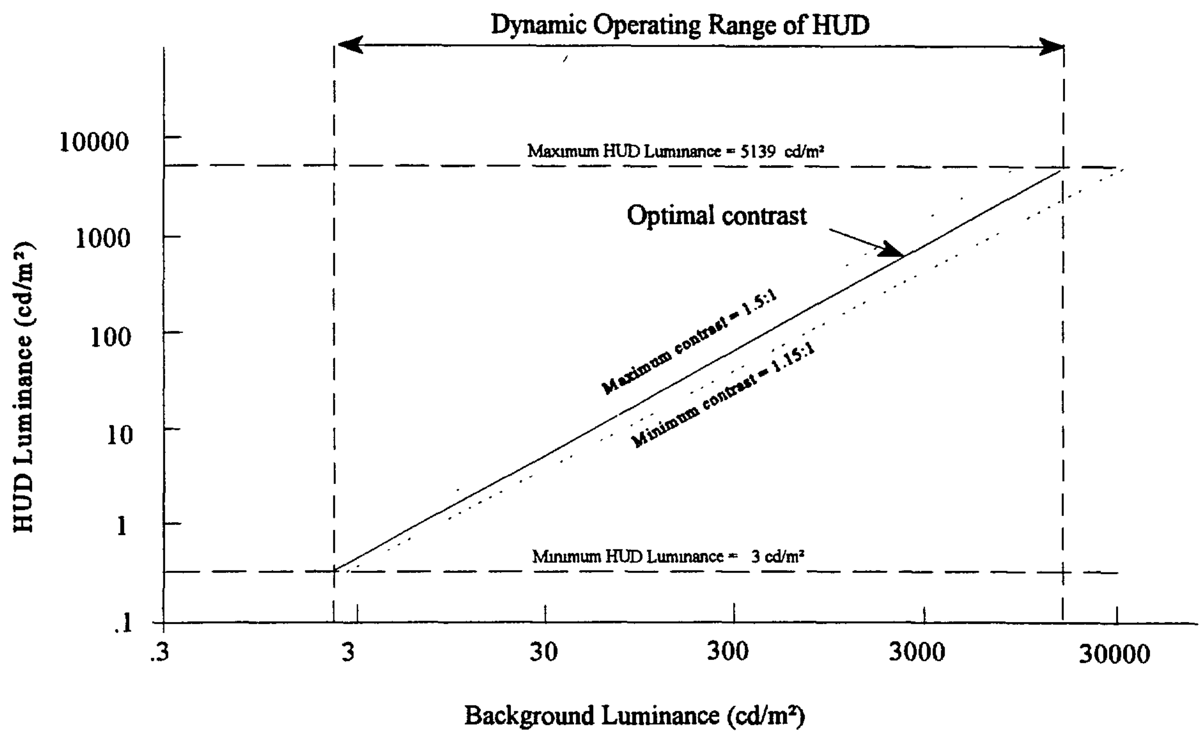

Figure 1. Schematic of the dynamic operating range of the DataVision HUD.

The maximum and minimum HUD luminance lines are estimates for the GM Hughes DataVision HUD. The dynamic range is determined by the ambient light levels corresponding to the endpoints of the optimal contrast line. In Figure 1, the dynamic operating range of the HUD is slightly larger than 4 orders of magnitude. This is somewhat less than the desired range of background luminances upon which the driver might view HUD symbology (roughly 6 orders of magnitude).

Operator Performance Issues

Visual and cognitive limitations of drivers need to be incorporated into the design of automotive HUDs. The specific topic areas that follow discuss critical human performance factors that have direct implications for HUD design specifications. In most instances, researchers assess the advantage of a particular HUD design using performance with a HDD as baseline. This is a valid approach; however, there may be limits to the generalizability of the research findings when HDD and HUD display parameters are not controlled. For example, the following variables represent typical differences between HUDs and HDDs:

- Display format: Most automotive HUDs use a digital speedometer whereas HDDs can be either digital or analog. Direct comparisons of HUDs using ***digital*** symbology versus HDDs using ***analog*** symbology is not valid due to the well-established performance differences between these two display formats.

- Displav contrast/luminance: The contrast of HDDs is fixed whereas the contrast of HUDs is variable and depends on background and display luminance

- Image distance: The viewing distance of HDDs is typically 30 inches (instrument panel distance) whereas HUD virtual image distances range from 1.5 to 6 meters

- Angular size: The angular size of the characters must be equated. Otherwise, differences in angular size alone can produce pronounced differences in RT, threshold contrast and other performance measures.

These are a few of the display control variables that should be considered in evaluating the generalizability of a particular research finding. In any event, the following topic areas are critical parameters in assessing HUD efficacy.

Contrast interference and visual clutter: Superimposing symbology on the forward driving scene theoretically will tend to mask external objects via contrast interference. This should become more of a problem as more contour (which correlates with the display of more information) is added to the HUD and when the contrast of the HUD symbology is higher than the contrast of the external targets. Okabayashi, Sakata and Hatada (1991) measured the effect of visual clutter and HUD contrast on the identification of Snellen E figures. They manipulated clutter by varying the percent of pixels that were turned on in a simulated HUD (fill factor). The location of pixels that were on was determined randomly. Thus, a HUD display with a fill factor of 50% represents a worst-case for visual clutter. With a HUD luminance contrast set at 1.3, percent correct recognition dropped from 80 % correct at 0% fill factor to 70% correct recognition at 50% fill factor. When HUD contrast was increased to 3.0, percent correct recognition at 50% fill factor dropped to 10%. This finding is noteworthy because the nighttime recommended HUD contrast is 4.0 (Weintraub and Ensing, 1992; Rogers, Spiker and Cicinelli, 1986). This represents a potential exception to this recommendation. If fill factor approaches 50% (even for localized areas of the display) and HUD contrast is set to 4.0, there may be a large potential for masking of external targets. This is especially true for low contrast targets typically encountered during nighttime driving. This issue is only important for low ambient light levels since contrasts of 4.0 cannot be obtained with existing HUDs at high ambient light levels. Furthermore, the visual clutter issue applies only when symbology is superimposed on the forward scene; as discussed below, symbology superimposition is not always used in some alternative HUD designs and interfaces.

Okabayashi et al. (1991) also assessed the effects of relative motion between the HUD symbology and external targets. The experiment was designed to simulate the effect of relative motion between HUDs and the external driving scene when negotiating turns. Depending on where the driver is fixating, this relative motion can degrade retinal image contrast of either the HUD symbology (i.e., driver fixates external scene) or the driving scene (i.e., driver fixates HUD). In the experiment, subjects were instructed to fixate the Snellen E targets. This would tend to reduce the retinal image contrast of the HUD and thus reduce the negative impact of visual clutter. In the worst-case condition for visual clutter mentioned previously (50% fill factor and luminance contrast of 3.0), percent recognition increased from 10% correct recognition to an asymptote of 50% correct recognition. This should be compared to baseline performance in which percent correct recognition was 80%. Thus, although relative motion will tend to reduce the negative effect of visual clutter when fixating the external driving scene, clutter will still degrade visual recognition performance when the HUD contrast is high. It should therefore also be of interest to investigate the effects of cognitive capture under conditions of relative motion. This could be used to obtain an objective measure of what observers are attending to (via eye movement behavior) as well as a stronger hypothesized cognitive capture effect when there is relative motion between external scenes and HUDs.

The visual clutter manipulation in the Okabayashi et al. (1991) study limits the extent to which the results can be applied to performance with HUDs. The clutter manipulation involved turning on a certain percent of the pixels in the simulated HUD. However, because recognizable characters or icons were not displayed, this precluded the researchers from measuring performance for information displayed on the HUD (e.g., percent correct identification of a vehicle status indicator). Also, it may have been an artificially demanding task since the subjects in the study could not segment the HUD display into meaningful units. This is important since information in the external environment can interfere with information acquisition from the HUD and vice versa. Regardless of these shortcomings, the fill factor may be a useful means of objectively quantifying visual clutter in displays as well as external road scenes.

The authors are not aware of any study of the effects of visually cluttered HUDs on information acquisition from the HUD. However, Kurokawa and Wierwille (1991) assessed the effect of visual clutter on a simulated instrument panel task. To some extent, the results of this experiment are believed to generalize to any in-vehicle display. Information acquisition from an in-vehicle display was assessed using a simulated instrument panel task. Kurokawa and Wierwille (1991) assessed the effects of display clutter by manipulating the number of cells in the panel (i.e., temperature, radio, navigation and cassette), the number of buttons within each cell (1, 2x2 or ***3x3)*** and abbreviated vs. unabbreviated messages, This panel was mounted in a simulator dashboard. The dependent measures were hands-off-wheel time, number and average length of glances to the instrument panel and total completion time. As predicted, as the number of control buttons and cells increased, responses were slower on all dependent measures. The largest increases were observed for the additional control buttons (termed microclutter). The mean number of glances to the instrument panel increased from about 1.2 for the single control button conditions to 2.6 for the 3x3 matrix of buttons. The average length of glances increased from about .75 seconds with 1 control button to 1.1 seconds with 3x3 control buttons.

The implication of the Kurokawa and Wierwille results for HUD use is that as the number of information elements increases, drivers may spend more time acquiring the information from the display. The unresolved question related to this research finding is whether performance is worse head-up than head-down with visual clutter. Neither of the two studies investigating visual clutter effects used both HUD and HDD conditions. Although visual clutter can certainly produce contrast interference which leads to missed targets, missed targets can also result from spending more time using the in-vehicle display, either head-up or head-down. In other words, even though a cluttered display would be expected to increase the time attending to and/or glancing at the in-vehicle display, this is expected to be more deleterious for the HDD because the external targets are further away from the fovea and thus less visible. Alternatively, if the clutter is within the forward scene and the primary task involves acquiring information from an uncluttered in-vehicle display, there may be a HUD ***disadvantage*** due to contrast interference from the forward scene. Without further research it is impossible to determine how these effects tradeoff, namely, are the HUD benefits attributable to eyes-on-the-road time so pronounced that the HUD advantage exists even in the presence of (1) cluttered forward scenes, (2) cluttered in-vehicle displays and (3) a combination of both types of clutter.

Once these tradeoffs are assessed, the results can then be used to determine performance-based safety criteria. As an example, Zwahlen, Adams and DeBald (1988) developed a guideline for determining what displays are unsafe based on the probability of lane exceedance measurements. The results for the Kurokawa and Wierwille study would be considered acceptable based on these guidelines. However, these guidelines may not take into account that drivers can orient with their peripheral vision. What the visual system is not good at in the periphery is detecting and recognizing spatially localized targets.

Although the approach used by Zwahlen et al. (1988) is valid and useful, it seems that the safety criteria for HUDs need to be based on the time to detect, recognize and respond to external targets. For example, when plotting average glance duration on the y-axis and total number of looks to acquire information on the x-axis (as in Zwahlen et al., 1988), acceptable/unacceptable criteria could be based on probability of detection of external targets. However, a more stringent criterion would be the probability that the driver would respond in time to avoid a pre-defined imminent collision scenario; namely, an external target comes into view during the time that the driver is acquiring information from the HUD. Aside from the safety implications, this performance-based safety analysis could also be used to quantify the HUD advantage relative to HDDs on several dimensions within a single graph.

One unique approach to eliminating visual clutter is to take advantage of parallel processing on auditory channels. As an alternative to collision avoidance systems based on visual presentation, it may be possible to take advantage of auditory spatial localization (Sorkin, Wightman, Kistler and Elvers, 1989). More recently, Begault (1993) demonstrated that visual search time can be significantly reduced (2.2 second faster search time) with the aid of a 3-dimensional auditory cue, when compared to a search with a monaural warning.

Virtual image distance: Surprisingly little research has addressed the issue of an appropriate virtual image distance. Although most studies compare performance for at least two different distances (HUD vs. HDD), many of the studies do not use actual HUDs in their experiments. Instead, many researchers use "simulated HUDs" in which the HUD symbology is digitally (as opposed to optically) superimposed on the graphics image for the forward scene. Simulated HUDs control for accommodation effects when addressing issues such as attentional tunnelling, cognitive switching and other more central limitations to information processing. The choice of virtual image distance for automotive HUDs is a critical design issue because: (1) normal reductions in accommodative range with age will limit the range of virtual image distances that older drivers can use efficiently and (2) the driver population is aging.

Two studies (Inuzuka, Osumi and Shinkai, 1991; Kato, Ito, Shima, Imaizumi and Shibata, 1992) assessed age effects on recognition time at virtual image distances from 1 to 5 meters. Although recognition times were always higher for older drivers, recognition times began to increase at virtual image distances closer than 2.5 m. Virtual image distances greater than 2.5 meters appeared to meet the needs of older drivers. Although not measured, this effect is attributed to the increased latency to make accommodative adjustments.

Almost all of the HUDs designed for automotive use are not collimated (see Appendix B). Unfortunately, the rationale for this is unknown. If it is true, as Weintraub and Ensing (1992) suggest, that automotive HUDs will always be used as a secondary information source, then HUD symbology should not be centered in the driver's forward field of view. Consequently, the HUD symbology should appear at a virtual image distance corresponding roughly to the distance to the background upon which it is superimposed (roughly 2 m). In other words, it is possible that the design virtual image distance is restricted by the choice of spatial location (azimuth and elevation) of the image. Thus, the rationale behind the choice of virtual image distance may be determined by the rationale behind the choice of spatial location of the HUD imagery.

The rationale behind the choice for image location will be discussed in more detail later. One factor that determines image location is driver preference. The placement of HUD symbology outside of central vision is preferred by most drivers (Inuzuka, Osumi and Shinkai, 1991; Weihrauch, Meloeny and Goesch, 1989). Although peripherally-located HUD symbology is acceptable for display of certain types of information (such as speed, gas gauge or vehicle indicator icons), it is not the optimal location for the display of conformal symbology. The benefits of conformal symbology (discussed in detail below) are maximized when: (1) the imagery is collimated (Weintraub and Ensing, 1992) and (2) the symbology is perceived as a single field of visual information (Naish, 1964). Contrary to studies demonstrating conformal symbology enhances operator performance (Long and Wickens, 1994), two studies investigating automotive applications of conformal symbology (specifically, vision enhancement systems or

VES) reported either no change or poorer performance. Bossi, Ward and Parkes (1994) showed that detection of peripheral targets was poorer in the presence of a simulated VES. The detection was particularly disrupted at eccentricities closer to the VES. Ward, Stapleton and Parkes (1994) also found no benefits of VES on (1) RT to detect a pedestrian, (2) mental workload or (3) speed variability. These results support an explanation based on attentional tunneling in which the focus of attention is reduced (Ward & Parkes, 1994).

The research findings to-date do not support the notion that the forward line of sight is the optimal location for HUD imagery. This is based on preference data as well as visual performance with wnformal symbology. ‘Assuming these results to be veridical, this constrains the virtual image distance. Until further results support the location of HUD imagery in the forward line of sight as optimal, automotive HUDs should not be collimated. Instead, virtual image distances should be located closer than optical infinity (i.e., less than 6 m). Combining this with the findings from accommodation research, virtual image distances of automotive HUDs should be in the range of 2.5 to 4 meters. This range of distances is expected to meet the needs of all drivers, particularly older drivers.

Misaccommodation/misconvergence effects: The “Mandelbaum effect” occurs when trying to view distant objects through nearer objects or surfaces. When interposed surfaces are located at different distances, the surface located closer to the observer’s resting focus tends to dominate the accommodative response (Owens, 1979). The implication is that the edges of the HUD combiner will tend to draw accommodation (termed “convergence-accommodation traps“ by Weintraub and Ensing, 1992, p. 98). This, in turn, would reduce resolution for both HUD imagery (since the virtual image is in focus beyond the distance of the combiner) and the external scene. Combiner edges can be eliminated by using the windshield as the combiner. Even in the absence of combiner edges, however, the potential for automotive HUDs to “trap” accommodation may exist because the virtual image distances are typically closer to the mean resting position of accommodation (or 1.5 diopters which corresponds to 67 cm) measured by Leibowitz and Owens (1975). The authors are unaware of any research that demonstrates the extent to which the Mandelbaum effect is a factor when resolving HUD symbology.

Another effect that misaccommodation and misconvergence can have is on size perception. Size constancy is the ability to perceive objects as being the same size even though retinal image size changes dramatically with distance. Size constancy is maintained by the visual system using various depth cues, including cues derived from accommodation and vergence responses. If these cues are disrupted, size constancy is not maintained. This, in turn, would have negative consequences for speed and distance perception while driving. Roscoe (1982; 1987) and others have asserted that HUDs produce misaccommodation which in turn leads to misperceptions of size (the ‘misaccommodation hypothesis’). Specifically, it is believed that HUDs induce a positive misaccommodation (i.e., observer focused to a distance nearer than optical infinity) which shrinks the apparent size of objects. Benel (1980) demonstrated that increases in accommodation (focus nearer) due to an interposed mesh screen were associated with decreases in perceived size (r = -.76). The implication is that if HUDs induce positive misaccommodation then size constancy will be disrupted. What is at issue here is the extent to which HUDs induce misaccommodation. Using an actual refractive HUD from a military aircraft (A-4) and an objective measure of accommodation, Sheehy and Gish (1991) were unable to demonstrate any misaccommodation attributable to viewing HUD symbology. Even if HUDs do induce some misaccommodation, it is generally believed that any disruption of size constancy that results from this misaccommodation is negligible (Weintraub, 1987; Weintraub and Ensing, 1992; Biberman and Alluisi, 1992).

Size perception is also affected by vergence responses. It has been hypothesized that the edges of the combiner can cause misconvergence (or proximal vergence) as well as misaccommodation (Weintraub and Ensing, 1992). To demonstrate the extent to which accommodation-induced convergence affects size constancy, Jones and Good (1986) measured relative size changes after partially paralyzing accommodation of one eye (i.e., cycloplegia) using a drug called mydriacyl. Since only one eye was cyclopleged, a measure of relative size change was obtained by comparing the perceived size of a target (two dot separation) between the cyclopleged and non-cyclopleged eye. Accommodative convergence (i.e., accommodation-induced convergence in the absence of binocular disparity cues) was measured as well as relative size changes over time. As predicted, the perceived relative size decreased in the cyclopleged eye. This was accompanied by an increase in convergence induced by increased effort to accommodate the target. The important implication for viewing HUDs is that accommodative convergence only accounted for about 10% of the change required to completely account for size constancy. In short, if HUDs cause misconvergence and/or misaccommodation, the effects on size perception will be minimal even under worst case conditions; namely, under degraded stimulus conditions (low contrast, low ambient light level) or under extreme oculomotor fatigue.

Binocular misalignment: Binocular misalignment can negatively impact drivers in a number of ways. This occurs when a single object in the HUD image cannot be lined up on the retina with appropriate fixation due to distortions in the image. Although horizontal disparities up to 1 milliradian (or 3.4 minutes of arc) can be tolerated by the visual system, vertical disparities of this magnitude produce visual discomfort and diplopia (Gibson, 1980). This is because the visual system cannot make vertical vergence eye movements to fuse vertical disparities. Other visual affects that can result from binocular misalignment include visual/oculomotor fatigue, binocular rivalry (see Glossary) and headaches. There are also large individual differences in the tolerance for binocular disparities.

Certain HUD designs are more susceptible to binocular misalignment problems. Iino, Otsuka and Suzuki (1988) discuss the design of a HUD that uses the windshield as the combiner. Although this approach has the advantage of maximizing transmittance of the forward driving scene, one significant disadvantage is that it can introduce vertical and horizontal disparities due to the curvature of the windshield. Iino et al. (1988) designed a special prism to correct for disparities. To implement this design in other vehicles, the prism would have to be specially designed for each type of windshield. Even for the same vehicle, the prism would need to be modified (or at least mounted in the HUD differently) for cars manufactured with left-mounted steering wheels.

Luminance contrast requirements: Backgrounds for automotive HUDs are very dynamic which increases the probability that contrast interference will occur. Superimposing HUD imagery on the hood tends to reduce these effects. However, Inuzuka et al. (1991) point out that even the hood is a dynamic background. They observed problems viewing HUD imagery against different hood colors and in the presence of reflections off of the hood (especially when the hood was wet). Also, some cars have hood lines that are very low in the visual field (i.e., lower than 10 degrees). Thus, the background of HUD imagery in these vehicles is likely to be the road surface. In any event, the luminance contrast requirements of HUDs is complicated by the fact that there is a large range of backgrounds onto which HUD symbology will be superimposed.

