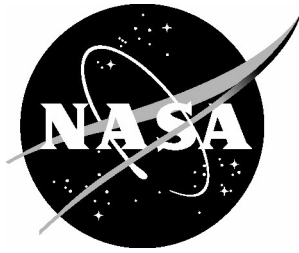


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Head-Up Displays and Attention Capture

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February 2004

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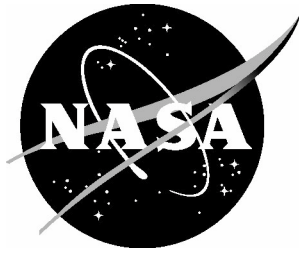
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Table of Contents

Table of Contents	iii
Abstract	v
Introduction	1
Characteristics/Purpose.....	1
Background and History	1
Current Commercial HUD Technology	2
Attention Capture and Head-Up Displays	5
General Head-Up Display Issues	5
Attention Theories	6
Attention Modes	6
Top-Down/Bottom-Up Processing	6
Spaced- and Object-Based Theories	6
Far- and Near-Domain Perceptual Processing	7
Reasons for Attention Capture	8
The Problem of Switching and Attention Capture	8
Symbology Format and Attention Capture	9
Symbology Conformality	9
Symbology Clutter	12
HUD Field-Of-View and Attention Capture	13
Expectancy and Attention Capture	13
Phase-Of-Flight	13
Contrast Ratio	13
Eye Accommodation and Attention Capture	15
Redundancy	16
Perceptual Load	16
Solutions to Attention Capture	16
Superimposed and Scene-Linked Symbology	16
Peripheral Symbology	17
Prevention Technologies	18
Synthetic Vision	19
Training and Practice	21
Conclusions	22
References	23

Abstract

The primary role of head-up displays (HUDs) is to provide primary flight, navigation, and guidance information to the pilot in a forward field-of-view on a head-up transparent screen. Therefore, this theoretically allows for optimal control of an aircraft through the simultaneous scanning of both instrument data and the out-the-window scene. However, despite significant aviation safety benefits afforded by HUDs, a number of accidents have shown that their use does not come without costs. The human factors community has identified significant issues related to the pilot distribution of near and far domain attentional resources because of the “compellingness” of symbology elements on the HUD; a concern termed, “attention” or “cognitive capture.” The paper describes the phenomena of attention capture and presents a selected survey of the literature on the etiology and potential prescriptions.

Introduction

Characteristics/Purpose

The primary role of head-up displays (HUDs) is to provide primary flight, navigation, and guidance information to the pilot in a forward field-of-view on a head-up transparent screen. Therefore, this theoretically allows for optimal control of an aircraft through the simultaneous scanning of both instruments and the environment. During visual meteorological conditions (VMC), the pilot can use the environment (e.g., the horizon) in addition to the instruments (e.g., artificial horizon line) to maintain appropriate control of the aircraft. However, during instrument meteorological conditions (IMC), the pilot must rely solely on instrumentation until visually acquiring the runway. The capability to stay “head-up” despite IMC conditions provides the significant advantage of HUDs. This advantage allows for reduced pilot workload, increased flight precision, direct visualization of trajectory, and increased flight safety (Newman, 1995).

HUDs have been undergoing continuous refinement for decades and are primarily used in military applications. However, commercial aircraft are now becoming retrofitted with HUDs and the general aviation (GA) community is also evaluating them. The most obvious advantage of HUDs is that they allow the pilot to view the primary flight instrumentation while simultaneously being able to scan the horizon for other aircraft, obstacles, weather, terrain, and runways. The superimposition of HUD information allows the pilot to maintain awareness of the instruments (near domain) and outside the cockpit (far domain) in the forward field-of-view. This display format is often compared to and contrasted with the alternative head-down displays (HDD) located on the instrument control panel (e.g., primary flight display; PFD) inside the cockpit. The type of HUD and its characteristics play a role in interpreting the displayed information and determining pilot performance. These HUD types include raster, stroke, collimated, and holographic HUDs among others. Alternative types of HUD formats that have been investigated include pathway/tunnel/highway-in-the-sky (HITS) displays, enhanced vision systems (EVS), and synthetic vision systems (SVS).

Background and History

The first “HUDs” were developed using reflecting gunsights in World War II fighters. The aiming symbol was generated from a light source and projected onto a semi-transparent screen mirror mounted between the pilot and the windshield. The projector was located in the top of the instrument panel. As a result, the aiming symbol appeared to float in the pilots’ forward field-of-view. Eventually, by the late 1950’s these reflecting gunsight images were generated by a cathode ray tube (CRT) controlled by a computer. The early HUDs provided several advantages over existing immovable gun sights: (a) the aiming symbol was dynamic and could account for range, drop rate, acceleration, and closure rate on target, (b) the ability to train the aiming cue in the same plane as the target minimized pilot accommodation, eliminating parallax errors, and (c) brightness control could reflect changes in ambient lighting condition thereby reducing perceptual errors and eye strain and fatigue (Newman, 1995).

In the early 1960’s HUDs began displaying flight information and were now considered useful for approach and landings. The British Royal Aircraft Establishment (RAE) began development of a HUD with a horizon line and aircraft reference symbol. At the time, the idea of a HUD was a means to improve airmanship in combat and there was interest to consolidate the large number of instruments into one display. These displays, however, were still primarily used for gunsights and bombsights. It was not until the mid-1960’s that the first contact analog HUD was developed by Klopstein that included a synthetic runway outline, which was the contact analog of the real runway (i.e., “Klopstein’s Runway”). In the 1970’s, USAF Tactical Air Command requested that the Air Force Instrument Flight Center (AFIFC) assist with researching HUD design and marked the beginnings of research to develop HUDs for primary instrumentation. All of this early work led to the discovery that HUD design was not simply

moving head-down information head-up; Instead, there were significant human factors issues that were unique to head-up displays.