Rogers, Spiker and Cicinelli (1986) assessed contrast requirements for a range of ambient light levels using two different legibility criteria: threshold legibility (just detectable gap in Landolt Cs) and comfort legibility (clearly detectable gap). At a background luminance of 13.7 cd/m^2 (4 ftL), neither measure of legibility revealed a significant difference when comparing 4: 1 and 8:l contrast ratios. At the moderate ambient light levels (96 to 418 cd/m^2), asymptotic performance was reached at a contrast of around 1.2 to 1.5. It was also noted that stroke symbology was highly superior to raster-scan symbols (no explanation for this effect was given). The authors conclude that lower luminance contrasts (1.5: 1 at 96 cd/m^2 background luminance versus 4: 1 at 13.7 cd/m^2 background luminance) produce asymptotic legibility performance as background luminance increases. Study 3 of this report investigated the effect of adaptation mismatch. This is analogous to what would happen at night while trying to view HUD symbology against oncoming headlights. The conclusion from Study 3 is that if the display and adapting luminances do not differ by more than a factor of 100 (2 orders of magnitude) then recovery is almost immediate.

HUD contrast and cognitive capture: There are no studies that have assessed the relationship between the contrast of HUD symbology and the potential for cognitive capture. However, there are studies of visual warning signals that may have implications for cognitive capture. In general, a visual warning signal is effective if it has the following attributes (from Guidelines in the Engineering Data Compendium, 1988):

1) At least 2 times brighter than surrounding signals.
2) Less than 15 degrees eccentricity for high-priority signals.
3) Must subtend at least 1 degree of visual angle.
4) Flashing against a steady background.
5) High-priority signals should be colored red.

It is clear that the guidelines described above were intended for display panels in which the "signals" are other indicators. It is not clear how to relate this recommendation to HUDs since salience of warning signals must be defined relative to external as well as HUD signals. Thus, there are two contrasts that influence the salience of warning signals: (1) Warning signal brightness relative to other HUD symbology and (2) Warning signal brightness relative to external road scene. Although HUD-to-road contrast should be high (roughly 3: 1) for warning signals, it is not desirable to use high contrast for lower priority symbology. One recommendation might be to use the range of acceptable contrasts at a particular ambient light level for different types of symbology.

The guidelines also recommend that high-priority alerting signals be coupled with an auditory warning signal. This may be particularly useful when HUDs are viewed against bright backgrounds because it may be impossible to present a visual warning signal that is twice the luminance of the background (i.e., a luminance contrast of 3: 1). For example, assuming a maximum HUD luminance of 5139 cd/m^2 (this is the specification for the DataVision HUD), then the maximum background luminance upon which a contrast of ***3:*** 1 can be presented to an observer is 2570 cd/m^2.

Spatial location: Iino, Otsuka and Suzuki (1988) measured reading times for a conventional HDIP and 3 HUD positions: centered in forward field of view, 10 degrees left and 20 degrees left. The other independent variable was vehicle speed. For vehicle speeds below 70 km/h, reading times did not vary among the 4 different displays. Above 70 km/h, two trends appear noteworthy: (1) reading times were always slower for the HDIP and (2) the central HUD reading times were always shorter and the difference was more pronounced at higher speeds. There were no pronounced differences for the 10 versus 20 degree HUDs They also measured observations of the front HUD for an alert driver and a drowsy driver. For one 30-second sample of external road scene vs. HUD observations, the drowsy driver spent twice as long (6.6 seconds) looking at the HUD compared to an alert driver (3.3 seconds). Although details about their methodology were not specified, their findings support the notion that cognitive capture due to HUDs is more likely for drowsy drivers.

Weihrauch, Meloeny and Goesch (1989) concluded that the optimal display location is centered in the forward field of view and 8 degrees below the line of sight based on subjective preference data only. To further assess the utility of HUDs, objective measures (steering variability and obstacle detection) were used to compare HDD vs. HUD performance. There was a 90 msec HUD advantage for obstacle detection and a 1.2 inch reduction in steering variability when viewing the HUD (steering variability was 1.3 feet with the HUD and 1.4 feet with HDD). Although statistically significant, these HUD advantages are of questionable operational significance.

Similar to the Iino et al. (1988) study, Inzuka, Osumi and Shinkai (1991) assessed optimal location using subjective ratings of 6 males. They determined the area within which drivers assessed the HUD imagery as “annoying”. Based on these results they recommend that HUD imagery be located between 6 to 10 degrees down and between 8 degrees left to 5 degrees right. As a validation of this recommendation, in Study 5 they assess the HUD advantage (located 8.5 degrees left, 6.5 degrees below and 2 m viewing distance) compared to a conventional HDD (center, 18 degrees below and .8 m viewing distance). The subjects were young (three aged 24-32 years) and middle-aged (three aged 48-59 years). The dependent measure, recognition time, was the time to acquire digital speed information. There was roughly a 100 msec HUD advantage for all conditions of vehicle speed (40, 70 and 100 km/h) for both subject age groups. Age did not have a significant effect on recognition times for the limited age range included in this study.

Isomura, Kamiya and Hamatani (1993) manipulated the peripheral location of a task. They demonstrated that information processing among central and peripheral tasks is traded off. At peripheral viewing angles of 10 to 40 degrees the central task degrades performance on the peripheral task when: 1) the central task is more demanding and 2) the peripheral task is more than about 30 degrees from the foveal task.

Fukano, Okabayashi and Sakata (1994) evaluated angles of depression for a HUD from 10 to 40 degrees down and two lateral positions, i.e., center of driver forward view and center of car (no angles were reported for lateral position). They used a dual-task paradigm in which the primary task was a recognition task (detect and respond only to black 20 mrad diameter circles and ignore 20 mrad x 20 mrad black squares) and the secondary task was a tracking task (simulated radio tuning task). Data were obtained for only two subjects. Data at two HUD locations were presented: 10 and 40 degrees below forward field of view. The results show performance tradeoffs primarily when the HUD was located 40 degrees down. Specifically, performance on the secondary radio-tracking task was degraded more when presented at the 40 degree down location. The primary task performance did not change significantly. Fukano et al. are recommending HUDs be located no further than 10 degrees from the fovea when looking straight ahead.

Foyle, McCann, Sanford and Schwirzke (1993) varied the location of a graphic HUD (i.e., HUD task generated graphically) in relation to a pictorial path following task which simulated flying. Although the primary application of this study is to pilots, the results have implications for automotive HUD locations. The graphic HUD information was displaced from the forward line of sight by 0 degrees (roughly overlapping the path task), 8.14 degrees and 16.28 degrees (displacement was diagonally upward on the display). The dependent measures were RMSE for altitude and path. The graphic HUD contained an altitude indicator. As predicted, the presence of the graphic HUD altitude reduced RMSE for altitude at all locations compared to absence of HUD. Interestingly, path performance was poorer when the graphic HUD was at the lower (0 degree separation) position. The alternative explanation for this effect based on masking was ruled out in a second experiment where irrelevant information (dynamic digital compass or static 2 digit display) presented in the same location produced no RMSE path increase. The findings were attributed to attentional tunneling which is a failure to switch attention between separate objects. Regardless of the underlying mechanism(s), the results do demonstrate interference with the primary path tracking task when the HUD information was located close to the primary task. The results cannot be completely explained based on an altitude/path performance tradeoff since path performance was unaffected in the first experiment for the 2 most displaced HUD locations. To determine if the attentional tunneling hypothesis is correct, eye movements would need to be monitored. As the authors suggest, subjects may have been fixating and/or attending to the graphic HUD more often when it was closer. It would also be of interest to manipulate workload. Under high path (higher frequency and amplitude of simulated wind disturbances) workload, subjects might exert more effort to perform the path tracking and therefore ignore the graphic HUD regardless of its spatial location.

The Foyle et al. (1993) study is unique in that it is the only study among those cited in this section demonstrating a performance-based HUD disadvantage for centrally-located (0 degree azimuth and elevation) symbology. Weihrauch et al. (1989) and Inzuka et al. (1991) obtained subjective preference data to support this conclusion. Based on the studies cited, it appears that 6 to 10 degrees below the line of sight is the range of optimal HUD locations. HUD symbology located less than 6 degrees from the line of sight may provide some benefit to drivers under certain conditions (Iino et al., 1988); however, the research does not provide a systematic basis for predicting the conditions under which centrally-located HUDs benefit drivers.

Cognitive capture and HUDs: Neisser and Becklen (1975) and Becklen and Cervone (1983) demonstrated that optically superimposed video sources cannot be processed in parallel. Specifically, subjects in these studies did not notice critical, unexpected events in the unattended video even though they were spatially superimposed and the subjects were well-practiced on the task. The findings from these studies demonstrate the phenomenon of cognitive capture which is operationally defined as the inefficiency or absence of passive or active cognitive switching. The mechanisms that underlie cognitive capture will be discussed in the following section (titled ***"Attention, mental workload and cognitive capture").*** What follows is a review of research on the nature of cognitive capture when using HUDs.

Early evidence for cognitive capture was found in a NASA-Ames study (Fischer, Haines and Price, 1980). Responses to an unexpected event (a wide-body airplane taxiing into the runway) took longer to detect when using a HUD (mean RT = 4.13 sec) than when using a conventional HDIP (mean RT = 1.75 sec). In fact, 2 out of 8 pilots did not detect the airplane in the runway at all (their RTs were 6 secs, which was the exposure time of the plane). Weintraub, Haines and Randle (1985) replicated this finding using a similar unexpected event; namely, 6 out of 8 pilots did not notice the jetliner taxiing onto the runway on the last trial. As further evidence in support of the cognitive capture hypothesis, Larish & Wickens (1991) report an interaction of workload (simulated levels of turbulence) with HUD vs. HDD. Attention to HUDs resulted in a 7 second longer RT (compared to HDD) in responding to an unexpected event during high workload. Wickens, Martin-Emerson and Larish (1993) repeated this study using a high-fidelity simulation environment. In this experiment, workload had no significant effect. Overall, there was a HUD advantage on lateral tracking performance and airspeed error. Although Wickens et al. (1993) found the same tendency for longer RTs to an unexpected event when attending to a HUD (6.2 seconds longer for HUD than HDD), the location effect (i.e., HUD vs. HDD) was not statistically significant.

Wickens, et al. (1993) attributed their failure to replicate previous findings of cognitive capture with HUDs to the existence of higher visual realism in their study compared to earlier studies in which static images were used. However, careful examination of the RTs from Larish & Wickens (1991) and Wickens et al. (1993) suggests an alternative hypothesis. The results of the two studies were compared for RTs to the unexpected far target at the HDD and HUD locations. The largest RT difference between the studies is for the HDD location: 16.25 seconds for Wickens et al. versus 13.1 seconds for Larish & Wickens). This is consistent with the fact that the HDD in Wickens et al. was placed 8.5 degrees down whereas the HDD in Larish and Wickens was 24.7 degrees down. In other words, the HDD in Wickens et al. (1993) may have been more susceptible to cognitive capture due to the smaller spatial separation and thereby minimizing the RT difference HU vs. HD. Research on the effect of spatial location/separation on cognitive capture is needed to resolve this apparent discrepancy.

Sojourner and Antin (1990) did not find any evidence of cognitive capture. They assessed performance in a simulated driving task in which subjects monitored a digital speedometer (head-up or head-down), detected peripheral targets and detected navigation errors along a route memorized prior to a trial. Observers performed equally well on the speed monitoring and navigation tasks regardless of display location. However, for salient cue detection, RTs were 440 msec faster head-up than head-down. Note that the temporal uncertainty (how accurately subjects can guess when targets will occur) of the peripheral cues in this study was not nearly as high as in experiments presenting single trial, unexpected events (Fischer, Haines and Price, 1980; Weintraub, Haines and Randle, 1985; Larish and Wickens, 1991). Another finding from this study is that salient cue RT was faster when located closer to the HUD speedometer. This is contrary to predictions based on data from Foyle, McCann, Sanford and Schwirzke (1993) in which RMSE path was higher when the graphic HUD altitude display was closer to the central tracking task. This apparent discrepancy could have been due to differences in workload characteristics of the primary (i.e., speed tracking in Sojourner and Antin study vs. path tracking in Foyle et al. study) and secondary (i.e., salient cue detection with relatively low spatial/temporal uncertainty in Sojourner and Antin study vs. altitude tracking with graphic HUD information in Foyle et al. study) tasks. Also, subjects may have been using different resource allocation strategies. In the Sojourner and Antin study, speed monitoring performance was perfect in the HU condition and nearly perfect in the HD condition (82 out of 90 speed violations detected). In comparison, Foyle et al. demonstrated task variability on both primary and secondary tasks.

Some overall conclusions can be drawn from this research. First, HUDs are likely to only capture attention from an external target under high workload and high temporal uncertainty (i.e., low expectation of an event). Secondly, the causes of cognitive capture need to be investigated. There is some suggestion that HUD-induced cognitive capture will be manifested under high temporal uncertainty which was not systematically manipulated in any of the studies. The following studies investigate possible causes and means to eliminate cognitive capture.

A number of studies from researchers at NASA-Ames have investigated the potential for attention problems when using HUDs. It is believed that cognitive capture results because observers develop inefficient attentional switching strategies in the presence of HUDs. Assuming that an attentional switch is required to acquire information from the 'far domain' (i.e., the forward driving scene) after attending to the 'near domain' (i.e., the HUD), cognitive capture of HUDs occurs when performance on the 'far' task (i.e., missed targets, slower RT) is degraded in the presence of HUDs.

Evidence for cognitive switching in an aviation HUD study was obtained by McCann, Foyle and Johnston (1993), who measured RT to cued targets. The targets were either a stop sign (indicating it is unsafe to land) or a diamond (indicating it is safe to land). They varied the cue location (HUD or runway) and relevant target location (HUD or runway). On WITHIN trials (i.e., cue and target were presented in the same domain: either both HUD or both runway), RT was shorter (average for RTs on WITHIN trials was about 1250 msec) than on BETWEEN trials (cue and target presented in different domains). For BETWEEN trials, median RT for cue on HUD/target on runway was 1400 msec and median RT for cue on runway/target on HUD was about 1340 msec. The 150 msec switching cost (HUD to runway switch; i.e., 1400 minus 1250) demonstrated in this experiment is not meant to be interpreted as an absolute measure of performance outside the laboratory. In a driving situation, after all, there are no cues to tell drivers when to switch their attention. The purpose of this experiment was to demonstrate a cost of attentional switching.

Attention switching appears be one mechanism underlying attentional limits when using HBIDS. Once the switch takes place, McCann et al. (1993) also determined what happens to the information in the unattended domain. This was assessed by presenting a congruent (distractor and target associated with same response) or an incongruent (distractor and target signal associated with different responses) distractor target. If information in the unattended domain is processed, RTs with congruent distractors should be faster than with incongruent distractors. Alternatively, if information in the unattended domain is not processed, no interference will result and the congruency effect is eliminated. As predicted, there was no congruency effect for distractors presented in the other domain on WITHIN trials. In other words, information on the unattended channel was not processed. This study suggests that three possible mechanisms underlie cognitive capture with HUDs (1) HUD information is not processed in parallel with external scenes, (2) there is a consequent RT cost associated with switching attention across information sources; and (3) the unattended domain (either 'far' or 'near') does not appear to be processed.

McCann et al. (1993) also found some support for an asymmetry in switching cost: RTs were slower switching from HUD-to-runway than runway-to-HUD. Support for this asymmetry was obtained in an experiment by McCann, Lynch, Foyle and Johnston, 1993. They measured performance on WlTHIN and BETWEEN trials in the presence or absence of differential motion cues from the runway scene. In the presence of motion cues, they obtained the same interaction noted earlier (i.e., WITHIN trials faster than BETWEEN). Without motion cues to segregate 'near' (HUD) from 'far' (runway) domains, the BETWEEN trial increase in RT was present only for HUD-to-runway trials. This asymmetry suggests that the HUD is a more efficient attention-getting stimulus than the runway without motion cues.

The cognitive switching hypothesis suggests a possible basis for eliminating cognitive capture effects attributable to HUDs. If the HUD symbology can be perceived as conforming to the outside scene, then there is no longer a need to switch attention from far to near tasks. Conformal symbology does seem to reduce HUD-induced performance degradations on far domain tasks. Naish (1964) demonstrated that conformal (also called contact analogue) symbology leads to benefits in terms of training time and performance on concurrent tasks typical of flying. More recently, Foyle, Sanford and McCann (1991) and McCann and Foyle (1994) measured performance enhancements on a simulated flying task. In the experiments, altitude and path RMSE were measured with and without a simulated HUD. The symbology on the HUD consisted of either high pictorial (altitude cues from scene-linked, virtual buildings) or low pictorial (fewer altitude cues) information. The high pictorial condition led to a predicted decrease in RMSE for altitude. Interestingly, the RMSE for path with high pictorial cues was not degraded. The implication is that if HUD symbology can be made to produce scene-linked cues, information can be processed in parallel with no attentional deficits.

There have been a few exceptions to the benefit of conformal symbology. Comparing traditional symbology (e.g., glideslope and localizer are relative to an aircraft symbol, which is partially conformal) with conformal (fully conformal, i.e., symbolic runway is referenced to world) symbology, Martin-Emerson and Wickens (1993) found that lateral tracking was much worse with conformal symbology. After careful consideration of the two display types, it was hypothesized that the poorer conformal performance was due to the fact that lateral alignment with the conformal symbology can only be achieved when vertical errors are small. This hypothesis is currently under investigation.

Long and Wickens (1994) suggest that conformal symbology may only benefit drivers in the absence of visual clutter. In fact, visual clutter was shown to produce poorer performance head-up than head-down. To reduce the impact of visual clutter on the processing of HUD information, HUDs can be viewed peripherally with minimal performance decrements. Research by Martin-Emerson and Wickens (1992) indicates that if displays are located within 6.4 degrees of the fovea there will be no significant performance decrements due to increased scanning. Therefore, to maximize the benefits of conformal symbology and minimize the effects of visual clutter, some types of conformal symbology can be placed peripherally but should be located no further than 6.4 degrees from fixation.

The applications of conformal symbology to automobile HUDs was studied by Ward, Stapleton and Parkes, 1994. This study showed either no benefits (RT to detect a pedestrian; mental workload) or even performance decrements (speed variability) attributable to a contact analogue visual enhancement system for night driving. To some extent, this may have been due to insensitivity of the dependent measures. In retrospect, the authors suggest alternative measures that might have been more useful such as lanekeeping variability, speed and distance judgements. Even so, there were consistent performance decrements that were not explained. These decrements may be related to the use of near infrared image intensifiers to generate their VES imagery which are inherently noisy (due primarily to photon noise), low-resolution images. Another problem with using infrared image intensifiers to enhance the driving scene is that the driver has to relearn fundamental perceptual processes; for example, assumptions about target distance based on contrast and size are sometimes reversed in intensified imagery. For this particular experiment, more practice should have been given to observers on the road and in the laboratory. In the laboratory, terrain boards are used to efficiently demonstrate how depth perception is disrupted when viewing infrared intensified images. Even if the observers had been adequately trained, the practical implication of a necessity to train drivers is that it will significantly limit the acceptance/utility of this type of technology to a small, specialized subset of the driving population.

An alternative approach for displaying route guidance information would be to take advantage of global positioning system (GPS) technology to produce conformal symbology overlays. As GPS applications become more widespread, it may be possible to use this technology to present the driver with conformal symbology such as turn arrows embedded within the driving scene, highlighting of landmarks, or even the overlay of lane markings. In addition, McCann and Foyle (1994) recommend the use of 'virtual billboards' to display speed, current location and other relevant traffic information. This would require the GPS system to locate blank, black backgrounds onto which HUD symbology would be overlaid. This would eliminate visual clutter and eliminate the propensity for cognitive capture since it would be perceived as part of the external scene. There are clear advantages to this approach but there remain a number of technological and cost issues.