Early HUD research found that, although it was a useful flight reference, there were significant human factors issues, such as decreased failure detection, increased spatial disorientation, and lack of standardization that prevented the HUD from becoming a primary flight reference (Barnette, 1976). It wasn't until the A-7E and F-18 that the military began certifying HUDs as a primary flight reference. Early HUDs, unfortunately, did not attempt conformality, probably due to the sensors technology at that time. Walters (1968) reported, for example, that conformal HUDs did not result in superior performance. As a consequence, Hall, Stephens, and Penwill (1989) noted that this was the primary rationale why early HUDs (e.g., AV-8A, AV-8B) used a 5:1 pitch ladder scaling format and that even modern HUDs are partially conformal displays that compress the pitch ladder at extreme attitudes. An example of this is the Fast-Jet RAE symbology that varies from 1:1 to 4.4:1 dependent upon whether the aircraft's nose is at the horizon or ends (i.e., nadir or zenith) of the pitch ladder range. Naish (1979) and others have reported that such a compressed pitch ladder increases pilot situational awareness (SA).

The concerns about conformality of the HUD were not the only issues discovered during the early development of HUD technology. The AFIFC found evidence for inadequate symbol dynamics, lack of standardization with symbology and operational use, inadequate field-of-view (FOV), intensity/contrast problems, night visibility issues, and an increase in HUD-induced spatial disorientation (Newman, 1980; 1995). As Newman (1995) notes, "recent accident histories of modern tactical aircraft indicate that spatial disorientation (SDO) is a major problem in military airplanes....Many factors are involved: aircraft-handling qualities, poor head-down instrument layouts, HUDs that are not designed for instrument flight, instrument procedures that do not recognize the effect of the velocity vector, and inadequate instrument training" (p. 15). Although HUDs are often blamed for these SDO accidents, quite often they are the result of multiple human factors shortcomings. Nevertheless, these early HUDs, because they did not reflect human-centered design, very often contributed significantly to these types of accidents. Because of the awareness of these issues, considerable effort was directed during the 1980s at HUD standardization as a prescription to these accidents.

Lovering and Andes (1984) and Newman and Foxworth (1984) reported on the beginnings of the HUD specification development. Newman (1987) produced a USAF three-volume guidebook that drew on these earlier specification efforts: Vol. I -- "Head-Up Display Design Guide"; Vol. II -- "Evaluation of Head-Up Displays to Enhance Unusual Attitude Recovery; and Vol. III -- "Evaluation of Head-Up Display Safety". Other important electronic display guidelines include: MIL-D-81641, MIL-STD -1787, -884, FastJet, ARP-4053, TR-91-01, and TR-87-3055. Despite the wealth of design guidelines and specifications, Newman (1995) expressed a number of recurring problems with HUD specifications including: lack of dynamic requirements, lack of standardization of symbology, hidden specifications, and "gold-plated specifications". Essentially, there is a significant lack of standardization from one HUD to another. However, if a specification is documented or accepted as fact (i.e., "hidden"), regardless of evidence supporting merit, the specification becomes rigid. Finally, there is often a technology-centered approach taken in HUD design to attempt to make HUDs perform every function. The momentum of these gold-plated specifications can often make it difficult for human factors to bulwark for human-centered HUD design, which can lead to a host of human factors problems with HUDs including attention capture.

Current Commercial HUD Technology

Despite the early road bumps in developing military HUDs, commercial HUD technology has benefited significantly from these efforts. The commercial aircraft HUD was developed in the early 1970s when the Sextant Avionique, for the Dassault Mercure aircraft, and the Sundstrand and Douglas Aircraft Companies, for the MD80, developed the first commercial aircraft HUDs. Flight Dynamics followed these with a holographic optical system, with a wide field-of-view, which provided precision flight path guidance. Alaska Airlines subsequently adopted the HUD technology for use in Cat IIIa (700

feet RVR) operations on the B727-class aircraft fleet. Since then, commercial aircraft have logged over 6,000,000 flight hours and 30,000 low-visibility operations using HUDs (Wood & Howells, 2001). Flight Safety Foundation recognized a 33% reduction in airline accident potential and an estimated \$60,000 saving per year / aircraft that can be realized by HUD technology (Rockwell Collins, 2000).

Head-Up Display technology has increased dramatically since initial military and commercial introduction. A number of commercial HUDs are in use today including the B737, A-320 HUD, FDI 1000 HUD, FV-2000 HUD, and the MD-80 HUD. Despite the impressive number of different HUDs available, the commercial HUDs share several commonalities. Today, all commercially certified HUDs use reflective, as opposed to refractive, optical systems. These HUD systems are composed of a pilot display unit (PDU) and a HUD computer. The PDU is the interface between the aircraft structure and provides the optical image to the pilot whereas the computer provides the electronic interface with aircraft systems and sensors. The computer is responsible for generating characters and symbology, calculating and verifying data, formatting, and algorithm generation and performance. The PDU and computer work in concert to produce an image on a high-brightness cathode ray tube (CRT) that is reflected off a combiner / collimator at near optical infinity in the cockpit design eye position (defined in FAR 25.773 and 25.777). Together, it produces an optical image that is reflectively “collimated”, or superimposed on the outside visual world, and produces a scene that allows for optimal total, binocular overlapping, instantaneous, and monocular FOVs (cf., Wood & Howell, 2001).