Attention, mental workload, and cognitive capture: The operational definition of cognitive capture provided in the Glossary does not identify any underlying attention mechanisms. This is due largely to the assumption that cognitive capture, whether attributable to inefficiency of "early" or "late" attention switching, has the same consequences for drivers; namely, degraded performance on primary driving tasks. Poorer performance is not limited to any particular dependent measure. Essentially, cognitive capture is manifested ***whenever***

switching between the secondary task (i.e., HUD or other in-vehicle display) and the primary task (i.e., scanning the external road scene) is less efficient ***or*** does not occur. For example, a longer RT for HUD-to-external-target transitions compared to an appropriate baseline RT (i.e., HDD-to-external-target transitions) ***or*** missed external targets are both manifestations of cognitive capture. Thus, it is not assumed that cognitive capture is either a "passive" or an "active" orienting of attention, even though the word "capture" might imply a passive process. Research on the allocation of attention is discussed below to better understand the conditions under which cognitive capture can occur. Of particular interest are studies investigating age-related effects on the efficiency of attention switching.

To identify the causes of cognitive capture, a distinction needs to be made between the allocation of attention and mental workload. Cognitive capture is typically viewed as a limitation of attentional allocation. However, an alternative hypothesis based on changes in mental workload can often be used to make the same predictions. The distinction is important because of the implications for HUD design. For example, assume that a study used only one "high" workload condition for both HUD and HDD displays, that the only difference between the displays was their spatial location, and that single-task performance was the same for both displays. Since workload was not varied, a dual-task decrement for the HUD can be attributed to inefficiency at any level in the information processing task. If a low workload condition had been included and a dual-task HUD decrement existed even under low workload, then "early" interference is the most likely cause (perhaps attributable to contrast interference). Since the low workload condition was not included, the latter possibility cannot be assessed. Unfortunately, the recommendations that are made based on the study findings depend upon the level of interference. As an example, "central" processing inefficiency might have implications for the ***amount and format of information displayed*** on HUDs whereas "early" processing inefficiency might have implications for the ***spatial location and luminance contrast*** of HUDs The three primary levels of interference that need to be identified in HUD studies are described below.

Three information processing stages are identified in the following discussion: (1) Encoding (E-level); (2) Cognitive (C-level); and (3) Response (R-level). Each level has many subdivisions; however, the level of specificity is adequate for understanding the interference effects that are expected from the current study. These levels can be identified using methodologies that allow inferences about the structure of underlying attention mechanisms involved in specific information processing tasks. One such method, the additive factors method (AFM), has been used (Stemberg, 1969; Sanders, 1980) to identify information processing stages by determining the relationship among various independent variables. One assumption of the AFM is that if two variables are additive in an ANOVA (i.e., main effects of each variable are significant and the interaction of the variables is not significant), then they are presumed to affect different processing stages. Specifically, if one variable increases the latency at one stage of the information processing task and another variable increases the latency at another level, then the latency increase should be additive. On the other hand, if two variables interact, then they are presumed to affect at least one processing stage in common. In other words, the effects of the two variables are multiplicative (i.e., overadditive interaction effect) since they are both increasing the latency of at least one common processing stage. If the processing stages overlap in time (i.e., stage 2 begins before stage 1 has completed), then underadditive effects can occur. The latter case presents difficulties for the AFM since various amounts of overlap can mask additive and overadditive effects. Although this limits the usefulness of the AFM as a tool for uncovering the underlying structure of an information processing task, it does provide a convenient shorthand for conceptualizing the effects of independent variables on information processing.

At each processing stage, there is potential for interference. Whenever there are multiple sources of input and/or output for a particular stage, an internal mechanism is required to select among the alternatives for further processing. In many instances the internal mechanism is under conscious control. However, there are instances in which unattended information enters consciousness (e.g., the cocktail party phenomenon). This process of selecting inputs for processing and rejecting others is one type of attention allocation. The two main types of attention allocation of interest for the current study are described below and in the Glossary. In defining these attention strategies, an “input” can be either a sensory modality (e.g., visual or auditory), a mental operation (e.g., counting backwards in threes or mental rotation) or a feature within a sensory channel (e.g., a spatial location). Also, inputs are typically presented simultaneously:

(1) Selective attention: attending to some inputs while ignoring others.
(2) Divided attention: attending to two or more inputs that are active simultaneously.

Sustained attention (or vigilance) is considered a meta-category since it refers to the time-span of attention allocation (i.e., time-on-task) and can be either a divided or selective attention allocation. This process of selecting relevant information and rejecting irrelevant information involves a ‘switching’ mechanism, the efficiency of which is manifested in performance measures such as latency, accuracy and detection measures in a dual-task paradigm. The primary stages are described below along with the variables that have influences at each level of processing.

The first stage in the process is the encoding level (E-level). This stage is responsible for transduction and preprocessing of stimuli for all sense modalities. A few of the independent variables that affect the efficiency of this stage include:

(1) stimulus features (e.g., luminance, contrast, exposure duration, color and size);
(2) spatial location (e.g., central or peripheral)
(3) sensory modality (e.g., visual, auditory, tactile)

The outputs of the E-level are pre-conscious representations of stimuli that can be selected for further processing or rejected. E-level interference can occur when any or all of the following conditions apply: (1) multiple inputs are attended; (2) targets are near threshold detection; (3) targets are embedded within “noisy” backgrounds. The interference is a result of optical (i.e., pre-retinal) or neural factors. For example, attending to an in-vehicle display (HUD) whose symbology spatially overlaps external targets while driving presents potential E-level interference in that targets that are spatially superimposed (i.e., contrast interference) or adjacent (spatial masking) tend to reduce the efficiency with which either stimulus is encoded. This interference can be somewhat reduced if the inputs are separated along one or more stimulus dimensions (i.e., spatial location and/or color) or presented in different sensory modalities (i.e., auditory).

Although auditory signals may reduce interference at the encoding stage, this does not preclude interference at other levels of processing. Suppose that an auditory signal is designed to indicate that 1 of 5 in-dash vehicle status indicators exceeds some critical level. In this situation, the driver would need to scan the in-dash displays to identify the problem. In essence, the auditory signal has modified the driver's visual search strategy from a driver-controlled (active or non-cued) to a vehicle-controlled (passive or cued) process. Although this may tend to reduce overall workload by reducing the number of visual scans to the in-dash displays, the resultant safety benefits, if any, are unclear. In general, it is somewhat risky to change driver behavior from active to passive since this creates a driver-dependency on hardware that may perform poorly or even fail. In the worst-case scenario, auditory signals may actually "waste" processing resources. For instance, in some collision avoidance systems a small percentage of auditory signals are false alarms. Although false alarms can be reduced, there is an inevitable tradeoff between false alarms and misses. Another human factors issue related to the use of auditory signals is the use of multiple auditory signals. Although research suggests that auditory signals can reduce driver workload relative to visual signals (Popp and Faerber, 1993), auditory signals are susceptible to interference when multiple auditory signals are presented simultaneously to drivers. Thus, E-level interference can be reduced by using separate sensory modalities but within each modality there is the potential for interference. Even if E-level interference is eliminated, interference can still occur in successive processing levels. Once the level of interference is isolated, countermeasures that eliminate or minimize the interference can be designed.

Following encoding, the cognitive level (C-level) selects inputs and represents the information at a conscious level. It is only through C-level processing that E-level representations of stimulus features can be selected for further processing and, in turn, be grouped into identifiable objects. C-level interference is manifested when targets are embedded in a scene containing multiple targets/distractors that cannot be distinguished automatically based on stimulus features alone (such as contrast, color or size). The following list includes independent variables that contribute to C-level interference in the current study:

(1) number of targets and distractors (correlates with display and/or scene clutter)
(2) stimulus uncertainty (e.g., unpredictable ***what target*** will appear)
(3) temporal uncertainty (e.g., unpredictable ***when target*** will appear)
(4) spatial uncertainty (e.g., unpredictable ***where target*** will appear)
(5) discriminability of targets and distractors (e.g., "pop out" of highly salient stimuli)
(6) relative event rate for far (i.e., road scene) and near (i.e., HUD) domains

All of these independent variables influence the efficiency with which relevant information can be acquired from various inputs. Therefore, it is believed that any laboratory manifestation of cognitive capture needs to incorporate a wide range of levels along one or more of these dimensions. To illustrate various situations in which cognitive capture would be expected, assume that a driver is viewing a HUD whose symbology spatially overlaps and is superimposed upon external road features. With conventional in-dash displays, the driver develops a search strategy which involves timing an overt eye/head movement away from the road scene to in-vehicle displays (Wierwille, 1993). With HUDs, the requirement for eye/head movements is reduced (or eliminated) but it ***is*** necessary to reallocate attention. This is a different type of search that can be characterized as a covert attention reallocation in the absence of an overt eye/head movements. The reallocation is based on higher-level representations than those that are available following E-level processing. C-level processing is required to separate far (road scene) and near (HUD) domains. Research suggests that switching between domains is necessary since it is impossible to process both simultaneously (Neisser and Becklen, 1975).

Anecdotal evidence for serial processing of superimposed stimuli can be obtained by observing ambiguous figures. These are figures that give rise to more than one perception. When viewing such a figure, each interpretation can be perceived but never simultaneously. The "switch" between interpretations is internal and is not guided by stimulus features alone. Interestingly, the "switch" is under conscious control and the efficiency of this "switch" increases with exposure. However, if a feature is added to the figure that eliminates the ambiguity, the alternative interpretation becomes more difficult to achieve (hysteresis effect). In effect, we have 'cognitively captured' one of the alternative interpretations. In a similar way, the efficiency of attention switching when viewing HUDs against road scenes depends on a number of stimulus parameters within far and near domains. For example, high event rates on the HUD, low discriminability of HUD messages and high uncertainty (temporal, spatial and stimulus) about external events would all be expected to increase the likelihood of cognitive capture. The largest demonstrations of cognitive capture have occurred under high workload and high temporal uncertainty.

The response level (R-level) in the information processing sequence involves: (1) the selection of the appropriate response from among a number of possible responses; (2) prioritizing multiple responses; and (3) response execution. The following variables influence the degree of interference at this level:

(1) number of response alternatives
(2) response uncertainty (e.g., unpredictable ***what response*** will be required)
(3) temporal overlap of appropriate responses
(4) stimulus-response mapping consistency

These variables represent conditions that pertain to typical driving conditions. Appropriate responses must be selected that often overlap temporally (i.e., braking and steering at a turn) and require immediate action (i.e., braking to avoid collision with lead vehicle). Stimulus-response mapping consistency is unique in that it applies to situations involving a change in the driver-vehicle interface. Inconsistent mapping is a potential problem with HUDs if the symbology of different HUDs is not designed to a consistent standard. Non-standardized HUD symbology design can lead to a reduced transfer of training (i.e., some relearning is required). An even more deleterious effect of inconsistent mapping is if well-learned responses have to be inhibited. Unfortunately, response inhibition of automatic responses is one aspect of skill acquisition that becomes more difficult with age (Korteling, 1994).

Although the 3 stages discussed above are described as sequential, the underlying processing is not assumed to be strictly serial. Not only do processing stages overlap in time (partial or even complete parallelism), there are instances in which the C- and/or R-level processing precede E-level processing. This occurs whenever a decision is made to fixate a different location of a visual scene. In this instance, the R-level (eye/head movement) precedes the E-level processing. Another way in which the stages are not serial is that most tasks provide feedback. This feedback, in turn, can be used to evaluate performance and make appropriate response adjustments to meet task demands. As an example, negotiating a sharp curve involves comparing a response (steering wheel adjustments) against some objective safety criterion (staying in lane) and making appropriate steering and/or speed adjustments.

Effect of HUDs on Driving Speed

Some opposition to automotive applications of HUDs has been based on the assertion that they will lead to drivers becoming overconfident which could lead to risky behaviors. This criticism is particularly relevant for vision enhancement systems (VES). VESs are supposed to extend visual performance beyond what would normally be possible while driving at night or through fog. One criticism of this technology is that any safety benefit will be offset by the fact that drivers feel safer and therefore drive faster. Ward et al. (1994) evaluated naturalistic speed choices with and without a night VES. Contrary to the concern that drivers would drive faster with VES, speed adjustments were actually lower with VES than without. Although there was a trend for speeds to increase on successive runs, on any given run mean speed with VES was always about 6 km/h slower than mean speed without VES. However, the speed variability was higher with VES than without VES along the same curved sections of the route .

Rutley (1975) reports data that suggest a safety benefit of HUDs; namely, the increased awareness of speed via a HUD speedometer is believed to have caused drivers to adhere to posted speed limits. Two more recent field studies did not find any difference in speed responses when using head-up versus head-down displays. Kiefer (1991) obtained this finding in spite of the fact that older (64-69 years) and younger (19-22 years) subjects glanced more frequently at the head-up display (indicating higher awareness and/or novelty) and spent more total time glancing at the HUD. However, when sampling vehicle speed, subjects spent 100 to 200 milliseconds less time in scanning the head-up than head-down digital speedometer. Older subjects took longer to look at both types of displays but there was no added benefit for older drivers. This may be related to the subjective questionnaire data in which 7 of the 8 subjects in the study preferred a head-up over a head-down digital speedometer. The reason they preferred the HUD speedometer was that it made it easier to maintain a desired speed. In agreement with the Kiefer results, Briziarelli and Allan (1989) showed no effect of a head-up speedometer on the mean speed of subjects. They also measured speed responses with and without speed adaptation (i.e., 25 miles of highway driving followed by .85 miles on a residential road) and on two different road types (residential and highway). The HUD had no effect on speed responses.

The overall conclusion from these studies is that if HUD speedometers do have an effect on the speed choices of drivers, the impact is small. Still, the HUD advantage in terms of time saved in acquiring information has been demonstrated by various researchers and may translate into larger advantages in an actual driving scenario where targets may be unexpected and the range of workload conditions is larger. Of course, a driver's need and/or willingness to monitor speed under 'extremely high' workload conditions is open to question. Future research needs to focus on better controls for overall workload and the timing of time-critical responses in studies of HUDs and speed choice.

Implementation Issues for Automotive HUDs

Will automotive HUDs ever gain widespread acceptance? Perhaps the biggest impetus for automotive HUD development is the advent of ITS technology. Navigation instructions; motorist advisories for road conditions and accidents; vehicle status; weather and other types of information have been proposed for future ITS applications of HUDs. If this information is not presented in a well-designed HUD interface, driver information overload (DIO) will result. Conformal symbology is one means of minimizing DIO. For example, Fukano, Okabayashi, Sakata and Hatada (1994) have tested an "on-the-scene" HUD for navigation. In their display, the HUD overlays a directional arrow on the image of the road surface. Visual clutter of the driver's view of the driving scene is minimized because the HUD symbology conforms to the contour of the road surface. Arguably, ITS information that cannot be displayed in conformal format should be displayed head-down or on a second HUD that does not overlap the forward driving scene (such as the DUET display discussed previously). Conformal symbology has also been tested for enhancing safety under low visibility conditions (such as driving at night or in fog) using radar and infrared image intensification.

The research reviewed in this report demonstrates a number of advantages of conformal symbology for pilots as well as drivers, but it has yet to be demonstrated whether it is necessary or feasible to implement conformal symbology for automotive HUDs. Swift and Freeman (1986) point out that the cost of implementing HUDs even without contact analogue displays may be enough to limit the widespread use of automotive HUDs In their view, it may not be necessary to optically superimpose the HUD virtual image on the forward driving scene, much less to display navigational information using a conformal format. In fact, none of the navigational systems currently in existence use conformal symbology, yet the majority are reported to be effective for practiced users. Other issues that need to take precedence aside from cost are size and ease-of-use (i.e., optical alignments that are necessary to compensate for the range of eye heights and eye-to-combiner distances of drivers). To maximize the benefits of HUDs due to eyes-on-the-road time and accommodation time, Swift and Freeman propose a collimated display whose images are located just above the dashboard. Their proposed design, termed the Instrument Head Level Infinity Display (IHLID), incorporates separate collimated units (each with 5 by 5 degree fields-of-view) located side-by-side on top of the dashboard with a large combined horizontal field-of-view.

Prior to widespread implementation, it will be necessary to evaluate various display formats. Zaidel (1991) has proposed the use of HUDs as "an alternative temporary display". The main idea is that information should not be displayed continuously. The driver should be able to display information only when he/she judges it safe to do so. For example, the HUD would normally be blank until the driver presses a button, or perhaps gives a verbal command, to display information. For warning information which does not require a request from the user, an auditory cue can be used to alert the driver. This approach has the added advantage that it minimizes visual clutter, thereby mitigating the need for contact analogue symbology.

Summary and Critique of Current Findings and Recommendations

In general, there does not appear to be a large, robust HUD advantage, either for aviators or for drivers. The results are somewhat mixed as to whether, how much and when HUD advantages are manifested. However, this is not altogether bad news for HUD proponents since this also suggests that there are no significant disadvantages of using HUDs. One possible exception is the propensity for cognitive capture when using HUDs, especially under high workload conditions and high temporal uncertainty for external events. Regardless of whether cognitive capture will manifest under actual driving conditions, various design recommendations have been suggested to minimize the potential for cognitive capture. A critical overview of this literature review is presented below, with a following discussion of implications for the design and testing of automotive HUDs:

- Virtual image distances should be between 2.5 to 4 meters from drivers' eyes. This is based on results suggesting that: (1) HUD symbology placed below the horizon will be superimposed on backgrounds in the range of 2 to 4 m and (2) recognition time (time to transition from 10 m to HUD distance and read digital speed) increases for older drivers when HUD imagery was located nearer than about 2.5 meters, which was attributed to presbyopia.

- For young observers. reaccommodation time-saved by presenting svmbols head-up (i.e., optical infinity) versus head-down (i.e.. optical distance of 1.33 D) is not statistically significant. In the Weintraub et al. (1985) study, subjects aged 19 to 27 made decisions about runway closure ***prior to*** reaching full reaccommodation which tended to minimize any performance benefit in terms of reaccommodation time-saved. Although depth-of-focus (DOF) and resolution requirements were not assessed, these factors might account for their finding. DOF, which is related to pupil size, increases the range of focus errors over which targets are in focus on the retina. Related to DOF is the criterion used to judge image sharpness. In other. words, big targets require less accurate focus adjustments (i.e., higher DOF) than small targets (i.e., lower DOF). Since the targets used in the Weintraub et al. study did not place high demands on resolution, their results may be attributed to a high DOF for detecting critical features in the symbology used (see earlier discussion for details). Another shortcoming of this study is that older subjects were not tested. In short, reacccmmodation time-saved with HUDs is presumed to benefit drivers (particularly older drivers) but the studies measuring accommodation to-date do not support this contention.

- Eyes-on-the-road time is higher with HUDs. Typically, effects for this measure are small (50 to 200 msec) and the magnitude of the HUD advantage has been shown to depend on factors such (1) static HUD location, (2) dynamic HUD location relative to fixation (such as driving on a straight versus a curved road) and (3) type of dependent measure (i.e., direct measure of eye movement scanning or recognition time). For direct eye movement measurements, the results are mixed as to whether there is a HUD advantage. If the dependent measure is mean time spent in a scan (i.e., roadway to HUD and back to roadway), head-up is better than head-down. However, if the measure is glance frequency (glances per minute to speedometer), head-down has a slight edge. The higher scans per minute head-up than head-down may be attributable to a novelty effect, since successive test sessions showed negligible differences HUD vs. HDD. Some caution should be used in interpreting these findings because eye movement data alone cannot determine what information a driver is actually processing (i.e., fixation location does not necessarily correspond with the focus of attention).

- Unlike HUDs currently in use by aviators, it is unlikely that automotive HUDs will be centered in the driver's field of view. Research suggests that drivers prefer to locate HUD symbology below the horizon and left or right (depends somewhat on whether HUD is designed for left- or right-mounted steering wheels) of straight ahead. This is also confirmed by the typical HUD locations in Appendix B. However, although peripherally-located HUDs are a consistent preference among drivers, two criticisms of these findings need to be addressed in future research. First, these findings consist of subjective preference data. Although user preferences are certainly important, they may not correlate with objective measures of performance ***and/or with*** actual use among experienced drivers. Secondly, the preferences were obtained for non-conformal, digital speed symbology. Thus, it is difficult to determine the extent to which subjective preferences are based on (1) low precedence for speed monitoring, (2) low tolerance for visual clutter and/or (3) perceived safety loss due to contrast interference.