Commercial HUDs are not just primary flight displays (PFD) presented “head-up”, but have different requirements for symbology presentation that change dependent upon the mode in which the HUD is flown (e.g., primary, IMC, approach). Additionally, commercial HUDs allow the pilot to “de-clutter” symbology from the HUD to reduce the amount of information (i.e., “clutter”) that may obscure the out-the-window scene. Because of concerns of clutter, not all symbology that is presented on a PFD is shown on the HUD. Figure 1 shows a HUD installed on the NASA B757-200 ARIES research aircraft. Figure 2 presents an example of typical HUD symbology that may include:

Pitch	Digital radio altitude	Advisories
Roll	Wind speed and heading	Inertial flight path information
Heading	Attitude	Flight path acceleration
Boresight symbology	Airspeeds	Flight Director (FD) Guidance
Barometric altitude	Autothrottle modes	FD arm and capture modes
Slip/Skid Indicators	Warnings	NAV source / data
Flare cues	Digital runway length	Stick shaker airspeed
TOGA Pitch Line	Rollout excessive deviation	V speeds
Bank Warning Indicator	Airspeed trend vector	Flap maneuver speed
Tail Strike Pitch Limit	Max/Min Allowable Speed	High speed buffet
Ref/ Manual speed	Windshear guidance cues	Speed bugs
Selected airspeed	GPWS, TCAS	Climb-out speed indicator
Altitude trend vector	Approach warning	DME
Localizer deviation	Glide-slope deviation	Vertical deviations



Figure 1. Rockwell Collins HGS-4000 HUD

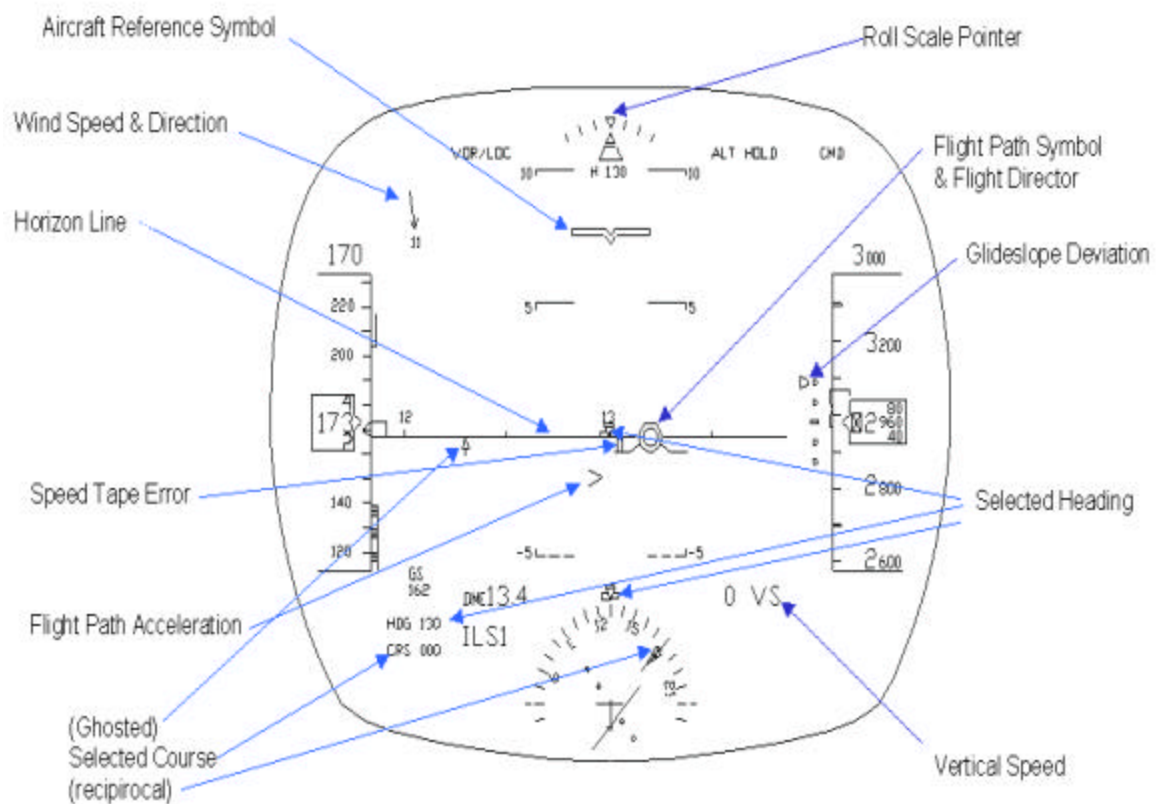


Figure 2. Typical HUD Symbology

Attention Capture and Head-Up Displays

General Head-Up Display Issues

SAE ARD50016 documents the collective input of the G10 subcommittee on current human factors HUD issues. The document stated that the scope was “primarily concerned with human factors issues relating to head-up displays in civil transport aircraft. It addresses issues associated with the interface provided by the head-up display with aircraft systems and the interface provided by the head-up display with the real-world, including the external visual scene” (p. 4). The purpose was “to provide a compilation of human factor issues regarding the impact of head-up displays on flight operations in the terminal area and flight navigation in the airspace system” (p. 4). The OPEN issues they identified include:

1. Lack of symbology across HUDs for transition from pitch reference to flight path reference
2. Differences in equipment capability require development of potential operational concepts, such as Hybrid HUD/ autoland, CAT II minima on ILS Type I, GPS with curved and angled approaches, and non-precision HUD approaches
3. Development of rules for mandatory go-around with HUDs
4. Issues regarding compressed vertical pitch scale
5. Issues regarding definition and phenomena of “clutter”
6. Limitation of scale linearity and conformity of symbology with real world
7. Location and format of roll scale -- attached to top of display or ground pointer and scale with flight path marker?
8. Use of analog airspeed information – necessary and issue of non-linearity of analog displays
9. Mode annunciations of selected airspeed information
10. Issue of analog altitude information when transitioning from one assigned altitude to another
11. Determination of when radar altitude should appear on the HUD during descent and whether it should be selectable for circling approaches
12. When the flight path marker is above the horizon, should an auxiliary heading scale be presented in compressed format
13. Issue of whether the flight path marker provides vertical speed information or does a digital VS scale need to be displayed
14. Concern about control law compatibility of HUD guidance systems and autoland / autoflight systems
15. Issues of HUD/ HDD symbology compatibility
16. Should takeoff lateral and rollout guidance be presented head-up?
17. Concerns about crew coordination, mode awareness, and pilot workload with HUD use
18. Issues of loss of situation awareness and attention capture with HUDs and Pathway-in-the-Sky HUDs

The list of issues, defined by the G-10 SAE committee, detail that a significant number of human factor concerns remain in the design and use of head-up displays. Many of these issues are inter-related. For example, Issue #8 and Issue #10 describe issues of analog altitude information and the effect of the presentation on pilot-HUD interaction. Similarly, Issues #5, 6, and 18 are related to the issues of symbology presentation and “compellingness” of HUD displays that can contribute to problems related to attention; most notably, attention, or cognitive, capture.