- Even low levels of visual clutter can negatively impact performance. This finding appears to hold true for responses to information acquired from the HUD display and for responses to targets within the external scene. Conformal symbology for navigation information (Fukano et al., 1994) has been proposed as a means of reducing visual clutter since: (1) fewer HUD display elements (or pixels) would have to be illuminated to convey the same navigation information to drivers and (2) there is minimal contrast interference between the conformal symbology and critical detail in the forward road scene. In the Fukano et al. study, a directional arrow indicating where to turn was superimposed ***in perspective*** on the image of the road without occluding roadside features.

- Cognitive capture with HUDs is well-documented, but not inevitable. When performance is measured under high workload conditions ***and*** there is a high degree of temporal uncertainty (i.e., external target is unexpected), cognitive capture by a HUD is likely to occur. A number of design recommendations have been made to minimize the potential for cognitive capture under such conditions. For example, conformal symbology can potentially be used to reduce interference because it 'fuses' with the external scene. In other words, observers are effectively attending to one domain (called the far domain) because conformal symbology merges with the external scene. However, it should be noted that all of the studies that demonstrate a benefit of conformal symbology to-date have used graphic HUDs Ward, et al. (1994) were unable to demonstrate a benefit of conformal symbology using an actual HUD while driving. Another recommendation is that HUD symbology (even conformal symbology) should be spatially separated from the forward driving scene. This would require refixation, but the amount of shift would be minimal. The extreme position is that there should be no overlap between HUD symbology and external scenes, as in the IHLID design.

The general conclusion from the review of the HUD literature is that the safety benefits of HUDs are generally small and in some instances HUDs produce poorer performance. Fortunately, almost all of the disadvantages found with HUDs can be attributed to inappropriate design of the HUD optics, symbology and/or the driver interface. The driver interface must allow the driver to have some executive control over the information content, location, rate and onset. For example, it has been suggested that drivers be allowed to turn various information sources on/off independently. Because of the unique design issues associated with automotive HUD design and the relatively short time that they have been developed and tested, it is possible that future HUD designs will manifest larger and more robust benefits to drivers.

Rationale for peformance measurement: One justification for using a particular dependent measure is that it has implications for driver safety. Once it is determined that a particular measure of performance is safety-relevant, it is then necessary to establish a criterion that discriminates "safe" from "unsafe" performance. Similar to establishing a criterion for statistical significance, safety significance involves a priori determination of an objective criterion that divides "safe" from "unsafe" levels of performance, Although this clearly depends on operational conditions, the criterion may be established relative to a reasonable worst-case scenario. This safety criterion has not been addressed in any of the studies included in the review. Some studies of HUDs reporting statistically significant results may be of questionable safety relevance due to small effect sixes. RT differences between HUD and HDD conditions less than half a second may be statistically significant but may not be significant from a safety standpoint. On the other hand, a half second difference in a laboratory study may translate into a much larger, safety-relevant difference for a less vigilant driver. The latter possibility suggests that the laboratory-based findings are not generalizable to an actual driving situation. In any event, if it can be assumed that the magnitude of the effect is (1) statistically significant, (2) replicable and (3) ecologically valid, a subsequent analysis is needed to evaluate the safety implications of the study findings.

Based on an evaluation of studies investigating HUDs, the following hypotheses were generated to explain effects that were of questionable safety relevance:

(1) Automatic processing of sub-tasks: one or both tasks in a dual-task paradigm are processed automatically.

(2) Insensitive denendent measures: the dependent measure is not sensitive to dual-task decrements.

(3) Restricted range of indenendent variable: levels of independent variable do not approach a range of test conditions (e.g., reasonable best-case to reasonable worst-case) defined with respect to the operational scenario to which the results are to be generalized.

(4) Low overlap of information processing demands: single tasks place demands on information processing stages that do not overlap.

There are a few notable exceptions to the small effect size studies. Most notably, the Fisher et al. (1980), Larish and Wickens (1991) and Wickens et al. (1993) studies all report large RT increases for detecting unexpected events when processing HUD information during high workload conditions. It is important to note that these studies were conducted with aviation applications in mind. Thus, the extent to which the findings generalize to automobile applications of HUDs is unknown. As mentioned previously, there are many differences between the two types of HUDs. For example, aircraft HUDs display information to aviators that may be monitored continuously and may even be considered primary sources of information. In contrast, there are fewer sources of information (e.g., perhaps heading and conformal symbology) that need to be presented to drivers continuously via HUDs. This has direct implications for investigating cognitive capture in automotive HUDs. Specifically, a "good" automotive HUD design does not present information to drivers continuously nor does it assume that the HUD is a primary information source.

Does this imply that cognitive capture when using HUDs is not a high priority safety issue for drivers? The research to-date does not provide a definitive answer to this question. Even so, there is reason to believe that cognitive capture when using ***HUDs*** is ***likely*** when high HUD workload is combined with high external target uncertainty (i.e., *what* to look for) and high external temporal uncertainty (i.e., ***when*** to look for target). Although these effects have not been investigated with older drivers, the propensity for cognitive capture would presumably be larger among older drivers. Korteling (1994) demonstrated that older drivers are particularly susceptible to dual-task interference when one of the tasks is new and involves the inhibition of well-learned, automatic responses. In the Korteling study, gas pedal polarity was either normal or reversed. Although the younger subjects showed no dual-task cost in the reversed gas pedal polarity condition, the older subjects exhibited significant dual-task costs. This was true even though subjects were given practice with all single- and dual-task conditions. These results support and extend previous findings of age-related declines in attention allocation among sub-tasks in dual-task situations. These findings suggest that older subjects may be more susceptible to cognitive capture via HUDs due to their novelty and potential interference at all levels of information processing. For younger observers, cognitive capture may be a relatively rare occurrence, especially within a laboratory experiment. However, the Korteling study includes extreme levels of uncertainty and workload that meet or exceed those of previous researchers demonstrating cognitive capture among well-trained, younger observers.

Critique of laboratory studies using experimental-use-only HUDs: A number of different experimental-use-only HUD designs have been used to study performance with HUDs in the laboratory. The common types are described below (and in the Glossary) as well as some of the significant advantages and disadvantages of each:

(1) <u>Graphic HUD</u>: A real image of the HUD symbology is electronically superimposed on the external scene. Thus, the two images are displayed at the same distance because they are generated using a single CRT display. Advantages: (1) controls for accommodation/vergence effects; (2) low or no cost (depending on software/hardware used to display external scenes). Disadvantages: (1) cannot assess interactions among oculomotor mechanisms and attentional allocation; (2) limited generalizability to actual HUD use.

(2) <u>Projected HUD</u>: HUD symbology is optically superimposed via a direct projection onto the surface displaying the external scene. Similar to the graphic HUD in that the external scene and the HUD symbology are at identical distances. Same advantages and disadvantages as for graphic HUD.

(3) <u>Binocular mirrored HUD</u>: Similar to a fully-functional HUD except that there are no optics between the image source and the combiner (a large piece of plate

glass). Thus, the virtual image distance is equivalent to the source-to-eye distance. To obtain a minimum virtual image distance of 2.5 m, the image source would need to be located outside of the simulator cab. Advantages: (1) complete binocular overlap of HUD symbology; (2) low cost. Disadvantages: (1) bulky hardware setup; (2) virtual image distance not easily manipulated as an independent variable.

(4) Partial overlap mirrored HUD: Similar to the binocular mirrored HUD except that the combiner is too small to allow maximum binocular overlap. Specifically, the right eye views the left half of the HUD symbology and the left eye views the right half of the HUD symbology. The amount of overlap depends on mirror width, interpupillary distance and distance to the mirror. Advantage: low cost. Disadvantage: depending on the amount of overlap, may produce binocular rivalry and/or fatigue symptoms.

(5) Monocular mirrored HUD: HUD symbology is optically superimposed using a mirror positioned so that one eye can view the HUD symbology. Advantages: (1) low cost; (2) standard 100% reflecting mirrors can be used. Disadvantages: (1) due to monocular presentation, HUD symbology could become invisible intermittently due to binocular rivalry; (2) monocular viewing can cause headaches; (3) complex interactions of HUD brightness, external scene brightness and time course of binocular rivalry; (4) lower tolerance for misalignment.

All of these HUD designs share the common disadvantage that they bypass one or more design challenges that must be confronted in the design of any fully-functional automotive HUD. This is a serious limitation for any study in which safety is a high priority issue because there are optical design challenges that directly impact safety such as combiner transmittance and reflectance. Combiner reflectance can be increased to allow better visibility of HUD imagery during bright daylight but the visibility of external targets through the combiner will be degraded. Thus, the findings of studies that do not use a combiner (graphic and projected HUDs) may tend to overestimate the safety benefit of HUDs. In any event, the generalizability of the study findings is specious.

Safety-relevant laboratory studies must also consider tolerance for misalignment. Because of the limited FOV and small eye-box of most fielded HUDs, their tolerance for HUD/combiner misalignment is low. Misalignments can reduce binocular overlap, image quality and contrast of HUD symbology. Realizing the optimal alignment in practice is particularly difficult when considering the wide range of interpupillary distances and eye-heights among users. Some adjustments are required of all the HUDs described above (e.g., eye height). However, 3 of the 5 designs described above have ***unrealistically high tolerances*** for misalignment relative to fielded HUDs (namely, the graphic HUD, projected HUD and binocular mirrored HUD). Again, the implication is that the results of studies using one of the above designs will tend to overestimate any safety benefit of HUDs that can be realized by actual drivers using automotive HUDs.

Another practical constraint of fully-functional ***HUDs*** that has ***indirect*** safety implications is that the HUD must be compact in order to fit within the cab of a standard passenger car.

Compact size is accomplished by minimizing the optical path length using mirror and/or lens combinations. It is the addition of these optical elements that impacts safety by reducing image quality (i.e., contrast, background "glow", distortion and sharpness). To minimize reductions in image quality, most automotive HUD designers use reflective rather than refractive optics (cf. Glossary for these terms). Another implication of the compactness requirement is that the display itself must be small which places a limit on the type of display that can be used as well as the resolution of the display. Resolution, in turn, limits the minimum size of the text or graphics that can be displayed on the HUD.

When safety is a priority issue for laboratory studies of HUDs, the HUD must meet the following minimum requirements: (1) Optical superimposition: HUD symbology must be optically superimposed onto external scenes (or images used for a primary task) using a combiner that is spatially separate from external scene display; (2) See-through combiner: a combiner must be used that allows the user to see through it; (3) Compact: HUD must be capable of being configured within the cab of most automobiles; (4) Virtual image distance: minimum virtual image distance of 2.5 m; and (5) Binocular overlap there must be complete or partial overlap between the left and right eye views of the HUD symbology (i.e., not monocular). If these requirements are met then the study findings would be expected to have high external validity.

Methodological Issues in Future HUD Research

Reliable assessment of HUD efficacy requires the development of a test methodology that predicts performance under reasonable worst-case conditions for HUDs; namely, (1) sample including older drivers with both visual limitations (20/40 acuity; presbyopia) and cognitive limitations (i.e., cognitive switching); (2) night driving test scenarios (i.e., low contrast external targets, perhaps with a drowsiness condition), (3) high mental workload conditions (such as when driving in an unfamiliar city in moderate to dense traffic); and (4) exposure to unexpected events that require a time-critical response (avoiding a roadway hazard or responding to a peripheral threat). Demonstrating an overall HUD advantage relative to a HDD control condition under these circumstances would provide compelling evidence for predicting a safety benefit from specified HUD applications. To maximize the sensitivity and generalizability of a laboratory-based HUD test protocol, the following requirements for the experimental setup are warranted:

(1) High Visual Realism: If these tests are to be carried out in a laboratory setting for greater control and feasibility, the simulated driving scenario should have a high degree of visual realism. As an example of the importance of high fidelity imaging systems, Wickens, Martin-Emerson and Larish (1993) demonstrated larger HUD advantages than a previous study (Larish and Wickens, 1991) from the same lab. This was attributed to the higher visual realism provided in the simulation in the more recent study.

(2) External (or Ecological) Validity of Dependent Measures: Test methodologies must assess a wide range of visual information processing tasks if laboratory results are to reliably predict actual driving performance. Standard acuity measures can be used to predict when a target can be detected under ideal

circumstances (i.e., if drivers know when a stimulus will occur, where it will be located spatially, and what the stimulus will be). However, an externally valid test methodology must incorporate variables that are sensitive to the higher-level cognitive abilities as well as the low-level sensory processes that are both important for overall driver performance.

(3) Variations in Workload: As indicated previously, research suggests that cognitive capture may be manifested primarily under high workload conditions. Workload should be manipulated at multiple stages of information processing (i.e., sensory- to cognitive- to response-level workloads). Workload manipulations also should involve performance of multiple tasks performed concurrently by drivers.

(4) Assessment of Oculomotor Adjustments: Various parameters of intraocular (i.e., accommodation) and extraocular (i.e., eye movements) adjustments have been assessed in HUD studies. Use of these measures which reflect the unobtrusive sampling of drivers' visual behavior, allows the development of operational definitions for workload, oculomotor fatigue, cognitive tunneling and various other phenomena related to visual information acquisition from HUDs.

(5) Links to Performance-Based Safety Criteria: Automotive HUD research requires measuring performance on tasks that have definite safety implications for drivers. Acuity measures have inferred safety implications since a given acuity can be translated into a detectability distance for high contrast targets. This is different from a direct determination of the , minimum acuity required to drive safely which is not as straightforward. Potentially more useful is a measure of the safety of in-vehicle displays based on the relationship between glance duration/frequency to the display and the probability of lane exceedance (Zwahlen, Adams and DeBald, 1988). The lane exceedance criterion used by Zwahlen et al. has clear safety implications for drivers. This approach could be readily adapted using other safety criteria such as detectability.

(6) Practice/Skill/Training Issues: One of the least recognized threats to external validity is inadequate preparation and training of subjects prior to the first experimental measurement. Although all subjects are experienced drivers, this does not guarantee transfer of training to a laboratory simulator. This is particularly important with respect to human factors issues with HUDs since most subjects have never used, or even seen, a HUD. Kiefer (1991) demonstrated asymptotic performance with HUDs only after the third of four experimental sessions.

(7) Selection Criteria for Experimental HUD: One potential limitation of laboratory-based studies relates to the design of the HUD used in the experiment. A number of different configurations have been used among the cited laboratory studies. The appropriateness of a particular HUD design depends on the specific research questions that are of primary interest. For example, if the experimenter wishes to control for accommodative effects in order to investigate attention mechanisms,

the graphic HUD (defined in the Glossary) is an appropriate choice. If the ultimate goal is to address safety issues for HUD use then the following minimal requirements must be met (see detailed descriptions in previous section): (1) optical superimposition, (2) see-through combiner, (3) compact, (4) 2.5 m virtual image distance, (5) complete or partial binocular overlap.

To accomplish these methodological goals: (1) response times should be assessed for all tasks, (2) tasks should be chosen that are representative of the range of workloads that occur in driving scenarios, (3) eye movements should be assessed unobtrusively during the performance of all tasks, (4) all subjects should be practiced to asymptotic performance levels, and (5) a HUD meeting the criteria stated above should be used in the study. What follows are recommended methodological tools and the types of conclusions that can be drawn using these tools.

Signal detection analysis and forced-choice paradigms: Analyses based on signal detection theory (SDT) are used to separate sensitivity changes from criterion shifts. In some psychophysical methods, observers set a criterion in making decisions about the presence/absence of a particular stimulus. SDT assumes that these decisions are also made in the presence of internal noise. When a stimulus is presented, the internal noise and the signal are assumed to be additive. Near threshold, the noise distribution (N) and the signal + noise distributions (S+N) overlap. When there is overlap between N and S+N, changes in criterion produce both a change in the proportion of correct detection of signals (saying a stimulus is present when it is) and a concurrent change in the proportion of false alarms (saying a stimulus is present when in it is not), To separate sensitivity from criterion, a measure d' (or detectability index) is calculated which is the z-score for hits minus the z-score for false alarms.

In many cases, it is possible to use psychophysical methods that do not involve the observer setting a criterion. For example, in two-alternative forced choice the observer has to decide which of two target areas presented simultaneously (or sequentially) contain a target. They are forced to respond (for example, left or right) based on an external comparison of two or more target areas. Depending on the number of response alternatives, chance performance is defined as l/n where n = the number of response alternatives. This test method makes it possible for observers to compare two external stimuli and does not require them to base their responses on an internal criterion.

Assessing dual-task resource allocation: Analogous to the way that SDT separates sensitivity from criterion shifts using receiver operator characteristic functions (ROCs) and d' analyses, dual-task performance and differences in resource allocation can be assessed using performance operating characteristics (POCs). This is calculated by taking the difference between single task performance on each task and the diagonal to the POC function.

Although none of the HUD studies included in this review have performed formal POC analyses, a number of studies have used dual-task methods. Typically, the results are not reported in such a way that resource allocation issues can be assessed. Thus, it is often difficult to determine the extent to which changes in performance are due to changes in resource allocation between the central/primary task and the HUD/secondary task. One exception to this is the study by Isomura et al. (1993) in which they plot primary task performance along the x-axis and secondary task performance along the y-axis. These functions are plotted for 3 different eccentricities of the secondary task. Although there is clearly a decrease in dual-task efficiency at larger eccentricities, they do not perform any analyses to determine the concurrent cost.

Objective measures of gaze direction: Gaze must be assessed in order to answer questions such as when, how often, and how long subjects look at the HUD or the forward driving scene. For the most part, it can further be assumed that observers are attending to whatever it is they are looking at. However, if the HUD symbology happens to be in the same spatial location (depth, azimuth and elevation) as external targets, measures of gaze direction alone cannot be used to suggest what observers are attending to. Typically, other dependent measures are used to determine what information is being selected for processing. Still, eye movement measures will remain useful to determine the eyes-on-the-road time and for correlation with differences in performance measures for HDDs versus HUD conditions.

Eye movements have also been used to develop operational definitions of workload. Galley (1993) used eye movement measurements (electrooculogram or EOG) to assess workload while using a HUD. Workload was operationally defined as: (1) an increase in duration of inspection, (2) decrease in blink interval (time between blinks), (3) increase in the number of high amplitude saccades and (4) an increase in the saccadic velocity when looking away from a display. Based on these criteria, the HUD placed lower demands on subjects when compared to performance on a conventional HDD. A similar application of eye tracking data in future HUD research should be valuable.

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Appendix A: Summary Table of HUD Research Findings

This appendix contains a summary table of articles investigating the application of HUDs for automotive use. A number of articles are not included in this table. To be included in the summary table, the reviewed article must: 1) involve laboratory or field experimentation with moderate to high ecological validity, 2) address an issue specifically related to the use of HUDs, 3) describe the experimental setup and test conditions, and 4) report results in graphical and/or table format, with some means of evaluating the statistical significance of the findings.

These criteria exclude a number of articles that are state-of-the-technology or future technology reports. Also excluded are engineering articles geared primarily towards describing the design of a particular HUD. These engineering reports are summarized separately in Appendix B.

The column headings in the research summary table were chosen to conform as closely as possible with common report formats among scientific journals. In some instances the columns are grouped to minimize space requirements. This is typically done for studies in which multiple experiments are described.

Summary table of research findings for those studies investigating automotive HUD applications.

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Benel, 1980	Investigate the relationship between the Mandelbaum effect and apparent size	Experiment 1: 24 observers with normal near and far acuities (minimum of 20/25) Stimuli: 1) High contrast target: 3 x 3 matrix of Snellen Es at 0, 1.25 2.5 and 3.75 diopters (D) 2) High contrast screen: 7.2 min arc strokes separated by 16.8 min arc. Distances: -.63 to 5.53 D in 1.25 D steps Dependent measure: Subjects report change in apparent size ("larger", "smaller" or "no change") Experiment 2: 12 observers (monocular viewing) Stimuli: 1) Collimated "moon" 2) Background: outdoor scene from 5th floor of a building which included trees and buildings 3) Mesh screen: .75, 1.5, 2.25 and 3.0 D distances Dependent measure: Variable diameter transilluminated disc for size-matching Protocol: 1) Each session began and ended with two accommodation measurements and size matches to scene and moon without the screen 2) Screen presented twice at each distance (counterbalanced order)				Exp. 1: 17 of 23 Ss reporting "smaller" judgements had nearer accommodative shift on trials in which they said the target was "smaller" 16 of 20 Ss reporting "larger" judgements had more distant accommodative shifts. Exp. 2: Correlation between accommodation and apparent size: $r=-.56$. Thus, apparent size decreased with near accommodation. Same relationship across screen conditions: $r=-.76$
Bossi, Ward and Parkes, 1994	Assess the effects of a simulated vision enhancement system (VES) on the recognition and discrimination of brief, irregularly presented targets at various eccentricities outside the enhanced central area.	Thirteen subjects: ages 24 to 39 (mean age 31.5) with normal or corrected to normal acuities. All experienced drivers	Driving scenes recorded onto videotape. Semi-rural single and dual lane roads. Speed 50 to 80 Km/H, headway 15-20 m Field of view: 50 degrees horizontal and 33 degrees vertical Eccentricities: 10, 15, 20 and 25 degree eccentricities at 4 different meridians Dark conditions via film post-processing Experimental conditions: 1) DARK 2) DUSK 3) DARK+VES 4) DUSK+VES	Primary tracking task: keep laser pointer within the rear number plate of the lead vehicle Secondary detection task: respond to target presentation (Landolt Cs presented at various eccentricities and orientations) by pressing a brake pedal and identifying orientation verbally.	Practice trials : 5 minutes on tracking alone 15 minutes tracking + detection Experimental trials: 25 minutes for each of the 4 each experimental condition (order of 4 conditions were counterbalanced) Two sessions required to complete the experiment per subject	Detection: - all main effects (VES vs. no VES, eccentricity and light level) significant - consistently poorer performance during DARK conditions with VES. Decrement larger for targets located centrally (i.e., closer to VES). - no significant differences VES vs. no VES when tested under DUSK conditions. Reaction times: - no significant effect of VES on RT - RTs longer during DARK - RTs increase with eccentricity

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Briziarelli and Allan, 1989	The effectiveness of a HUD was investigated as a means of controlling drivers' speeding behavior on a highway, a residential road, and as a means of minimizing the effects of speed adaptation.	40 Subjects: 17 males 23 females Age range: 18 to 40 with a mean of 24.6 years. All had valid drivers' licenses (mean of 8.2 years of driving experience) NOTE: Ss told that the experiment was about navigation skills	Test vehicle: 1982 front-wheel drive Oldsmobile HUD: Stemco Engler Speedometer (analog display in mph) HUD location: 118.75 cm from bottom of windshield, 3.15 cm above bonnet surface and 21.2 cm in from the car's left side. Highway: 25.95 mile, 2 to 4 lane asphalt road which served as speed adapting part of course. Posted speed = 55 mph Residential road: .85 mile, straight road with one bend. One lane each direction. Posted speed = 25 mph NOTE: All testing conducted during high visibility conditions with low traffic density.	Average speed of subjects along the course was monitored by the experimenter in a separate following vehicle. Debriefing followed by subjects answering two questions: 1) Were you more aware of your speed with the head-up display? 2) How comfortable did you find the head-up display as compared to a conventional speedometer?	Group 1: Drive on residential road using conventional speedometer WITHOUT speed adaptation Group 2: Drive on residential road using conventional speedometer WITH speed adaptation Group 3: Drive through residential district WITH HUD and WITH speed adaptation Group 4: Drive on residential road WITH HUD and WITHOUT speed adaptation	No significant main effects or interactions Responses to questions after the experiment: 1) Were you aware of your speed with the head-up display? 18 of 20 that used HUD said yes 2) How comfortable did you find the HUD as compared to a conventional speedometer? 14 of 20 replied HUD was easier to use Differences from Rutley (1975) study attributed to use of analog speedometer (Rutley used digital speedometer). Comments: Highway driving speeds were 65 mph which is a typical average traffic speed on highways. No data for individual drivers who tend to speed (i.e., much greater than 65 mph speed choice without HUD) was presented.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Fischer, 1979	Two primary objectives: 1) Assess the interference caused by superimposition of HUD symbology and external scenes. 2) Effect of divided attention on extracting HUD and external scene information.	<u>Subjects</u>: 12 Ss (5 captains, 4 first officers, 3 flight-engineers) 33 to 59 years <u>Stimuli</u>: Tachistoscope presentation (7.9 deg x 8.9 deg) of 35 mm slides (24 external scenes and 24 HUD displays). Exposure times: Durations limited to durations that produced 80% accuracy. External scene: aerial photographs of runway scenes for 4 airports; 6 of 24 slides had aircraft visible in the sky. Also, used homogeneous blue-gray scene to simulate clouds. HUD symbology: altitude, localizer and horizon symbology corresponded to external scenes. Dynamic elements: slides changed position or value from slide to slide. Light green filter used to approximate P1 phosphor. <u>Experiment 1</u>: Part A (Exposure duration: 25 ms): Effects of superimposed information sources on *processing information from the external scene*: 1) Baseline: external scene shown alone and answer question about which of 4 airports the scene represents and whether or not there are any other aircraft. 2) Experimental: superimpose HUD and scene and ask same questions. Part B (Exposure duration: 200 ms): Effects of superimposed information sources on *processing information from the HUD*: 1) Baseline: HUD alone and then Ss reported their altitude and glideslope. 2) Experimental: superimpose HUD and scene and ask for altitude and glideslope. <u>Experiment 2</u>: Same procedure as before but answer one of the scene questions and one of the HUD questions on each trial Exposure times: 112 ms (Rationale: one HUD and one scene question require half of total time of 225 ms)				Learning effects: stabilized after 6th trial Exp. 1: Process HUD <u>or</u> External Scene Scene Questions: - First 6 experimental trials: 4% accuracy decrease with superimposed HUD ($p<.01$). - Last 6 experimental trials: performance produced no decrement due to superimposed HUD. HUD Questions: - First 6 experimental trials: 11.5% accuracy decrease with superimposed external scene ($p<.01$). - Last 6 experimental trials: 5% decrement ($p<.01$). Exp. 2: Process HUD <u>and</u> External Scene - Attending to both HUD and external scene increased performance on HUD questions (75.1% correct for HUD only vs. 81% HUD + Scene) - Attending to both HUD and external scene had no effect on performance on scene questions (89% scene only vs. 89.4% HUD + scene) Problem: Need dynamic simulator to make results more like flying; ergo, generalizable

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Fischer, Haines & Price, 1980	Determine pilots' ability to perceive and act upon unexpected events in either outside world or in the HUD symbology.	Subjects: 8 Ss (5 Capts. and 3 1st officers) Apparatus: Fixed-based 727 simulator HUD Symbology: 24 deg horizontally by 21 deg vertically. Conformal symbology. Environmental Variables: E1 = Low visibility (cloud ceiling 120 ft., visual range 1600 ft., light turbulence, no wind, decision height 100 ft E2 = Strong headwind shear (30 knots) E3 = Moderate headwind shear (25 knots) E7 = Variant of E1 (cloud ceiling 180 ft, visual range 2000 ft., decision height 150 ft Cognitive Variables: Vertical boresight offset (VBO): 2 deg high symbology offset (relative to external scene); if detected then land short; otherwise, land O.K. Lateral boresight offset (LBO): random 3 deg symbology offset left or right; if detected then land off runway; otherwise, land on runway. Lateral instrument-landing-system offset (LIO): 90 ft bias left or right Obstruction on runway (OB): wide-body aircraft taxiing into runway No offset: symbology was aligned correctly with external scene Performance measures: Eye movements, Head movements, Pilot communications, RMS for glide-slope and localizer deviations Procedure: 1) Training: get Ss practiced to asymptote; 2) Data runs: Pilot responds with button press on detecting runway and then deciding if it's safe to land				VBO: HUD offsets did have an influence on vertical tracking but no statistically significant. Pilots unaware of offsets. LBO: No significant effects. Pilots were aware of the offset but mistakenly attributed the offset to crosswinds. LIO: did not affect lateral performance with or without the HUD. Pilots responded to the offset a little sooner without the HUD. With ILS offset, pilots resorted to using visual guidance only. Runway obstacle: 2 pilots did not see airplane on runway with HUD (RTs for these subjects was 6 secs which is the time that the airplane taxiing onto the runway was visible in the simulator). RTs to detect obstacle higher with HUD than without (4.13 sec vs. 1.75 sec).
Foyle, McCann, Sanford and Schwirzke, 1993 [NOTE: These results are also reported in Sanford, Foyle, McCann and Jordan, 1993]	Investigate the role that object-based and location-based attention models play in the tradeoff between altitude/path performance. Location-based model predicts better performance on both tasks when distance between altitude and path information decreases. Object-based hypothesis predicts no effect of spatial location.	<u>Experiment 1</u> Subjects: 14 Ss, Male Stimulus: Graphical display of superimposed symbology and "out-the-window" information. Symbology location: HUD digital altitude located in lower, middle or upper part of the display Simulated Horizontal and Vertical wind disturbances: root-mean-square error (RMSE) altitude and RMSE path <u>Experiment 2</u> Subjects: 10 Ss, Male Same task as in Exp. 1. Three tests used with symbology in lower location only: 1) Relevant altitude: replicates exp.1 2) Irrelevant dynamic: dynamic digital compass values presented 3) Irrelevant static: constant two-digit value presented. <u>Results and Conclusions</u> Exp. 1: HUD decreased RMSE for altitude (all positions) and increased RMSE for path ONLY when the HUD symbology was placed in the lower position only). Conclusions: Neither attentional hypothesis supported since performance tradeoff only at lower HUD symbology location (i.e., there is an effect of position (which was not predicted by the object-based attentional hypothesis) and it is in the opposite direction to that predicted by the location-based hypothesis. Exp. 2: Digital altitude information reduces RMSE in altitude (replicates Exp. 1). Irrelevant dynamic and static displays produced same RMSE as when HUD absent. For path RMSE, the presence of HUD altitude increased RMSE. Irrelevant dynamic and static information produced the same performance as absence of HUD symbology. This rules out visual masking as an explanation for Exp. 1 results. Overall: Results support attentional tunneling hypothesis: objects placed in close proximity in the visual field interfere more due to inefficient/absent attentional switching.				

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Foyle, Sanford and McCann, 1991	Tested the hypothesis that the pilots' inability to process both world and HUD information is due to ineffective division of attention between the two frames of reference.	Eight male college-age subjects with normal or corrected to normal vision.	Flight task simulation: Silicon Graphics 3130 workstation displayed on 19 inch color monitor. Flight controlled via a joystick Viewing distance: 65 cm HUD Altitude: present or absent digital altitude display. 6.5 cm to the left and 3 cm up from the center of the screen. Pictorial altitude: "virtual buildings" provide altitude information via rooftops change shape with altitude adjustments (assigned altitude of 100 feet).	Altitude RMSE in feet Path RMSE in feet	Testing time: one 3.5 hour session 1) Verbal instructions 2) Practice of flight task (maintain 100 feet altitude). 16 practice trials for all conditions 3) Instructed to attend to both altitude and flight path tasks. 4) 10 second pre-trial warm-up before each trial 5) Feedback provided on altitude and path tracking error (RMSE)	Presence of HUD reduced altitude tracking error ($F(1,7)=5.98$, $p<.05$) but path error increased ($F(1,7)=6.3$, $p<.05$) High pictorial cues improved altitude performance ($F(1,7)=5.39$, $p<.05$) but had no effect on path performance Conclusions: Information within different frames of reference (or attentionally segregated objects) cannot be processed in parallel. When two objects share a common frame of reference (i.e., high pictorial and path information) parallel processing without cost is possible
Fukano, Okabayashi, Sakata and Hatada, 1994	Investigate the benefits attributable to HUDs in terms of ease of operation and legibility. Also, demonstrate the benefits of HUD conformal symbology for navigation	Experiment 1: Display location and peripheral detection performance under dual-task situations Subjects: 2 subjects (22 and 34) tested. Each had normal acuities Forward scene: 1) 3 x 3 matrix of CRTs with a white screen mask surrounding the CRTs. 2) Luminance = 2 cd/m^2 3) Viewing distance = 5 meters 4) Primary task: discriminate 20 milliradian circle from square with 20 milliradian sides. Subjects respond to circles only Secondary (HUD) task CRT (80 cm viewing distance): 1) Locations centered on drivers line of sight: 10 and 20 degrees below horizon 2) Locations centered with respect to vehicle: 20, 30 and 40 degree depression angles 3) Secondary task: simulated radio-tuning by having subjects adjust position of small circle within larger circle Eye movements monitored Procedure: 1) 10 min. adaptation, 2) 30 practice trials, 3) Present 5 display positions, 4) Single task control measures obtained Experiment 2: Navigation HUD using "on-the-scene" symbology (conformal symbology) On-the-scene navigation symbology: lower F factor (i.e., fewer pixels turned on to display information) via presents only conformal arrow indicating direction of turn and a destination name. Subjects: 3 aged 34, 38 and 38 with normal acuities Displays: HUD and forward scene both displayed at 2 meter viewing distance. HUD: subtended 35 x 50 milliradians. Luminance contrast = 1.75. Location: centered horizontally and 7 degrees below Independent variable: Conventional navigation instructions vs. conformal navigation instructions Dependent measures: RTs to respond to navigation instructions (latency to detect correct turn ahead) Eye movements monitored Procedure: 1) 10 min adaptation, 2) Press button at detection of correct intersection for turn, 3) Tested at two types of intersection				Exp. 1: Plotting primary task performance on the x-axis and secondary task performance on the y-axis, there appears to be less dual-task interference when the HUD display location is degrees below the horizon than when the display is 40 degrees below and to the left. Eye movement data: Number of eye movements per minute increases from 0 at nearest display position to 25 at farthest display location. NOTE: The graphs are difficult to interpret via change in scales of vertical axes across subjects and the axes do not represent performance improvements consistently (i.e., x-axis performance improves as numbers increase whereas y-axis performance improves as numbers decrease). Exp. 2: 60% faster RTs for on-the-scene HUD. Frequency of glances 40% lower for the on-the-scene HUD

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Iino, Otsuka and Suzuki, 1988	Develop and test a HUD for automotive use that does not produce cognitive capture and does not interfere with viewing external targets.	<u>HUD Designs Considered</u>: 1) LCD Panel attached to top of dashboard 2) HUD Combiner mounted on top of dashboard (flat reflection hologram) 3) HUD Combiner adheres to windshield (hologram conforms to windshield curvature) 4) Windshield alone used as combiner * The 4th design was implemented because of maximum visible transmittance <u>Problem</u>: Using windshield as combiner introduces both horizontal and vertical binocular parallax (or disparity) <u>Solution</u>: Specially designed prism corrects for binocular parallax. <u>Yazaki HUD</u>: Uses 10 W incandescent lamp to produce brightnesses of $4x10^4$ cd/m^2 (4000 cd/m^2 after combiner losses). Display is an LCD panel (84 x 16 pixels). All images collimated. <u>Experiment 1</u>: Subjects tested on Tomei Expressway <u>Independent variables</u>: 1) Vehicle speed (60 to 100 Km/h in 10 Km/h increments) 2) Display type (HDIP vs. HUD) 3) HUD location (2 degrees down; 0, 10 & 20 deg. left). 4) "Sleepy" driver compared to alert driver (number of subjects not reported) <u>Dependent variables</u> (No details about methods reported): 1) Reading time (time to read HUD information) 2) Eye fixations to HUD (Eye-mark recorder). <u>Experiment 2</u>: 6 male subjects (20 to 40 years of age) Subjective rating (4 point scale from Bad to Very Good) of the 3 HUD locations on an Urban road and the expressway.				NOTE: No statistics reported. <u>Experiment 1</u>: Reading time results: 1) No systematic differences HDIP and HUD for slow speeds (60 and 70 Km/h). 2) HDIP reading times longer than HUD reading times (all locations) at car speeds of 80, 90 and 100 Km/h. 3) At 80 and 90 Km/h, there is a systematic ordering of best to worst reading [illegible] 0 degree is best, followed by 10 [illegible] 20 degree left and HDIP. Observation times: - Observation times compared for a 'sleepy' and an alert driver. Over a 30 second segment, the sleepy driver spent 6.56 seconds looking at the HUD vs. 3.33 seconds for the alert driver. <u>Experiment 2</u>: 10 degree left position rated best overall

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Inuzuka, Osumi and Shinkai, 1991 **NOTE: data reported in this study also appears in Kato et al., 1992	Conducted a series of studies to evaluate appropriate values for display location, character size, brightness and color	Study 1: In-plane location (azimuth and elevation) Subjects: 2 male subjects accustomed to driving with eye-mark camera in place Dependent measures: 1) obtained objective measure of fixation distributions during driving using an eye-mark camera 2) subjective measures of "annoyance" as a function of display location 3) background surroundings: assessed background "stability" at various locations while driving Road conditions: 1) Urban road and 2) Expressway Results: 1) Fixation distributions obtained and the eccentricities up/down/left/right within which 90% of fixations occurred: a) Urban: 6 degrees above, 5 degrees below, 12 degrees left and 11 degrees right (NOTE: For right-side steering wheel driving) b) Expressway: 4 degrees above and below, 11 degrees left and 5 degrees right 2) Subjective annoyance: unacceptable to place symbology within an area bound by 8 deg. left, 7 deg. right, 8 deg. down and 5 deg. up 3) Background stability: best location based on criteria of minimum brightness change is 6-10 degs down and between 8 degs left and 5 degs. right Study 2: Virtual image distance Subjects: 4 Younger (20 to 29 years) and 10 Older (50 to 70 years) subjects participated. Independent manipulation: subjects change fixation from target at 10 meters to speedometer at nearer distances (.8, 1.5, 2, 2.5 and 5 meters). Location: 10 degrees down, 0 degs horizontal Dependent measure: *Reading time* was time from 10 meter target offset to onset of reading speedometer. To obtain *recognition time*, subtracted simple RT to offset of light. Results: 1) Overall, older subjects respond slower than younger (about .28 sec recognition time at 5 m for older vs. .2 sec for younger) 2) Older subject recognition times increase monotonically from .28 sec at 2.5 meters to .4 sec at 1 meter. Study 3: Character size preferences as function of viewing distance Subjects: 7 males Independent variable: HUD display distance (1.1, 1.3, 1.5, 2 and 2.5 m) Dependent measure: subjective assessment of most legible character size Results: Preferred visual angle decreased monotonically from 1.2 degs. at 1.1 m to .8 degs at 2.5 m (NOTE: Size constancy prediction. However, criterion not stated) Study 4: Brightness and color: 3000 cd/m^2 required for snow-covered road in daylight. At dusk, required luminance adjustment Study 5: Follow up of study 2 Accommodation: Using 3-dimensional optometer, 18 and 54 year old accommodation measured. Accommodation changed to instrument panel for younger subject only Recognition time: Measured objectively with EOG at three different driving speeds. Subjects: 3 24-32 year olds and 3 48-59 year olds. Results: Mean recognition time significantly different HUD vs. HDD ($p < .01$). HUD faster by .1 second.				
Isomura, Kamiya and Hamatani, 1993	Dual-task paradigm used to determine information processing limitations of concurrent central and peripheral tasks	3 subjects: 2 males (32 and 28) and 1 female (23)	Apparatus: Driving simulator consisting of 3 separate screens onto which 3 segments of a single scene are displayed. Provides a combined 40 deg field of view Peripheral task: respond to detection of peripheral targets. Targets appear in 1 of 5 spatial locations to the left of the central task. Central tasks: 1) Respond to detection of "same" successive targets when successive targets can vary in orientation, shape and color. 2) Speed monitoring and control Scenery manipulation: Tasks performed in the presence of homogeneous background, static driving scene and dynamic driving scene. Dependent measures: 1) Peripheral task: percent detection 2) Central tasks: Percent correct response to "same" successive targets and speed error (target - vehicle speed)			Scenery effect: Dynamic background produced fewer detections on peripheral task (highest is 90% detections at 10 deg eccentricity) and detections decreased to 70% at 40 degs. Central-peripheral task tradeoff: Better performance on central task coupled with peripheral task decrements. Whole visual burden: a measure of the tradeoff at each eccentricity. Larger eccentricities show larger performance tradeoffs especially for more difficult central tasks (i.e. speed monitoring).