Attention Theories

Prior to a discussion of attention capture and HUDs, it is necessary to introduce the reader to the concept of attention. The construct of attention has been the subject of a substantial amount of research, all of which are not necessary for a review of attention capture issues. Therefore, the next section describes several concepts and theories that form the framework of the majority of attention capture research.

Attention Modes. There are a number of theories and models of attention. However, there are three “modes” of attention that are often discussed in the HUD literature: Selective, focused, and divided attention. Selective attention serially determines what relevant information in the environment needs to be processed. Pilots may use serial processing while completing a checklist during an in-flight emergency. Focused attention refers to the ability to process only the necessary information and filters out that which is unnecessary. A pilot making an approach using a HUD would often use this mode of attention. Finally, divided attention is the ability to concurrently process more than one attribute or element of the environment at a given time. Divided attention is an attention mode that is often used by pilots in which they must divide attention across aviate, navigate, and communicate responsibilities.

Because expert pilots do not tend to serially process information, focused and divided attention are perhaps the most important modes. However, sometimes these modes can also lend themselves to aviation accidents and incidents. For example, pilots that focus intently on landing the aircraft may not perceive other aircraft or vehicles on the runway, which can lead to a runway incursion. Focused attention has also been implicated in several accidents in which the flight crew focused all attention on a single problem, without sufficient crew resource management, and a separate problem caused the aircraft to crash (e.g., Eastern L-1011 crash, 1972). However, other accidents have resulted because the pilots divided their attention across too many tasks and there wasn’t sufficient delegation of duties (e.g., United DC-8 crash, 1978).

Top-Down / Bottom-Up Processing. Related to the three modes of attention, top-down and bottom-up processing can influence what is selected for processing in response to the information (Yantis, 1993). Top-down processes involve those that are driven from past experience and knowledge by cognitive mechanisms to form a mental model of the situation. Therefore, pilots often make decisions based on what they may have experienced before. Those experiences that have been seen repeatedly eventually evolve into “skill-based” or “automatic” processing, and the response is quick and automatic. Other situations may require the pilot to apply decision rules and “heuristics” or “rules-of-thumb” to solve a problem. These often take the form of “If-Then-Else” rules. Top-Down processing can also involve new encounters that the pilot may not have seen before and he or she has to apply “knowledge-based” reasoning to the problem; that is, use their experience to try different options to solve a problem. Most often, however, pilots use skill or rule-based processing while flying and may resort to these modes even when knowledge-based processing is required. For example, several accidents have occurred because the pilot applied a decision rule inappropriately (e.g., Air Florida, 1982).

Bottom-up processes, on the other hand, are those driven by the characteristics of the stimuli in the environment. Pilots sample information from the environment with a frequency proportional to the cost of not sampling. For example, pilots may not spend much time head-up under instrument flight rules (IFR) in Instrument Meteorological Conditions (IMC). However, during visual meteorological conditions (VMC), the pilot-not-flying (PNF) may spend considerable resources scanning for other traffic because of the “see-and-avoid” responsibility even while under air traffic control (ATC) surveillance.

Spaced- and Object-Based Theories. The processes of divided and focused attention have been examined with two theories of how visual attentional resources are allocated. In space-based theories, the negative impact of visual scanning and the negative impact of clutter are considered. Space-based theories model attention as a spotlight that supports concurrent processing of elements that are close to one another in space. The negative impact of visual scanning refers to the notion that two sources farther

apart will require more eye movements to process them both. The negative impact of clutter, on the other hand, suggests that sources in close spatial proximity will inhibit the ability to focus on one and not the other (Broadbent, 1982). Object-based theories of attention, in contrast, suggest that attention capture is not necessarily spatial proximity. The theories posit that concurrent processing is instead supported by attributes that reside within a single contoured object, independent of space proximity or envelope (Wickens & Long, 1995). It is currently thought that sources of information belonging to the same object facilitates divided attention but may inhibit focused attention (Wickens, 1997). However, there is considerable evidence to support both models of attentional theory for HUD design (Kramer & Jacobson, 1991).

Far- and Near-Domain Perceptual Processing. Within the context of piloting an aircraft, the far domain, near domain, and the aircraft domain are sources of information that require attention. These three domains represent task categories relevant to HUD use. The far domain consists of objects such as other aircraft that need to be detected and processed; near domain requires attentional processing of display information (either HUD or HDD); and the aircraft domain requires the allocation of attention for aircraft control and flight path maintenance. The psychological mechanisms of attention can be associated with each of the tasks. Sources of information in the near and far domain require focused attention, whereas flight path control requires the allocation of divided attention because it integrates information from the far and near domain while other sources of information must be extracted from scanning the HDDs (Wickens, 1997).

The uses of far and near domain and space- and object-based processing concepts are important considerations for a psychological understanding of the benefits and costs of HUD use. As Wickens and Long (1995) describe, tasks can involve the (1) focus of attention either on the far domain (e.g., traffic), or (2) near-domain (e.g., airspeed information), or (3) integration of related or redundant information between the two domains (e.g., a spatial symbology such as a runway outline represents an object in the far domain). So, the processing of HUD information can be divided into three states of attention required: It can be divided between concurrent processing of information in the two domains, can be focused on one domain while ignoring the other domain, or it can be switched from one domain to another as when the pilot must check approach guidance cues and visually acquire the runway in the far domain. Each of these states has implications for attention capture.