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Kiefer, 1991	Examine the visual sampling behavior of drivers under naturalistic testing conditions with head-up and head-down speedometers	4 male and 4 female subjects. Half of the subjects in each age group young (mean = 20.8 yrs.) half were older (mean = 67 yrs) NOTE: Subjects were excluded if corrections required via difficulty in scoring visual sampling behaviors	Apparatus: Test vehicle instrumented with a digital head-down and head-up speedometer HUD location: 2.4 meter distance, center, 6 degrees below horizon. Cameras: One for monitoring subjects visual scanning and one directed to forward driving scene. Recording equipment located in back seat. Test course: 6 mile course in Stony Creek Metropark in Washington, Michigan Head-up conditions: head-down display left on via this is what 1st generation HUD-equipped automobiles will have. Counterbalanced HU and HD presentations	Speed control: percent of time subjects drove above 35 mph and speed variability Video sampling measures: obtained from visual inspection of videotapes. Included: 1) mean time in the speedometer scanning cycle (or SSC; time from roadway to speedometer and back to roadway) 2) Glance frequency to the speedometer 3) Percent of total visual sampling time in SSC: divide total time in SSC by total visual sampling time (or driving time).	1) Arrive at test site 2) Questionnaire given (re: subjects health) 3) Informed consent 4) Practice drive on course 5) Experimental run: drive 30 to 35 mph 6) Verbal responses: say "speed" when looking at speedometer for 2/3 of trials (as a calibration for later scoring) 6 course runs per session (3 head-up and 3 head-down 4 sessions After last session, Ss filled out a questionnaire.	Speedometer location: effect on mean SSC time (781 msec HU vs. 925 msec HD). Practice effect: Decrease in glance frequency on successive sessions. Speedometer location by session interaction: 1) Mean SSC time: overall less for the HU than HD speedometer. However, the interaction is due to the fact that the difference HU vs. HD tended to increase with sessions. 2) Glance frequency: higher for HU but decreased on successive sessions (attributed to a novelty effect) 3) Total time in SSC: higher HU than HD but difference decreased on successive sessions. * No significant age effects. * No effects on speed performance. Questionnaire data: 1) 7 of 8 Ss preferred HUD over HDD 2) Preferred via easier to monitor speed 3) 3 of 4 subjects in each age group preferred HU via allowed attention to both road ahead and vehicle speed. Experimenter acknowledge that initial high glance frequency could be novelty effect but could also be involuntary distraction effect Also, no age effect may be via low workload conditions.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Kurokawa and Wierwille, 1991	Investigate effects of instrument panel (IP) clutter on automotive IP task performance. Clutter manipulated 3 ways: 1)macroclutter: number of instruments or control cells, 2) microclutter: number of controls within a cell and 3) labelling of controls· i.e., full word vs. abbreviations	Experiment 1 and 2: 8 subjects (4 male and 4 female) ranging in age from 18 to 26 years. Each experiment used a different group of 8 subjects.	Apparatus: moving-base computer-controlled driving simulator in the Vehicle Analysis and Simulation Laboratory at Virginia Polytechnic Institute and State University. Road scene: two-lane simulated roadway Experiment 1: Four panel types: 1) single cell, 2) triple cell, 3) 2x2 cells and 4) 2x3 cells. - each cell labeled with common IP labels and contained 6 consecutive numbers on left and 6 randomly assigned letters on right half of cell. - subjects pressed specific button in a cell Experiment 2: Three control cell formats: 1) single button, 2) 2x2 array of buttons and 3) 3x3 array Labelling formats for buttons: 1) single-line abbreviation, 2) double-line abbreviation and 3) fully spelled label	Three measures use: 1) Task completion time: time from experimenter cue to perform task to completion by subject. 2) Hand-off-wheel time: concurrent manual demand of a task via time subjects hands were off the wheel. 3) Eye movement data: recorded using a videocamera and analyzed manually after experiment. Eye movement measures include: 1) Glances to roadway, 2) Glances to IP (length and number of glances) and 3) eye transitions. Operational definition of task difficulty = length of a glance Operational definition of overall task complexity = number of glances.	No details about procedure given. Subjects prompted to find IP buttons and make a response.	Experiment 1: - Number of control cells had a significant effect on task completion time and the number of glances to the IP. - Label type also had a significant effect on task completion time. Buttons labelled with randomly assigned letters took longer to find than the consecutive numbered buttons. Experiment 2: - Significant effect of number of buttons within a control cell on all dependent measures. - Length and number of glances longer for 3x3 array than 2x2 array of buttons. However, time to press the buttons in both cases about the same as measured via the hands-off-the-wheel time (significant effect on this measure due to difference between 1x1 and other conditions). - Single-line abbreviations significantly shorter task completion times and fewer IP glances - Interaction between touch panel configuration and label abbreviation on task completion time and number of glances to IP. Labelling had an effect for 3x3 but not 2x2 or 1x1.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Larish & Wickens, 1991	Investigate potential for attentional tunneling to both expected & unexpected events on HUDs and in external scene	2 Female 18 Male All instrument rated pilots, 18 to 33 yrs.	1) Viewing Condition: Head-up vs. Head-down (10.7 degrees down from external scene image; between subjects variable) 2) Workload: High and Low (no more detail on how this was manipulated) Display: 1) Glideslope and horizon with digital altitude, vertical velocity, fast-on-slow speed indicator, speed, heading. 2) Two trials presented unexpected shear warnings and plane warning (plane taxiing into runway)	Reaction time: onset of runway signal, shear anomaly or plane anomaly to time for Ss to respond to these events.	Trial types: 1) First session: 14 practice trials 2) Second session: 5 practice trials then 14 experimental trials. NOTE: Trials 11 and 14 were always anomaly trials (anomaly-shear and anomaly-plane) Trial procedure: 1) Breakout of clouds at 1260 ft. 2) Maintain course using HUD instruments 3) Determine if signal on runway yellow/red 4) Detect warning signals (unpredictable intervals) and maintain speed at 90 knots 5) Feedback on lateral and vertical tracking, RT and speed regulation at end of trial	No significant differences between NO HUD/HUD conditions on flight performance. Exception: Better lateral tracking with HUD before landing. Fig 3: RTs faster for HUD (for both workloads) compared to no HUD. High workload produced larger HUD advantage. Results for unexpected events (shear & plane anomalies): Fig 4: RTs vs. HUD/no HUD for shear anomaly. 1.4 sec HUD advantage for low workload but much slower for high workload. High workload produced 7 sec longer RT for HUD compared to no HUD (i.e., head down display). Fig 5: RTs vs HUD/noHUD for plane anomaly. 7 sec longer RTs with HUD under high workload.
Lloyd and Reinhart, 1993	Investigate the information transfer to pilots under different flying conditions and estimate the minimum raster image luminance requirements. NOTE: Typically, HUD imagery is stroke-written which is typically much brighter than raster images.	Five aircraft pilots: 3 commercial pilots, 1 with private & military experience and 1 private pilot.	HUD: Glare-shield-mounted; split combiner; 10x10 FOV. Peak raster luminance set to 280 ftL (optimal for 1000 ftL scene luminance). Combiner located at 16 inches All pilots tested with/without standard sunglasses (nonpolarized, 20% transmittance, neutral density) Images: 1) Daylight forward-looking infrared (FLIR) of low-level helicopter flight over rural areas containing fields, a road, cars, a stream and a lake. 2) Daylight CCD imagery of low-level helicopter flight over Arizona desert, a lake and a dam 3) Daylight CCD imagery of approach and landing at a Phoenix airport Cockpit mockup: diffuse white reflective dome in front of forward three windows of cockpit simulator. Illumination: 4000 W metal halide arc lamps. Luminance controlled with metal apertures in front of lamps. Forward scene luminance levels: 5, 500, 1000, 1700, 2400, 3500, 4900, 7000 and 10000 ftL Rating scale measure: 1 to 100 with verbal anchors (i.e., 75 = acceptable quality). Pilots rated 1) Visibility, 2) Contrast and 3) Utility Experiment details: 1) Single 2 hour session, 2) 12 practice trials, 3) Rating scale of each HUD image, 4) Randomized luminance order (with 5 minutes of adaptation at each of the 9 levels			- Collapsed rating scale measures across Sunglass conditions via no effects. - All rating scales decreased as forward scene luminance increased. - Ratings generally highest for HUD approach video via high-contrast runway markings. - Visibility and contrast ratings combined. Also, FLIR and water videos combined. - Regression equations fit to ratings as a function of inverse modulation of videos. - HUD raster image luminance must be on the order of 50% of the forward scene luminance if the pilot is to maintain awareness of general terrain using raster images. Can be 15% for familiar, high-contrast scenes (i.e. runways).

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Long and Wickens, 1994	Experiment designed to investigate the predictions of space-based vs. object-based attention models using a simulated instrument approach. Also, attempt to replicate earlier findings that HUDs lead to missed targets in external scene.	32 licensed pilots (26 males and 6 females) Age range: 19 to 44 years	Simulation: Instrument Landing System (ILS) approach to an airport. Symbology and outside scene projected onto a 3 m by 2.2 m high screen viewed from 3 m. Conformal symbology: localizer course (lateral) guidance via a virtual runway that overlayed and moved in unison with the real runway. Also displayed a velocity vector. Non-conformal display: No velocity vector and used a conventional course deviation indicator (CDI) for lateral guidance Other information present in both symbology sets, some of which was non-conformal, some conformal. The primary difference is the virtual runway.	Airspeed tracking error: RMSE for deviation of airspeed Position tracking error: RMSE for deviation in position (vertical and horizontal errors added). Speed of transition from instrument to visual flight references Latency to respond to an unexpected runway incursion	- 16 subjects randomly assigned to each level of symbology type. - Each subject flew half of trials head-up and half head-down - 36 approaches, 10 of which were practice, in varying simulated weather conditions - Cloud ceilings: 340 feet, 285 feet, 220 feet and 50 feet (simulated weather changes) - Missed approaches: if subjects thought it unsafe to land they signaled a missed approach (decision height = 200 feet) - Last trial = Boeing 727 taxi onto runway. Post-experiment questionnaire administered	Logarithmic transformation and elimination of outliers (4 out of 1180 position observations and 5 out of 1477 airspeed observations) produced normal distributions and stable variance (homoscedasticity). <u>Prior to breaking out of clouds</u>: - tracking head-up better than head-down (both symbology types) - airspeed error lower (i.e., better performance) head-up when guidance information was conformal BUT not when symbology is non-conformal <u>After break-out</u>: - display location did not matter for non-conformal display (slightly worse head-up) - head-up advantage remained for conformal symbology - best performance was head-down for airspeed error * No significant differences for latency to report runway in sight ($p < .08$). However, head-up is slightly faster than head-down. <u>Runway incursion</u>: faster detecting runway incursion head-down than head-up and faster with conformal than non-conformal symbology. Location main effect due to non-conformal/head-up being significantly worse than non-conformal/head-down <u>Conclusion</u>: HUD advantage primarily via conformal symbology fuses with far domain information. No HUD advantage when displaying non-conformal symbology.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Marin-Lamellet, Dejeammes and Kerihuel, 1994	Observe whether the display of simple symbolic information using a HUD or LCD screen causes different reactions in young and older drivers.	Subjects: 9 young drivers (25 to 35) and 20 older drivers (60-75 yrs.). Older subjects significantly poorer acuity, short-term memory and WAIS-R tes but all older subjects within normal limits for their age (i.e., no pathological conditions detected with any tests) and 60-70 no different from 70-75. Apparatus: RENAULT driving simulator. Operational accelerator, brake and indicator controls. Engine noise reproduced as a function of speed Electro-oculography (EOG) and video camera: eye movements recorded to determine visual search strategies. Used only for gazes to LCD panel Simulated lane closures: obstacle ahead and close one, two or all three lanes of the road ahead. Four messages: move right, move left, keep straight or stop. Subjects' task: drive in center lane at 100 Km/h. When message displayed, make appropriate response Displays: 1) LCD colour screen: 15.23 cm diagonal. 20 degrees down and 23 degrees right, 80 cm viewing distance, 94% contrast. 2) LCD Screen + auditory cue: signalled the onset of new information on LCD screen with auditory cue. 3) HUD: matrix vacuum fluorescent device. 5 degrees down and 3 degrees left, 1.7 m viewing distance Driving scenarios: 3 routes (for each display type) were developed. Obstacles along route included trucks, cars, road work Procedure: 1) First session: training on simulator for 10 to 20 minutes; 2) Practice test run; 3) Experimental runs (2 hours): 3 sequences Data collected: 1) Overall time to perform a run, 2) RT from display of message and appropriate response (indicator or brake), 3) response accuracy, 4 number of glances at LCD screen, 5) message reading time, 6) duration of glances away from LCD screen				<u>RT data</u>: Age ($F(1,501)=10.66$, $p<.0001$) and Method of Display ($F(2,501)=23.25$, $p<.0001$) effects. Shortest RTs were for HUD: 1 (younger) to 1.2 (older) second mean RTs. Longest RTs Screen + Auditory = 1.6 secs for younger to 1.8 for older. [NOTE: Standard deviations highest with HUD.] * Age effect due to difference using screen (older 300 msec slower RT to screen only) <u>Accuracy data</u>: no significant differences <u>Visual strategies</u>: 1) Younger Ss: Duration of looks to LCD screen higher when coupled with auditory signal 2) Older Ss: Duration of looks higher with auditory signal BUT number of glances lower with audio signal (Also, glance more than young for screen + sound) <u>Driving time</u>: HUD produced small but significantly quicker times for younger Ss (Screen + Sound slowest). Same effect for subjects under 70 only. Elderly subjects take longer to finish for all screens.
Martin-Emerson and Wickens, 1993	Hypothesis: The extent to which the HUD symbology is conformal will determine the extent to which pilots will be able to divide their attention between the two images	6 subjects. Licensed private pilots 3 pilots trained and tested with conformal symbol configuration and 3 with traditional symbol configuration	Symbol configurations (between subjects): 1) Conformal: flight path guidance via symbolic runway and flight path symbol. 2) Traditional: localizer and glideslope (partially conformal) Display conditions (within subjects variable): superimposed HUD vs. dual display (includes head-up and head-down display for alphanumerics) Changes in visibility: cycled between minimum and maximum to force pilots to transition between instrument flight and visual flight rule. Dependent measures: Flight path deviation or RMS lateral and vertical error Protocol: 1) First session was practice; 2) Second session: 18 approaches (9 for dual display condition and 9 for HUD condition) RESULTS <u>RMS Vertical Error</u>: Small in HUD condition than in dual display condition for both symbol configurations. Also, conformal symbols produce smaller error for both display conditions. <u>RMS Lateral Tracking Error</u>: HUD advantage manifested for this measure as well. However, traditional symbol produce much smaller lateral tracking errors than conformal symbology. Attributed to the fact tha lateral alignment can only be achieved with small vertical error. <u>Effect of symbol configuration on attention</u>: As visibility changes, conformal symbology produced stable vertical RMSE. In contrast, vertical RMSE was high under low visibility conditions and decreased as visibility level was increased. Thus, conformal symbology fuses with far domain which obviates the necessity for attentional switching.				

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Martin-Emerson and Wickens, 1992	Establish the cost function of vertical separation between two displays in a dual-task paradigm. Namely, does the display of "head-up" information at small angles of separation result in any performance decrements relative to superimposed information	24 student observers, 12 in integration task and 12 in dual-task Used an incentive pay structure to reward performance	Primary task: compensatory tracking task within a window at the top of a Silicon Graphics color monitor Secondary task: small circle appearing in 1 of 12 positions below tracking symbols. Separations: 0 to 35.3 degrees head-down (3.2 degree separations). Subjects respond with either right or left response corresponding to the directional arrow displayed within the circle Task condition (between subjects): 1) Integration: respond to secondary task only when tracking cursor was within target symbol 2) Dual-task: respond to secondary task regardless of position of cursor for primary task. Workload: High and Low varied by changing the bandwidth of the cursor movement	RMS tracking error: recorded during the one-second presentation of the discrete stimulus for the secondary task and for one second immediately following stimulus offset Response time: for discrete task Response identity: correct, late correct (i.e., respond after 1 second), incorrect or omission. For the integration task, correct response when correct button pressed during the time that cursor was within the tracking target. Auditory feedback provided for correct responses.	Prior to each block: 2 minute practice period (primary tracking only) Four blocks of 12 trials (each trial represents a different display separation): 2 blocks = low workload, 2 blocks = high workload Within a trial: subjects respond to 12 1 second presentations of the discrete stimulus for the secondary task. Random interstimulus interval of 2 to 10 seconds. Workload was counterbalanced	<u>Significant effects for RT Data</u>: Task: Integration task takes longer than dual-task (F(1,22)=13.55, p<=.001). Workload: High workload longer than Low Workload (F(1,22)=7.52, p<.01) Position: Longer at greater separations (F(11,22)=10.98, p<.001) Task x Workload: RT constant across workload for dual-task whereas integration task produced increases in RT as workload increased (F(1,22)=7.87, p<.01). Task x Position: Cost of separation higher for integration task (F(11,22)=2.96, p<.04). <u>Effects for RMSE Data</u>: Workload: higher workload produced greater RMSE than low workload (F(1,22)=216.97, p<.001). Position: greater error as separation increased (F(11,12)=9.85, p<.001). Task x Position: F(11,12)=2.84, p<.04). <u>Response Identity Data</u>: No speed-accuracy tradeoffs via errors increased with separation for both tasks. <u>Three components identified</u>: Performance <6.4 degrees equivalent. Second component: equivalent from 9.6 to 22.5 degrees. Third: >22.5 degrees