Reasons for Attention Capture

The discussion above noted several traditional theories of attention that form the theoretical basis for the etiology of attention capture. A HUD presents a potential advantage by reducing the time spent head down scanning the instrument panel and then having to transition back to a scan of the outside world. The experimental literature has documented the phenomenon of “change blindness” in which small changes in the visual environment are difficult to detect with small saccadic eye movements and short intervals when the visual scene is not present (Carlson-Radvansky & Irwin, 1995; Simons, 1996). This has been discussed as a possible reason why the HUD has an advantage in the detection of expected events (Fadden, Ververs, & Wickens, 1998) but can lead to poorer vigilance for undetected events, such as an aircraft on a runway. The reason may have to do with the difficulty in “cognitively switching” between the two sources of information when the pilot fails to parallel process and, because of the salience of the near domain symbology on the HUD, may become “captured” leading to an inability to adequately switch to the far domain. The problem is acute as described by Fisher, Haines, and Price (1980) who noted that, “several pilots admitted that from time to time they caught themselves totally fixating on the symbology, oblivious of anything else, and had to consciously force their attention to the outside scene.” Attention capture may stem from the inappropriate selection of attention to the HUD or the outside world.

Stuart, McNally, and Meehan (2001) discuss four non-exclusive hypotheses for why this may happen. First, although the HUD is collimated, the display is transparent and does appear to overlay the

external scene which is a difficult perceptual depth cue to overcome causing the pilot to direct attention to one of two planes in three-dimensional space. Next, humans often group like perceptual elements together to form a field (e.g., similar motion). The strength of the grouping can often make it difficult to switch between fields when one of two fields overlap in the same depth plane. Third, attention can become “bounded” when one of two or more objects are combined to form a single element from overlapping fields particularly when the symbology is conformal to the outside world. Finally, attention can be directed to specific scene elements or a specific location in the HUD (e.g., velocity vector or flight director) at the expense of other elements. The eyes become fixated on the symbology and, without the benefit of scanning, may reduce the effectiveness of the HUD to perceive peripheral information.

The Problem of Switching and Attention Capture

The problem of cognitive switching and HUDs has been known for some time. For example, Fisher (1979) published a NASA contractor report that examined the construct and showed that pilots had difficulty with detection when using these displays. The author and his colleagues published a NASA Technical Paper the next year (Fisher, Haines, & Price, 1980) describing the cognitive problems, including cognitive switching, involved in HUD use. These authors prefaced attentional tunneling and attention capture and reported that pilots, using a HUD, failed to notice a plane taxiing onto the runway before the aircraft was to land. The report led to a significant amount of research examining the construct. The general finding from the literature was that task-irrelevant symbology was disruptive to the task because of difficulty in cognitive and perceptual processing involved in switching between the near and far domain. However, although the phenomenon was being documented and shown through empirical research, few studies were able to provide the etiology for attention capture. The reason, as Weintraub and his colleagues have noted (Weintraub & Ensing, 1992; Weintraub, Haines, & Randle, 1984; 1985), was that many of the studies were not based on the controlled evaluation of how HUDs differ from head-down displays, such as location, optical distance, and symbology. Also, few studies had designed the experiments from a theoretical framework.

Wickens and Long (1995) represents research that accomplished both of the objectives necessary to understand attention capture. These researchers examined attention capture and HUDs within the attention theory framework of object versus space-based models of visual attention. The Wickens and Long (1995) experiment was unique because, although a number of experiments have validated the advantage of HUDs over head-down displays (e.g., Fisher et al., 1980; Lauber et al., 1982), few studies have been carefully controlled to eliminate instrument, collimation, and conformal differences between the two; this is important in evaluating space- and object-based theories of attention allocation. Some earlier work found that switching between the two domains was faster with a HUD (Weintraub et al., 1984; 1985) leading to better landing (Wickens, Martin-Emerson, & Larish, 1993) and taxi performance (Lasswell & Wickens, 1995). Despite these results, studies have also shown costs associated with clutter (discussed below) leading to cognitive tunneling and unexpected runway incursions (Fisher et al., 1980; Foyle, McCann, Sanford, & Schwirzke, 1993). Therefore, the Wickens and Long study was designed to examine conformal and non-conformal formats with head-down and head-up display conditions that had similar collimation. Thirty-two FAA-licensed pilots were asked to fly 36 instrument approaches (ceiling and visibility levels ranging from 104m / 1.61km to 15m / 0.20 km, respectively) in a high-fidelity simulator using either conformal or non-conformal symbology sets. Half the trials presented the symbology head-down and half the trials presented the symbology in a HUD fashion to the pilot participants. The researchers were especially concerned about the psychological construct of cognitive tunneling in which pilots fixate on the near domain at the exclusion of important far domain information (e.g., runway obstacles; traffic). Therefore, an unexpected far domain event was presented to subjects on the last trial (resembling that used in Fisher et al., 1980; Larish & Wickens, 1991; Lauber et al., 1982) in which a widebody jet taxied into takeoff position with the dependent variable being time to initiate go-

around after breaking out of the clouds. Table 1 presents the Wickens and Long (1995) effects of moving imagery from a head-down to head-up location.

Table 1. Effects of Moving Imagery From Head-Down to Head-Up Location

Spaced-Based Effects		Object-Based Effects
Nonconformal	Decreased Scan Divided Flightpath Tracking Switching Event Detection Airspeed Monitoring	Increase Clutter Divided Flightpath Tracking Switching Event Detection Focused Airspeed Monitoring Event Report
Conformal	Decrease Scan Divided Tracking	Increased Parallel Processing Divided Attention Flightpath Tracking

During the pre-breakout period, airspeed error and tracking RMSE were significantly better with the HUD compared to HDD and were also significantly better with the conformal symbology. Therefore, conformal HUD symbology resulted in the best performance prior to breakout from clouds and decision height. After breakout and with the far domain in view, no tracking differences were found for display location but there was, “a marked advantage for head-up presentation of conformal symbology appeared” (p.188). Airspeed error increased from 18 to 22 knots after break-out with the HUD, but was not statistically significant. However, these researchers also reported, “that the concern for HUD-induced cognitive tunneling may be real” (p.191) and found that the HUD produced significantly slower responses to the unexpected runway incursion. Average time from break-out to go-around initiation for runway incursion event was 5.5 to 6.7 seconds for the head-down location and 7.2 and 9.1 for the head-up location for conformal and nonconformal symbology, respectively. Therefore, there was an average increase in latency of between 0.5 to 3.6 seconds between HDD and HUD, dependent upon whether the symbology was conformal or nonconformal, with the nonconformal HUD significantly increasing reaction time to initiate go-around to avoid the taxiing aircraft.

Symbology Format and Attention Capture

One reason for attention capture may have to do with the format of the symbology that has a high degree of “salience” or “compellingness”, or an excessive amount of “clutter”. Research has been directed at determining features of symbology sets (e.g., conformal / nonconformal) and operational use of symbology in relationship to onset of attention capture. Issues identified include features of symbology, such as conformality, superimposition, and scene-linked symbology; formatting of symbology, such as clutter, contrast, and field-of-view; how pilots use HUD symbology during different phases-of-flight; and perceptual issues of accommodation and depth perception.

Symbology Conformality. Display conformality refers to a change in instrumentation consistent with a change in the pilot’s visual angle and symbology with the external environment. Full conformality indicates that the display elements (e.g., pitch ladder and heading tape) are consistent with the external environment. In other words, the distance between the horizon line and the 10-degree pitch bar are exactly 10 degrees of visual angle. Thus, elements of the display that reflect changes in aircraft attitude, moving at the same angular scaling as do environmental references, are conformal. Another conformal display technique typically reserved for approaches and landings is scene- linked displays (discussed

later), which use navigation data and ground references to overlay HUD symbology exactly on the runway.

Some have argued that it may be the conformal characteristics of the symbology, rather than the superimposition of symbology, that support divided attention and a performance advantage for HUDs (Weintraub & Ensing, 1992). As HUDs have evolved they have become less conformal with an increase in symbology density and the addition of alphanumeric information. Partial conformality or a compressed display refers to a display format that only has some characteristics of a 1:1 ratio of the symbology to the external environment. An example of this is to condense the distance between the markings on the pitch ladder and heading tape and provide symbology to alert the pilot of the non-conformality (e.g., chevrons that appear on the HGS-4000). The advantage to the partial conformal display is that more information can be placed on the HUD, and it has been demonstrated that there is no significant advantage to having a full conformal display during the cruise phase of flight. Therefore, the use of a partial conformal display can provide more information without a performance loss (Ververs & Wickens, 1998). Although there are reports showing increased flight technical error during landings with conformal HUDs (Fadden & Wickens, 1997), the general conclusion is that conformal format HUDs significantly improve approach and landing performance but make little difference during other phases of flight (Martin-Emerson & Wickens, 1997; Wickens & Long, 1995).

A number of studies have also been conducted on conformality and attention capture. Wickens and Long (1995), however, represents the literature on the effects of conformal symbology on attention capture. They reported a benefit found for HUDs for conformal, but not for nonconformal symbology with conformal symbology resulting in a 30% decrease in flightpath deviation. Overall, the HUD was also significantly better for tracking prior to breakout from the clouds compared to HDD, but also had significantly increased latency in responding to runway incursion event. The potential for runway incursions was particularly acute for the non-conformal HUD format. Although conformal symbology did significantly reduce the potential for missing the runway obstacle due to the object-based benefits of attention allocation by fusing the guidance symbology with the far domain runway, reaction times were slower than for HDD display conditions. Despite these findings, Wickens and Long (1995) stated that, “our judgment is that the overall HUD benefits to tasks that are performed frequently ..., considerably outweigh the costs of unexpected event detection. Yet designers must still be wary of the factors that lead to the occasional tunneling and clutter costs and seek remedies to eliminate these” (p. 191). These authors went on to state, “one remedy is to resist the temptation to place too much nonconformal imagery head-up, as the degradation in bottom-up quality of both near and far domain information will increase the vulnerability to negative top-down influences on the processing of unexpected events”. Another remedy they suggested was “...to seek ways to better distinguish near and far domain information when focused attention is required” (p.191). The NASA Synthetic Vision project, for example, is developing enhanced vision sensor technology for the HUD that will present feature-integrated, symbolic representations of potential runway incursions that will distinguish it from near domain information (Williams et al., 2001).

Because of inconsistencies across studies investigating conformality and HUDs, Fadden, Ververs, and Wickens (1998) performed a meta-analysis based on eighteen experiments gathered from journals, conference publications, and technical reports and “although there are many more studies which present research relevant to the use of head-up displays and conformal imagery, the selected studies represent those that present data in a manner compatible with answering the question ‘which type of display allows for better performance: head-up or head-down, or, conformal or non-conformal?’” (p. 17). Studies were categorized according to task and display characteristics, and data were coded in relation to HUD costs, benefits, or no effect based on tracking or event detection data. Experimental results were combined utilizing the Stouffer method of adding z-scores and weighted all measures used in each study rather than selecting on dependent variable of interest. The results of the analysis are presented in Table 2 and Table 3 with the former based on location (i.e., HUD costs or benefits) and the latter based on display format (i.e., conformality costs or benefits). Of particular interest to attention capture are the results based on

“detection” which was found to “...indicate that detection performance is equivalent between HUD and HDD conditions ($p = .215$ for the one-tailed assumption), suggesting that detection of events is not reliably enhanced (or degraded) when a HUD is utilized” (p.19). However, the results are suspect because of the presence of heterogeneity and the possibility that “...expectancy might influence whether a pilot will effectively switch attention between the HUD symbology and the far domain, or over-attend to the HUD at the cost of monitoring events outside the cockpit” (p.20). Therefore, these authors analyzed the event detection studies on the basis of expected and unexpected events and found a reliable effect of expectancy ($Z = 1.968$, $p > .026$). The result confirms that when the pilot expects an event, the HUD results in significantly better detection performance but incurs a cost when the event is unexpected, which confirms the results reported by Fisher, Haines, and Price (1980).