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
McCann and Foyle, 1994 (NOTE: This paper provides a good review of research on cognitive effects.)	Replicate previous findings of altitude/path RMSE tradeoff in the presence of digital altitude on HUD and study the impact of "virtual" buildings as a possible solution	14 subjects	Four flight conditions: 1) No HUD control condition 2) Digital HUD 3) Scene-linked HUD: virtual buildings with an assigned height of 100 feet 4) Combined 2 and 3: Both graphic HUD and scene-linked HUD information provided to subjects simultaneously.	RMSE Altitude: the error, in feet, in tracking the altitude. RMSE Path: error, in feet, for staying on a path indicated in the display.	Subjects flew 12 flights in each of 4 conditions (total of 48 experimental flights plus some practice trials). RMSE Altitude: - Digital altitude improved altitude performance - Virtual buildings also reduced RMSE altitude by an amount equal to the graphic HUD. - Combined digital/virtual altitude HUDs produce slightly smaller RMSE than each alone. RMSE Path: - Graphic HUD produced decrement in path performance (higher RMSE) which replicates previous studies. - Small benefit in path performance with virtual buildings. Supports contention that scene-linked HUDs ameliorate the concurrent processing problems with standard HUD symbology Future: With GPS, virtual billboards can be displayed for surface operations (NOTE: Proposed for aircraft but would generalize to automobile applications as well). Also, visual augmentation of roadway features can be used during low visibility conditions and for path guidance as a navigational aid.	
McCann, Foyle and Johnston, 1993	Test two hypotheses: 1) HUD and world are separate perceptual groups; processing HUD excludes world from processing and vice versa 2) Determine whether transitioning from HUD to world requires attention shift.	20 under-graduates served as subjects. Each had normal or corrected-to-normal vision.	Low fidelity simulated approach to a runway at night. Viewing distance = 60 cm Color segregation: HUD in light blue, runway in light yellow. IFR vs. VFR: Ss monitored runway or HUD for one of these two cues. VFR cues Ss to take relevant information from runway and ignore HUD. IFR cues Ss to monitor HUD and ignore runway. Targets: diamond (indicating runway open) or stop sign (runway closed; require different responses from subjects). These appeared in 1 of 4 HUD boxes or 1 of 4 runway boxes (displayed in perspective) Attention switching manipulation: Intra-group trials (i.e., IFR displayed on HUD) will be compared to Inter-group trials (for example, VFR displayed on HUD). Congruency effects: if irrelevant information is excluded from processing, RT will be same regardless of whether irrelevant target requires same (congruent) or different (incongruent) response. If there is some processing of irrelevant information, congruency will decrease RT and incongruency will increase RT.		4 blocks of 144 trials each. Cue appeared in one of the HUD boxes for first 2 blocks and on the runway in final 2 blocks. Each block contains 36 replicates of target location (HUD vs. runway) and target vs. non-target relationship (congruent or noncongruent) All testing performed in sound-attenuated booth. Trial sequence: HUD and runway for 1.5 second, present cue, 250 msec delay, present geometric figure target	No upper limit on RTs so distributions had a large positive skew. Thus, all analyses based on median RTs Effect of trial type: Cue x Target Interaction: When relevant target was on HUD, Ss were 63 msec slower to respond when cue was on the runway. When relevant target was on runway, Ss were 148 msec slower to respond when cue was on HUD. ($F(1,19)=42.2$, $p<.001$). Also significant on error rates ($F(1,19)=9.0$, $p<.01$). Congruency effects: On intra-group trials, no congruency effect. On inter-group trials, congruent cases were 33 msec faster than incongruent cases.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
McCann, Lynch, Foyle and Johnston, 1993	Test attention-sharing vs. attention-switching models by manipulating the cues that lead to segregation of HUD ('near' domain) and runway ('far' domain).	48 students at San Jose State University. All were between ages 18 and 40 with normal or corrected to normal vision Half of subjects get IFR/VFR cue in lower HUD boxes. Remaining Ss, appears on runway.	Runway/world scene: horizon line with perspective runway HUD domain: pitch lines, four small boxes and an airplane symbol. Color cue: if present then HUD drawn in light blue and world in light yellow. If absent, HUD and world drawn in light yellow. Congruence effects: If irrelevant domain excluded from processing, than RT should not change when pseudotargets require same or different response. If irrelevant domain NOT excluded, RT should increase for pseudotargets requiring a different response and decrease for pseudotargets requiring the same response. Experimental stimuli: 1) IFR/VFR: abbreviations for instrument flight rule (IFR; i.e., respond to HUD targets) and visual flight rule (VFR; i.e., respond to runway targets). 2) Relevant domain Targets: stop sign (runway closed) or diamond (runway open) 3) Relevant domain Distractors: triangle and square 4) Irrelevant domain targets/distractors are identical but placed in irrelevant domain. Motion cues: runway simulated pitch and yaw buffeting on approach. If absent, runway was stationary on screen. Dependent cue: reaction time to targets and accuracy of response.		<u>Task</u>: subjects instructed to imagine that they are landing an airplane and that the response indicates intent to land or go-around based on stimuli imbedded in either the HUD or runway. 4 blocks of 144 trials each Each block contained 36 replicates for the combination of target domain and target-pseudotarget relation (i.e., congruent vs. non-congruent). Perceptual conditions were blocked according to four combinations of color cue and motion cue presence/absence.	No upper limit on RTs so distributions had a large positive skew. Thus, all analyses based on median RTs. No effects involving color or congruence were significant in an ANOVA. <u>HUD advantage</u>: $F(1,46) = 4.51$, $p<.05$) <u>Cue x Target interaction</u>: Cue on HUD, RT faster when target also on HUD. If cue on runway, faster responding to target on runway. $F(1,46) = 13.23$, $p<.001$. <u>Cue x Target x Motion</u>: With motion, cue x target interaction maintains. Without motion, magnitude of the interaction reduced. Namely, domain effects were attenuated when differential motion not available. Due to both a slowing on WITHIN (cue and target on HUD or runway) and faster on BETWEEN (cue and target in different domains). <u>Analysis of errors</u>: mirror of RT analyses <u>Congruency effects</u>: incongruent pseudotarget only had effect when displayed on HUD. <u>Asymmetries</u>: congruence effects higher for runway WITHIN trials. Also, no WITHIN advantage (i.e., slower on within trials) when no motion cue present and cue is on runway. <u>Conclusions</u>: Segregation benefits pilot when they have to monitor one domain at a time. However, if task requires monitoring both domains, segregation is detrimental. Also, asymmetries suggest HUD acts as an attentional "trap".

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Naish, 1964	Investigate the effects of position and form of HUD symbology (including contact analogue symbology) on the combination of information in superimposed fields, as shown by the performance of associated concurrent tasks.	<u>A. Influence of relative position of visual fields</u>: *Exp. 1A*: Combination of simple fields superimposed in different relative positions *Subjects:* 11 *HUD Conditions*: a) Fields in same location and same distance (240 in); b) same direction, different distances (25 in.); c) peripheral location, near distance (25 in.) *Concurrent simple tasks:* 1) Recognition of numbers: foveal; 5-25 fL; .67-.97 contrast; .6 to 1 sec random interstimulus intervals; 2 and 3.5 minarc) 2) Tracking task: 5 different speeds; tracking integrated over 50 seconds; locations varied as in a, b and c above *Exp 2A*: Combination of complex fields Subjects: 6 pilots with at least 50 hours of instrument flying experience Concurrent complex tasks: 1) Detection of low contrast light at irregular intervals and random positions within 30 degree field 2) Two-dimensional tracking task Dependent measures: 1) Detection task response time 2) Tracking task error in azimuth and elevation Display modes: U-mode = HUD; D-mode = HDIP. Order of U and D-modes was counterbalanced among subjects Test conditions (use task numbers and U/D as shown above): 1, 2U, 1+2U, 2D, 1+2D OR 1, 2D, 1+2D, 2U, 1+2U Exp 3A: Confirmation of combination in real flight 17 pilots used a reflective HUD on take-off and during an 'instrument' approach Subjective assessment by pilots Exp 4A: Flight simulator study Replicated field study findings. Pilots could monitor altitude indicators as well as forward view <u>B. Influence of form of presented information</u> Exp 5B: Combination of conformable fields - Ease of learning pictorial display Pictorial display = contact analogue (i.e., analogue of the forward view with which visual contact is supposed) Training times: 4.25 minutes training required for experiences pilots; 20 minutes training novice pilots Follow-up study: Two groups: Trained using simulator (11 pilots) and Untrained (7 pilots) Exp. 6B: Representation within common framework Three display types: D1 = experimental display with altitude, perspective cues, steering, horizon and other pictorial information; geographic reference D2 = Same as above except no perspective and orientation ambiguous; aircraft references used in cross-hairs D3 = steering demands only				Exp. 1A: No significant differences between a, b or c when compared on linear display speed (.47 in/sec to 4.78 in/sec). NOTE: b and c did produce "visual distress" Exp. 2A: No significant dual task decrements except for azimuth tracking D-mode. Detection task: RTs 1.23 seconds without concurrent tracking. With tracking U-mode RT is .88 vs. 3.86 D-mode. Also, more misses in D-mode Exp 5B: 10 to 1 reduction in training time for pictorial display vs. symbolic displays Follow-up: no significant differences trained vs. untrained in performing 4 tasks with HUD Exp 6B: Heading and height tracking errors were minimized with D1, then D2 next best followed by D3. This ordering corresponds to pilot preference rankings.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Okabayashi, Sakata, Fukano, Daidoji, Hashimoto and Ishikawa, 1989	Experiments conducted to verify the effectiveness of a HUD designed for automotive use.	Experiment 1: Optimum display position on the windshield - Ss 8 males (20 to 38 years) - Subjective rating scale: 5-point evaluation of obstruction/frustration and legibility. Optimal display location determined as the point where these two ratings intersect. - Horizontal positions: do not report actual horizontal locations in degrees. However, the two subjective rating scales intersect at "5.5X" at a low and high speed (speeds not reported). Experiment 2: Evaluation of display legibility for HUD and HDD - Ss 7 males (20 to 41 years) - HUD: .8 meter distance, 10 degrees left and 8 degrees down. Luminance: 8 cd/m^2 - Primary Task: Detect orientation of Landolt Rings (duration = .48 sec) in 4 positions displayed on a forward screen. - Secondary Task: Read two digit random numbers on either the HUD or HDD - Results: Report only error rates. HUD = 27.8 (s.d.=11.5) vs. HDD = 58.7 (s.d.=11.5). HUD advantage = 30.9. Statistically significant (no test statistics reported) Experiment 3: Evaluation of recognition time between HUD and HDD during actual driving. - Ss 4 males (21 to 38 years) - Recognition time: measured using an eye-mark-camera (EMC). Defined as the time that the subjects fixate the display - Verbal response: Ss read off the speed indicated on either the HUD or the HDD. - Driving conditions: Straight road at 40, 70 and 100 Km/h and Curved road at 40 (30-80 meter radius) and 70 Km/h (80 to 150 meter radius). - Results: HUD recognition times faster (80 to 180 msec difference HUD vs. HDD) under all driving conditions. However, HUD advantage larger on straight roads than curved. Attributed to shift of fixation away from HUD on curved roads. Also, HUD advantage increases as vehicle speed increases (attributed to shift of attention/fixation to forward line of sight) Experiment 4: Effect of legibility distance between driver's eyes and displayed images. - Use same dual-task setup as in experiment 2. - Screen distances: 4 meters or 12 meters. Virtual image distances: 1 m to abcut 11 m. - Error rates decreased 30% to about 5% as virtual image distance approached screen distance. Experiment 5: Optimum HUD and HDD brightness - No experimental detail provided. They present a curve for allowable range of HUD brightness as a function of forward scene brightness. The contrasts were not reported; however, from the figure presented it appears that luminance contrast ranged from 2.0 to 6.0. They also measured the effect of ambient illumination on HDD. At high ambient levels (>10^4 lux), the HDD must be from 10 to 100 cd/m^2 The remainder of this article deals with HUD design issues. The above results were taken into consideration in the design of the HUD NOTE: Weintraub and Ensing caution against the use of error rates as measured here via they limited viewing time of the Landolt ring which is not ecologically valid.]				

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Okabayashi, Sakata & Hatada, 1991	Investigate the interference resulting from superimposition of HUD images and objects in the forward view.	Subjects: 7 males (20 to 35 years). Visual Acuity 1.0 to 1.5 <u>Forward View Snellen E acuity targets</u>: 1) Orientation of E varied 2) Varied "boldness" (apparently a change in size of Snellen E) in Experiment 1 and contrast in Experiment 2 [NOTE: Inconsistent with later procedure writeup for Exp. 2] 3) Moving target: angular velocity varied from 0 to 1.8 degrees/sec. [NOTE: no information is provided about the waveform of target movement, amplitude or timing of the onset of the targets relative to HUD image. 4) Peripheral viewing: foveal and 15 degrees in the periphery. 5) Stimulus duration = .8 sec <u>HUD Parameters</u>: 1) Fill factor (F): percent of square segments turned in a matrix. Simulates complexity of HUD image. 0% = no segments on, 50% =half the segments on (worst case for complexity), 100% =all segments on. 2) Luminance contrast (R): 1.3 to 3.0 3) Viewing Distance (L): .7 m to 5 m [NOTE: Although unclear from the writeup, it is assumed that this refers to viewing distance of the HUD image only which is meant to simulate the distance to a HDD.] <u>CRR (Exp. 1)</u>: Correct response rate. The proportion of trials on which the orientation of the Snellen E acuity targets were correctly identified. <u>CRR (Exp. 2)</u>: Although the same name is used, the parameters in the calculation are different. How they are different is unclear.			<u>Experiment 1</u>: 1) Dark adapt (10 mins) and then 100 practice trials without HUD. 2) *Foveal* viewing of Snellen Es. 3) Obtain Snellen E size that yields CRR of 80%. 4) Obtain CRRs for changes in F, L, R and Snellen Velocity. <u>Experiment 2</u>: 1) Dark adapt (10 mins) and then 100 practice trials without HUD. 2) Fixate a character on center screen and view Snellen Es 15 degrees in the *periphery*. 3) Snellen E size that yields 80% CRR. 4) Obtain CRRS for changes in F, L, R and Snellen Velocity.	1) As fill factor (F) approaches ~50%, CRR decreases. The largest decrease in CRR (from 80% to ~10%) occurs when the HUD contrast is highest (R=3.0). 2) Viewing distance (L) had no effect. 3) Snellen Velocity had a beneficial effect of CRR. At the highest HUD contrast (R=3.0), CRR increased from about 15% at 0 deg/sec to an asymptote of 50% at 1 deg/sec.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

<table>
<tr><th rowspan="2">Author(s), Year</th><th rowspan="2">Objectives</th><th colspan="4">Methods</th><th rowspan="2">Results & Conclusions</th></tr>
<tr><th>Subjects</th><th>Independent Variables</th><th>Dependent Variables</th><th>Procedure</th></tr>
<tr><td>Rogers, Spiker and Cicinelli, 1986</td><td>Assess luminance and luminance contrast requirements for symbol legibility of self-luminous displays in aircraft cockpits</td><td colspan="5">Study 1: Luminance contrast effects in low ambient illumination
- 33 observers. Each was tested for far acuity and color vision
- Stimuli:
1) Landolt ring symbols viewed from 4.27 meters. Varied in size from 1.53 to 24.56 minutes of arc via a zoom control. Symbol luminances: 13.7, 14.1 and 82.2 (4, 12 and 24 fL)
2) Background: changed luminance to vary contrast ratio.
3) Contrast ratios: 2:1, 4:1 or 8:1
- Response: Using method of adjustment, subjects increased the size of the symbol until they could barely see the break (threshold) and to increase until clearly visible (comfort level).
- Results: Luminance contrast was the only statistically significant result for both threshold and comfort legibility. Post-hoc analyses reveal 2:1 significantly different from other contrasts.
Conclusions: No improvement for contrasts greater than 4:1

Study 2: Luminance contrast effects in moderate ambient illumination
Subjects: 10 observers. All tested for normal far acuity
All testing conducted in a moderately illuminated (108 lux) room. Illumination on CRT provided by two spotlights. Following conditions and stimuli were used:
1) Illumination at the screen: 29062, 53820 or 107639 lux
2) Display modes, stimuli and task: raster vs. stroke display modes used to display Landolt Cs. Threshold size obtained by changing viewing distance (threshold and comfort distances obtained)
3) Symbol contrast ratios (obtained by changing both symbol and background luminances): Raster = 1.2, 1.4 and 1.5 Stroke = 1.2, 1.5, 3 and 7.5
Results: 1) Effect of display mode: stroke mode produced much higher legibility at 1.2 ($t=6.012$, $df=18$, $p<.001$) and 1.5 ($t=5.255$, $df=18$, $p<.001$)
2) Effect of contrast on legibility: Raster-scan: no performance benefit for contrasts above 1.4. Random-scan: no performance benefit for contrast greater than 1.5

Study 3: Luminance contrast effects in high ambient illumination
Subjects: 10 observers. Normal or corrected-to-normal far acuity.
Task and Procedure: 1) View an adaptation field for 2.5 minutes 2) After cue from experimenter, turn to CRT with 13 minute of arc Landolt ring displayed 3) Measure the voice-activated RT
Adaptation stimulus: 400 Watt metal halide lamp transilluminating a piece of opal glass subtending 36 degrees. Adaptation luminances: 3.4, 34.3, 1083, 3426, 10834 and 34264 cd/m^2
Symbol variables: Contrast ratios: 1.4, 1.8, 2.2, 2.7, 3.2, 4, 10, 20. Display background luminances: 3.4 and 34.3 cd/m^2
Results: 1) Contrast ratio and adaptation luminance: All main effects (contrast, background luminance, adaptation luminance) and interactions significant. Only highest two adaptation luminances (10834 and 34264 cd/m^2) produced any RT delays. At the highest adaptation level and background luminance of 3.4 cd/m^2, RT ranged from 70 sec at 1.4 contrast to 30 sec at 3.2. For background luminance of 34.3 cd/m^2, the highest adaptation luminance produced RTs of 22 seconds at low contrast and about 4 seconds at the highest contrast.
2) Plotted RT as a function of log ratio of adaptation luminance to background luminance for the high (3.2) and low (1.4) contrasts: functions begin to rise at log ratios of 2 (i.e., x100 difference between adaptation and background luminance.</td></tr>
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Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Sakata, Okabayashi, Fukano, Hirose and Ozono, 1987 [NOTE: Some of the results from this study were reported later by Okabayashi, Sakata, Fukano, Daidoji, Hashimoto and Ishikawa, 1989. Please refer to this study where indicated]	Experiments conducted to verify the effectiveness of a HUD designed for automotive use.	Experiment 1: Different in legibility between HUDs and HDD [Refer to Exp. 2 of Okabayashi, et al., 1989] Experiment 2: Effect of image distance on HUD legibility [Refer to Exp. 4 of Okabayashi, et al., 1989] Experiment 3: Effect of display legibility on object recognition in the forward view. Subjects: 5 males (20 to 40 years) HUD: 2.5 meter viewing distance, 10 degrees left and 8 degrees below straight ahead. Display Brightness: HUD = 4 or 14 cd/m^2 HDD = 8 or 13 cd/m^2 Dual-task: Subjects were instructed to read off digits on either the HUD or HDD and then identify orientation of Landolt rings on a forward screen presented for .48 seconds Results: Error rates higher overall for HDD at both display brightnesses (difference HDD minus HUD 14.8 for darker displays and 16.8 for brighter display). Experiment 4: Comparison of display recognition time [Please refer to Exp. 3 of Okabayashi et al., 1989] Experiment 5: Effect of combiner tinting Subjects: 6 males (20 to 40 years) Task: Fixate at center of forward screen and indicate the direction of Landolt rings at 4 different positions. Independent variable: Combiner transmittance was 30%, 40% and 50% (no combiner used as baseline = 84% transmittance) Results: No significant difference between error rates for 40%, 50% and control (84% transmittance of windshield only). However, 30% combiner did increase error rates about 5% Experiment 6: Optimum HUD brightness considering brightness variation of forward view [Please refer to Exp. 5 of Okabayashi et al., 1989] Experiment 7: Sensory test by driving HUD installed vehicle Subjects: 7 males (22 to 40 years) Dependent measure: 5-point scale (where 1 = no effect, 5 = large effect) subjective evaluations to 4 questions: 1) Is the display distracting? 2) Does it seem overbearing? 3) Do you feel any uneasiness due to reduced forward visibility? 4) Are you troubled by display glittering? Task: Drove HUD-equipped vehicle along a predetermined course at three speeds (25, 70 and 100 Km/h) and three virtual image distances (1, 5 and 10 meters) Results: Mean ratings ranged from 2 to 3.5. No statistics reported. Uneasiness via lower visibility reduced at higher speeds (no reasons given)				
Sheehy and Gish, 1991	Assess the effects of collimation and proximal vergence on the accommodative state of observers.	2 subjects with normal or corrected to normal acuity.	<u>HUD</u>: A4 HUD used. HUD combiner: 40 cm from observer. 102.3 mm focal length. 1.5 ftL mean luminance. Varied the position of Air Force bar chart behind Petzval lens (field flattening lens) to change collimation. Subjects monitored bar chart passively (i.e., no responses were required of subjects to maintain high level of resolution). <u>Contrast Sensitivity</u>: Spatial frequency of 24.4 cyc/deg 6.57 ftL mean luminance) displayed on a CRT (circular grating subtended 3.25 degrees in diameter). Contrast was varied to obtain threshold contrast using a staircase procedure. The grating target was displayed through the HUD or viewed directly. <u>Response times</u>: The time taken to respond to a grating presentation was measured <u>Decollimation of HUD</u>: Inside of infinity (+.75 diopters), collimated (0 diopters) and beyond infinity (-.75 diopters). <u>Accommodation measurement</u>: Humphrey <u>Auto Refractor (Model 570)</u> used to monitor accommodation during the experiment. A "hot" mirror (transmits visible light, reflects infrared) was used to allow binocular viewing of targets.		7 thirty minute sessions required to complete the experiment. 1st session: accommodative range measured 2nd to 7th session: Experimental sessions	The HUD decollimation had no effect on the mean accommodative state of the subjects across block number or session. Also, there was no change in the variability of accommodation as a function of HUD decollimation. The results for displaying the contrast threshold grating through the HUD had no effect on any of the dependent measures. Conclusion: The 'coming in' sensation of pilots is not attributable to a shift in accommodation EVEN when the HUD is decollimated. Other explanations such as an attentional shift are implicated.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Sojourner and Antin, 1990	Compare effects of simulated HUD and conventional speedometer on various perceptual driving tasks in a simulated environment.	20 subjects participated. Each had a valid driver's license and corrected far acuity of at least 20/40. Ages: 19 to 51.	Videotaped scene: Filmed on various roads in Durham, NC using VHS videocassette. Digital speedometer: computer graphics image overlayed onto driving scene. Display screen: 1.8 m diagonal projection TV. Average screen luminance: 9 cd/m^2 Display configurations (between subjects variable): HUD or dashboard speedometer (viewing distance of HDD = 50-70 cm). Road type: two-lane rural, four-lane highway and four-lane city. Salient cue location: 570 arcmin left/right of center.	Tasks and dependent measures: 1) Speed-monitoring: verbal report whenever speed exceeded posted speed limit by at least 5 mph. Measure: percent correct 2) Navigation task: Subjects memorize schematic of a route and remember appropriate turns. When a wrong turn is made in the video (3 deviations filmed), Ss report this to experimenter. Errors: false alarms (i.e., say wrong turn when was a correct turn) and misses. 3) Salient cue detection: detect a child's green ball that appeared in roadway. Record RT from stimulus onset to button press.	Three sessions: 1) Task familiarization: each task performed on a 5 minute test route. Ss practiced to adequate performance levels 2) Route memorization: verbal instructions and the map depicting the correct route. Also, watch videotape of correct route. Session complete when Ss could indicate the correct route orally. 3) Test session: viewed the test route while performing the three tasks. Session lasted about 24 minutes. Post-experiment questionnaire regarding the study and the desirability of HUDs.	Salient cue detection: HUD users missed 3 out of 90 possible cues. HDD users missed 9 of 90 cues (not significantly different). RT effects: 1) Display configuration effect: HUD mean RT was 570 msec and HDD mean RT was 1010 msec (440 msec difference). 2) Cue location effect: salient cue location had an effect on RT. Order from lowest RT to highest RT: center (.61 sec), right (.83 sec) and left (.93 sec). Speed violations: Ss in HUD condition detected 100% of speed violations. HDD Ss missed 7 of 90. Questionnaire: Ss were indifferent about utility of HUDs (half reported it helped in speed monitoring; most reported HUD ineffective as a navigation aid or as an aid in salient cue detection). Would prefer peripheral location.
Ward, Stapleton and Parkes, 1994	Evaluate the effectiveness of a prototype near infra-red vision enhancement system using a contact analogue HUD presentation.	Five subjects (3 male, 2 female) with median age of 26	HUD: Contact analogue images produced via output from a near infra-red camera. Scene illuminated with an infra-red source. 5 meter virtual image distance. 13 degree field of view. Driving route: 1 Km rural road with a bend midway along course. Pedestrian silhouettes: 1.7 m high cutout placed along the course at unpredictable locations. Workload assessment: the NASA TLX-R used to assess workloads before 1st run and after runs 5, 10, 15, 17 (system failure run) and 20.	Mean speed on course: computed mean speeds along the course for runs 1, 10 and 20. Speed variability: standard deviation units along the course (3 zones: straight portion of course and 2 areas where there is a bend in the road). NASA TLX-R: Mean composite workload rating scores.	1st session: 1 hour familiarization which included description of how to operate the VES unit and a test drive at night with VES. 2nd and 3rd session: 1 hour sessions. Four practice trials followed by field trials with or without VES (order was counter-balanced among subjects). Field trial runs: 20 runs (10 each direction) along course. 4 of the runs had pedestrian targets. Run 17 spontaneous system failure.	Speed: VES operation yielded significantly slower speeds across runs. However, mean speed increased as the number of runs increased. Speed variability: Significantly higher speed variability when using VES within the curved section of the route. Mental Workload: VES operation produced significantly higher workload across runs. Sources of the higher workload: "mental effort" and "mental demand" Pedestrian detection: No significant effects. However, it should be noted that the conspicuity of the target was roughly equal under normal and IR lighting. System failure: Simulated failure did not produce any significant increases in workload or speed.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods: Subjects	Methods: Independent Variables	Methods: Dependent Variables	Methods: Procedure	Results & Conclusions
Weihrauch, Meloeny and Goesch, 1989	Human factors issues addressed in the development of an automotive HUD.	All studies done using a driver-in-the-loop simulation as well as on-the-road tests Maximum acceptable vertical binocular disparity: Disparities of up to 25 milliradians acceptable. Diplopia started to occur at 17 mrads. Design goal: 5 mrad. Display location: variable geometry HUD installed in test vehicle. Obtained driver subjective preferences for azimuth and elevation of HUD virtual image. Results: Directly below driver's line of sight (0 degrees horizontally and about 8 degrees down) with a virtual image distance of 2.4 meters. Performance measures: 1) Steering variability: HUD about 1.2 inch lower steering variability than HDD; 2) Obstacle detection: HUD about 90 msec faster obstacle detection RT. Display brightness: Previous research used to define contrast requirements as 1.2 (minimum) to 1.5 (design goal) Glare trap design: Contrast washout was prevented via the design of a louver-type glare trap. Problem: this type of trap puts horizontal lines on the HUD image. Optimum louver width 9 mm				
Weintraub, Haines & Randle, 1984	Assess the advantage of HUDs vs. HDDs in terms of virtual image distance and location.	18 Male Ss (7 of these were pilots), 19 to 28 yrs	HUD Parameters: 1) Display symbology luminance: 87 cd/m² or 2.8 cd/m² 2) Display contrast ratio: Head-up = 2:1; Head-down (10 deg) = 12:1. 3) Location: Straight ahead or 10 deg down. 4) Display optical distance: 0, 1.33 or 4 diopters.	Response times: 1) Decision times: time to decide if altitude or airspeed are out of limits and whether runway is open or closed. 2) Eye tracker: track eye movements and changes in accommodation.	Blocks of trials (6 practice trials and 72 main trials per block): 1) Blocks 1 to 3: Eyetracker + RT data 2) Blocks 4 to 13: RT data only 3) Block 14: Replicate eye tracker block at 4 diopters, straight ahead and low luminance. Trial procedure: 1) Simulated Boeing 727 instrument-landing approach to Monterey, CA airport: 1) Initial airspeed 130 knots, altitude 220 ft. against gray background (simulating overcast atmospheric conditions). 2) Blink display so Ss know that a trial is starting (change in airspeed and altitude). 3) Display runway scene. 4) Check airspeed (within 5 knots of 130) and altitude (with 5 feet of 200) and respond if out of limits (airspeed/altitude RT). 5) If out of bounds, next trial initiated (4 sec delay). Otherwise, runway appeared as either open (diamond) or closed (X). Respond with keypress after accommodating to runway (runway decision RT).	Fig. 2: RT vs. HUD distance for runway decision. - No difference runway open vs. closed decision times. - Large difference between eyetracker and no eyetracker trials. Attributed to practice effect via last block (eyetracker replication) lower than no eyetracker data. - Increase in RT for nearer HUD distances. Fig. 3: RT vs. HUD distance for low/high luminance (all decisions) - Luminance effect significant for runway decisions only. - RT increases for nearer HUD distances. - No effect of display location (planned comparison showed significant HUD advantage of 86 ms between 0 diopter/head up and 1.33 diopter/head-down). - Lack of display location effect via confounded with symbology contrast (2:1 head up vs. 12:1 10 deg down). Fig. 4: Accommodative change vs. time - Subjects complete .74 of the total accommodative change when they respond.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Weintraub, Haines & Randle, 1985	Same as 1984 study by same authors	8 Male Ss, 19-27 yrs, 5 were pilots	HUD parameters: 1) Display optical distance: 0, 1.33, 2.67 & 4 diopters. 2) Symbology: 2.6 cd/m^2 3) Runway scene 1.0 cd/m^2 4) Background for 10 deg down was black. Dependent Measures: Decision times and eyetracker data Experimental Protocol: Blocks of trials (6 practice and 54 main trials): 1) First 4 blocks with eyetracker 2) Next 8 blocks without eyetracker 3) Final block at 4 diopter with eyetracker. Trial procedure: Same as 1984 study except that runway decision first THEN airspeed/altitude decision.			Fig. 2: RTs vs. HUD distance, decision type and eyetracker/no eyetracker trials. - Small increases in RT for near HUD distances (all decision types except runway closed decision). - Difference between eyetracker/no eyetracker trials (all decision types except runway closed). Likely a practice effect. Fig. 3: RTs vs. HUD distance, HUD location and decision type - Nearer HUD distances produced longer RTs for all decisions except runway closed decision. - HUD location had no systematic effect - Although not statistically significant, HUD advantage (0 D/HUD vs. 1.3 D/HDD) was 80 to 90 ms. Fig. 4: Accommodative change as a function of time. - Ss decide long before accommodation stabilized. [NOTE: No mention of pupil size or estimates of depth of focus.] - Some evidence to support the "cognitive clutter hypothesis": runway closed RTs increase as HUD optical distance gets closer to runway (0 diopter) distance. - Unexpected event on last trial (jetliner protruding onto runway) went unnoticed by all but two Ss.

Summary table of research findings for those studies investigating automotive HUD applications (continued).

Author(s), Year	Objectives	Methods				Results & Conclusions
		Subjects	Independent Variables	Dependent Variables	Procedure	
Wickens, Martin-Emerson and Larish, 1993	Replicated all of the conditions and manipulations of Larish and Wickens (1991) study BUT using a higher fidelity display system with a wider field of view and a smaller separation between simulated HUD and HDD.	10 instrument-rated subjects were assigned to either a HUD of HDD condition.	Display: Evans and Sutherland SPX500 graphics display generator. Viewing distance 4 m. Images: simulated airport, runway and surrounding terrain. Instruments: IRIS graphics system used to generate. Projected to superimpose on the runway or 8.5 degrees of visual angle down from the runway. Shear warning and digital warning (expected instrument event) used on some trials. Unexpected event: airplane taxiing onto runway.	Vertical tracking error Lateral tracking error Airspeed error	1st session: 14 practice trials 2nd session: 5 practice trials and 14 experimental trials Trials: Alternate low/high turbulence. Anomalies occurred on trial 11. Runway incursion on trial 14. Trial sequence: 1) Trials begin at 2000 feet 2) First break-out of clouds at 1260 feet 3) Determine if signal on left of runway was yellow or red and respond accordingly. 4) Detect digital warning (0 or 1) appearing 3 times within a trial. Task: Monitor speed and maintain close to 90 knots.	Only high workload conditions discussed. HUD advantage for lateral ($F(1,18)=12.83$; $p<.002$) and vertical tracking ($F(1,18)=3.91$, $p=.06$). HUD supported more rapid detection of the expected instrument events ($F(1,14)=11.0$; $p<.001$). No differences in response to environmental events. No effect of display location on responses to unexpected events. This did not replicate previous study. (NOTE: This may be attributed to high subject variability as the authors point out. However, it is the HDD RT which shows the largest change. Since the Larish and Wickens study used a lower HDD (24.7 degrees down), the lack of replication may not be as surprising).

Appendix B: Current and Proposed Automotive HUD Designs

A typical optical design of a HUD consists of the following main components: 1) a display screen on which symbology is presented (either stroke or raster displays), 2) a relay lens placed close to the display, 3) a folding mirror (folds the optical path 90 degrees or more), 4) a large diameter exit lens and 5) a combiner to both reflect HUD imagery into the observers eye and allow see-through capability of external scenes. The summary table in this appendix describes the design specifications for prototype automotive HUDs in those instances where detail is available. Unique features of some other HUDs are described in more detail below. It is important to note that the Japanese HUDs were typically designed for automobiles with right-sided steering wheel, and display locations should be evaluated with this in mind.

- DataVision HUD (GM Hughes): This HUD is commercially available and is unique because it uses a CGA video format (input is either CGA or RS-170 video). This is ideal for experimental purposes since it allows flexibility in the design of the instrument display. The use of video sources, as opposed to fixed icons, is desirable for actual automotive applications as well.

One disadvantage of this system is the use of raster display technology. For the same CRT, it is possible to obtain higher contrasts with stroke compared to raster symbology (Weintraub and Ensing, 1992). In any event, DataVision can produce contrasts of 1.3:1 at 5000 ftL ambient illumination (i.e., display luminance of 1500 ftL, or 3426 cd/m^2).

- AutoVision HUD: This is a *monocular* system that accepts standard video signals. As with the DataVision HUD, it uses a combiner mounted on the windshield and the projector is located on the car's roof. The virtual image distance is 15 feet. Because of the small size of the combiner, the HUD imagery can only be viewing with one eye at a time. This has the potential for introducing binocular rivalry since the eyes are receiving different images. In any event, this HUD is being marketed primarily for entertainment purposes.

- Yazaki HUD: Two versions of the Yazaki Corporation HUD are described in two separate studies. The 1988 Yazaki HUD uses a 10 W light source behind a LCD display which is then collimated with a lens (Iino, Otsuka and Suzuki, 1988). The windshield is used as a combiner which maximizes luminous transmittance. To correct for distortions due to the curvature of the windshield, a specially designed binocular parallax correcting prism in placed over the collimating lens. Symbol contrasts were not reported.

In the 1992 Yazaki HUD (Sugita and Suzuki, 1992), the biggest change is the use of a holographic optical element (HOE) that maximizes the brightness of the VFD used in the HUD. VFDs are susceptible to brightness loss as they are exposed to higher heat. Thus, the HOE was designed to reflect visible light (peak reflectance wavelength roughly matches the peak wavelength of the VFD emission spectrum) and transmit infrared light. The HOE also has some optical power (focal length of 300 mm) to reduce the optical path within the HUD which in turn saves space. One disadvantage of the HOE used is that it was produced using dichromated gelatin (DCG). Although DCG produces good optical quality holograms (i.e., minimal haze and ghosting), it is well-established that they are susceptible to moisture. Although the holograms are typically sealed around the edges, the seals can rapidly deteriorate with exposure to environmental extremes thus exposing the hologram to moisture in the air. It might be preferable to use the relatively new dry-process photopolymers developed since they are much less susceptible to moisture.

- Instrument Head Level Infinity Display (IHLID): This is essentially a head-up display that appears at the top of the instrument panel (Swift and Freeman, 1986). The virtual image does not overlap external scenes because the authors are not convinced that this would have any advantage for drivers. However, because the IHLID is located higher than conventional displays and because the virtual image distance is closer to external scenes, Swift and Freeman believe IHLID optimizes the potential benefit of HUDs for drivers without any negative effects of visual clutter, cognitive capture and contrast interference. Another advantage is the relatively large horizontal FOV due to the use of multiple HUDs placed side by side. IHLID was proposed as a possible optimized HUD design for further consideration by engineers.

- Reflective vs. Refractive Optics and the Design Eye Box: Refractive HUDs have been in use in military aircraft since the 1940s. One of the shortcomings of refractive HUDs is that obtaining the full field of view through the refractive HUD requires precise positioning of the observer's pupil. With reflective optics, the exit pupil of the system is formed close to the pilot's eye and the instantaneous field of view is larger (Enderby & Wood, 1992). This creates a more convenient viewing situation since the eye box is larger and the observer does not have to carefully position their head to obtain the full field of view. Although many of the HUDs use reflective optics, few of the reports provide an eye box specification. The GM Hughes HUD uses folded-reflective optical design and has an eye box of 150 x 65 mm. Thus, once the HUD is aligned for a particular observer, the HUD imagery will not be seen if the observer's pupil moves more than 75 mm left or 75 mm right and 32.5 mm up or 32.5 mm down. However, this is a monocular eye box because it is calculated for movement of one eye's pupil only. For an interpupillary distance of 70 mm, the horizontal eye box for binocular viewing is about 80 mm (i.e., 40 mm left and right). Although this does not seem overly restrictive for an actual driving scenario, it does suggest that binocular viewing may be difficult to maintain especially if the HUD is not optimally aligned.

- Dedicated Space vs. Reconfigurable HUDs: Of the automotive HUDs listed above, most are fixed display, dedicated space HUDs. The DataVision HUD is a reconfigurable HUD since it accepts either CGA or NTSC inputs. Delco Electronics is also developing a version of their EyeCue HUD that will be reconfigurable. There are a number of potential advantages of reconfigurable HUDs including: (1) Flexibility of display elements: a user can adjust various features to best meet their needs such as location, focus, activation (i.e., on/off), display format (text vs. symbols, font, letter height), physical location on the dashboard, etc.; (2) Upgradability: with the emergence of new technologies a reconfigurable HUD is less likely to become obsolete (i.e., upgrading might involve a software change rather than a hardware change); (3) Transportability: the extent to which the HUD can be used with different vehicles; and (4) Multi-functionality: with the ability to input a number of video sources (such as computer graphics or standard NTSC) the HUD can be used for many different tasks. These potential HUD advantages can best be realized with reconfigurable HUDs.

Summary table of Automotive HUD Specifications

HUD Manufacturer and Type	Reference	Horizontal x Vertical Location	Focus Distance	Field-of-View	Brightness of Virtual Image	Maximum Source Brightness	Source/Display	Combiner Type and specifications.	Adjustments	Unique features and specifications	Display features and General Comments
GM Hughes Electronics DataVision reflective HUD (marketed for law enforcement)	Product literature	4.4 degs. up and 18.1 degs. right	8 to 12 feet (2.4 to 3.7 m)	4.9 degs high by 6.7 degs. wide	1500 fL (5139 cd/m²)	Not stated. Estimated to be 4286 fL (14684 cd/m²) based on reflectance of combiner.	1) Roof-mounted projection unit 2) Halogen Lamp and 234x382 pixel LCD matrix. CGA format 16 rows and 40 columns	1) Windshield-mounted semi-transparent plastic 2) Transmits 60% of forward scene 3) Reflects 35% of source	1) Optical axis location 2) Focus distance 3) Manual brightness control	Input RS-170 video (NTSC) via electronics unit. Accepts serial data input up to 19.2K BPS	ASCII upper- and lower-case character set, special characters, analog symbology and icons
General Motors folded-reflective HUD (installed in a 1988 Oldsmobile Cutlass Supreme	Weihrauch, Meloeny and Goesch, 1989	0 degs. horiz. x 2 to 6 degs. down (adjustable)	2.4 meters	3 x 1.5 degs.	500 fL (1713 cd/m²) max. (adjustable down to 1 fL with day/night switch and dimming potentiometer)	3000 fL (10278 cd/m²)	Vacuum Fluorescent Display (VFD). Fixed icons and letters.	Reflected off of standard production windshield. Distortions corrected internally. Reflectance: 25%	1) Two brightness ranges (day/night) selected via headlight switch. 2) Manual control of VFD brightness. 3) Vertical adjustment	Glare reduction louver. Distortion compensating prism. Eye box: 150 x 65 mm	Displays digital speed, turn signal arrows, check gauge indicator, fuel, high beam.
Nissan reflective HUD (installed in a 1988 Nissan Silvia)	Okabayashi, Sakata, Fukano, Daidoji, Hashimoto and Ishikawa, 1989	7 degrees down and 11 degrees right (fixed)	1.1 meters	.9 degs. vertical by 1.9 degs. horizontal	2000 cd/m² down to 2.2 cd/m²	8000 cd/m²	VFD with fixed display elements	Windshield coated with a dielectric thin-film to increase reflectance (26%) of VFD light.	1) Day/night mode via headlight 2) Manual brightness 3) Enhancement mode (contrast gain)	1) Glare reduction via curved aperture cover. 2) Nonspherical mirror used to focus.	Digital speed only Optical path folded to minimize space requirements
Toyota reflective HUD (installed in 1991 Toyota Crown)	Kato, Ito, Shima, Imaizumi and Shibata, 1992	8.4 degs left and 6.7 degs down	2 m (optical path of 800 mm)	Character height: .9 deg Width: 1.4 degrees	3000 cd/m²	30000 cd/m²	Halogen lamp with a LCD matrix display. To reduce heat through LCD, concave dielectric mirror designed that reflects only visible radiation.	Windshield	1) Day/night mode 2) Manual dimming 3) Automatic dimming system via an illumination sensor on dashboard 4) Motorized control of optical axis (+- 5 degs elevation).	Use a holographic lens to perform focussing (concave mirror), minimize glare from the sun and selectively reflect two colors green (speed) and amber (warning)	Digital speed and a master warning light (alerts driver to vehicle problems).
Yazaki refractive HUD (1988)	Iino, Otsuka and Suzuki, 1988	Tested 0 to 20 degs. left and 2 to 20 degs down.	Infinity	Not stated. However, dot dimensions are .15 mm x .31 mm	4000 cd/m²	40000 cd/m²	10 Watt incandescent lamp with 84 x 16 pixel LCD panel	Windshield used as combiner without any coatings.	Motorized control of optical axis	1) Distortion correcting prism corrects binocular parallax 2) Small size	Because the display is a matrix of pixels, many types of information can be displayed
Yazaki reflective HUD (1992)	Sugita and Suzuki, 1992	10 degs left and 5 degs. down	2 m	1 x 3 degs	1200 to 6 cd/m²	8000 cd/m²	VFD with fixed display elements	Windshield used as combiner.	Brightness adjustment via changing duty cycle	Dichromated Gelatin hologram used to maximize brightness of VFD by reflecting only visible light (see text above).	Digital speed only