Table 2. Fadden, Ververs, and Wickens (1998) Meta-Analysis Results Based on HUD Location

Task(s)	D.V.	Tails	Studies	Z-Score	P-value		Test of Homogeneity	P-value	
All tasks	Tracking	2	13	6.344	.001	Sig.	20.197	.063	N.S
		1		6.846	.001	Sig.	21.996	.038	Sig.
	Detection	2	13	3.375	.001	Sig.	29.328	.004	Sig.
		1		3.444	.001	Sig.	32.613	.001	Sig.
Cruise flight and approach/landing	Tracking	2	9	3.481	.001	Sig.	9.209	.238	N.S
		1		3.938	.001	Sig.	10.784	.148	N.S
	Detection	2	7	1.730	.042	Sig.	12.261	.056	N.S
		1		1.569	.058	N.S.	14.448	.025	Sig.
Cruise flight only	Tracking	2	3	-2.455	.007	Sig.	1.525	.467	N.S
		1		-2.605	.005	Sig.	1.686	.430	N.S
	Detection	2	3	3.203	.001	Sig.	7.677	.022	Sig.
		1		3.331	.001	Sig.	7.753	.021	Sig.
Approach/landing only	Tracking	2	6	5.753	.001	Sig.	3.575	.467	N.S
		1		6.397	.001	Sig.	4.193	.381	N.S
	Detection	2	4	-0.350	.637	N.S.	2.803	.423	N.S
		1		-0.659	.745	N.S.	4.469	.215	N.S
Taxi/driving only	Tracking	2	3	5.093	.001	Sig.	2.763	.251	N.S
		1		5.397	.001	Sig.	3.114	.211	N.S
	Detection	2	4	2.976	.001	Sig.	5.035	.169	N.S
		1		3.330	.001	Sig.	6.054	.109	N.S
Laboratory only	Detection	2	3	1.092	.137	N.S.	11.140	.001	Sig.
		1		1.092	.137	N.S.	11.140	.001	Sig.

Overall, the meta-analysis showed that HUDs are of benefit compared to head down displays (HDDs) displaying the same information. Since HUDs are displayed at optical infinity, they reduce the problems of visual re-accommodation between instrument viewing and viewing the far domain. Similarly, because they are superimposed on the far domain, they reduce visual scanning necessary to monitor both the near and far domains. However, it should be observed that simultaneous viewing of the two domains does not always mean simultaneous detection of events. Additionally, HUDs are more capable of presenting ground-referenced information in the air space over the ground such as a pathway guidance tunnel (Fadden, Ververs, & Wickens, 2000). Despite the benefits of HUDs, there is still the cost of clutter that can potentially mask near and far domain events both physically and cognitively (Martin-Emerson & Wickens, 1997; Ververs & Wickens, 1998) and the cost is greater with nonconformal HUDs, which can reduce the benefit of visual scanning (Levy, Foyle, & McCann, 1998; Wickens & Long, 1995).

Table 3. Fadden, Ververs, and Wickens (1998) Meta-Analysis Results Based on Conformality.

Task(s)	D.V.	Tails	Studies	Z-score	p-value		Test of Homogeneity	p-value	
Cruise flight, approach/landing, and taxi/driving	Tracking	2	5	3.771	.001	Sig.	6.577	.087	N.S.
		1		4.043	.001	Sig.	7.431	.059	N.S.
Approach/landing, and taxi/driving	Detection	2	2	1.935	.026	Sig.	1.263	.261	N.S.
		1		2.205	.014	Sig.	1.601	.206	N.S.
Approach/landing only	Tracking	2	3	2.482	.007	Sig.	1.932	.165	N.S.
		1		2.860	.002	Sig.	2.248	.134	N.S.

Symbology Clutter. A common concern with HUDs is clutter in the pilots' visual field and the accompanying problem of attention narrowing. Clutter refers to the superimposition of instrumentation in a pilot's forward field-of-view potentially making it difficult to scan the environment. Ericksen and Ericksen (1974), for example, reported that the foveal target item in a known location in close proximity to non-target items significantly increased reaction time to the target. Therefore, reaction time decreases with increasing separation between display elements and can mitigate attention capture. High workload conditions can compound the problem and further induce narrowing of attention directed towards processing the routine information in the display. The pilots may become fixated on the symbology causing a disruption to scanning patterns for low probability events (Larish & Wickens, 1991). This may be of particular concern with the pathway display HUDs leading to design suggestions that pilots should be provided with a minimum of two-levels of declutter capability (preferably a button located on the yoke) that could remove non-essential HUD symbology (Newman, 1995).

HUD Field-Of-View and Attention Capture

A HUD has a fixed field-of-view (FOV) of approximately 28 degrees horizontal that limits the presentation of symbology (e.g., traffic) which may contribute to attentional narrowing. In a recent study, Berringer and Ball (2001) examined display conformality of pathway displays in head-up and head-down presentations using conventional instruments as a baseline in a GA simulator. Their display conditions included head-down compressed, head-up compressed (40-degree FOV), and head-up conformal (20-degree FOV) presentations.

Berringer and Ball (2001) reported significant differences in performance for horizontal flight path error (RMSE) only, which was greatest for the conformal display. The result was probably due to greater tracking error in the turns due to the loss of view of the path at some point in the turn requiring the pilot to cut inside the turn to keep the path in view. There were, however, no error differences found between the head-down and head-up compressed formats. Subjectively, pilots preferred the compressed HUD during turns and conformal HUDs during straight-and-level flying. For the object detection task, however, the two HUD conditions (compressed, conformal) did not differ but were both significantly worse than HDD and confirmed earlier research showing penalties associated with unexpected runway incursion detection. Overall, Berringer and Ball recommended that nothing less than 40-degree FOV be used regardless of display location (i.e., HUD, HDD) and that scan training be required for low-time pilots. SAE ARP5288 provides the following recommended design guidelines for field-of-view issues:

- The cockpit head motion box minimum size should be 76.2 mm lateral X 50.8 mm vertical X 101.6 mm longitudinal
- The design eye point should meet FAR 25.773 and 25.777
- A minimum monocular FOV should be visible from all points within the HUD eye box
- HUD installation should provide adequate FOV for all flight configuration, environmental conditions, and flight attitudes
- External view and HUD display viewing angles should not provide excessive pilot workload or discomfort to accommodate total visual view
- HUD should meet FAR 25.777 and accommodate pilots 157.5 to 190.5 cm tall
- The HUD eye reference point should be coincident with the design eye point and tolerances should be allowed for natural movement
- HUD alignment should match conformal display parameters and stowable combiners should be ensured to be fully deployed before symbology is active

Expectancy and Attention Capture

The purpose of a HUD is to allow the pilot to view instrumentation and scan the environment almost simultaneously without having to allocate attention inside the cockpit. Therefore, it is important to understand how attention is moderated between the HUD and the environment given the task at hand and the display characteristics of the HUD. The focus of attention is determined by location of the information needed by the pilot. These areas of attention requirements in the cockpit can be divided into four categories: The objects in the environment (e.g. runway and aircraft), the superimposed instrumentation overlapping the environment intended to draw attention out of the cockpit, the superimposed instrumentation in an area in space closer to the pilot which does not draw attention outward and gets processed closer to the pilots' resting dark-focus point, and the traditional head-down instrumentation panel inside the cockpit (Ververs & Wickens, 1998).

Phase-of-Flight. Depending on the phase of flight, the pilot may be required to filter out unnecessary HUD information (i.e., clutter). For instance, during the cruise phase of flight, scanning the HUD and the environment are equally important. Yet, during final approach with the runway in sight, the pilot's attention should be primarily on the environment and not so much on the instrumentation although this may be argued with the use of pathway guidance HUDs. Nevertheless, the basic premise behind information clutter is that the presence of visual information in a display will be disruptive if it is not required to complete a given task. A simulation study demonstrated that HUD use slowed responses to an unexpected aircraft taxiing onto a runway when compared to a similar HDD (Wickens & Long, 1995). This suggests that although HDDs allocate attention inside the cockpit thereby reducing time spent scanning forward, the removal of clutter from the HUD when scanning resumes, has performance benefits (Martin- Emerson & Wickens, 1997; Wickens & Long, 1995). Therefore, there appears to be a scanning and clutter trade-off with the use of HUDs and HDDs depending on the tasks determined by the context of the situation (i.e., phase of flight).

A number of studies have manipulated the presence of information to determine the effects of clutter on performance. Generally, the finding from the basic attention and applied aviation literature is that unnecessary visual information is disruptive to the performance of the task, such as landing an aircraft and scanning for other traffic. Even more alarming, Wickens and Long (1995) and Martin-Emerson and Wickens (1997) found that even relevant HUD imagery can impose a clutter-performance cost particularly if presented in a nonconformal fashion. These past studies have focused on the approach and landing phases of flight, and the general conclusion is that the lower the contrast ratio, the greater the potential for object detection at the expense of detection of commanded flight changes and maintenance of desired flight path (i.e., tracking).

Contrast Ratio. Although the literature seemingly agrees that clutter and contrast is a concern during the approach and landing phases of flight, there is relatively little research examining the issue for

other phases. As Ververs and Wickens (1998) observe, "...past investigations have not examined the critical issues in all phases of flight, particularly the cruise phase. It is during this phase of flight that it is important to scan the environment for traffic (e.g., see and avoid) as well as monitor the instrumentation...." (p.380). Therefore, these researchers performed two experiments to answer two address two issues: Understand how clutter costs (vs. scan costs) effect event detection both for symbology and environment during cruise phase of flight; and, second, to determine the effects of intensity and contrast that may modulate the effects of clutter, which was answered through manipulating the weather against which the instruments was displayed and level of the symbology intensity.

Experiment One focused on how pilots would respond to events on the symbology and in the environment when attention was modulated through location, intensity, and conformality of the symbology in a low fidelity simulation. Ververs and Wickens (1998) hypothesized that HUD symbology would benefit far domain traffic detection because it is an expected event in cruise flight during VFR. However, any added clutter would significantly increase reaction time and reduce detection because it may obscure the presence of other aircraft. Additionally, detection of discrete changes in commanded heading, airspeed, and altitude indicators were expected to favor the HDD. Third, the degree of contrast was predicted to influence performance and object detection only for the HUD location. Symbology with the largest contrast ratios would best support tracking performance and symbology event detection because of the salience of the indications against the background. However, it was also hypothesized that a highly salient display could distract the pilot and capture their attention and, therefore, increase response times to aircraft events. Stated another way, a high contrast ratio would benefit symbology event, but not aircraft event, detection compared to low contrast ratio. Therefore, a midlevel contrast ratio was also examined. Finally, Ververs and Wickens introduced a conformal and partially conformal HUD symbology format into the experimental matrix. These independent variables produced a mixed 2 X 2 X 3 X 3 factorial design with effects of location (head-up, head-down), symbology set type (partially conformal, conformal), intensity (dim, midlevel, bright) and weather (clear, partly cloudy, cloudy).

The results of the first experiment were that detection of commanded flight changes and flight-path tracking was superior in the head-down condition due to the high contrast ratio of the HDD. However, midair traffic detection was better in the HUD condition. Also, there was a main effect found for weather with increased event detection during clear conditions (2.71 sec) compared to cloudy (2.91 sec) and partly cloudy conditions (3.17 sec). There was also a weather X intensity interaction in the HUD condition in which the intensities produced the highest contrast ratio with the background yielded the fastest response times. The dim intensity of the cloudy condition had a negative contrast ratio of 1:1.60 compared to 1:1.50 (midlevel) and 1:1.24 (bright). However, the bright intensity for the clear condition had a contrast ratio of 1.5:1 compared to 1.25:1 (midlevel) and 1.17:1 (dim). Therefore, intensity of symbology influence on symbology detection changes depended upon the weather conditions that produce different contrast ratios. A dim intensity produces a higher, although negative, contrast ratio in cloudy condition than bright intensity, but this changes in clear conditions where bright intensity symbology produces a higher contrast ratio. This finding was limited to symbology event detection only, however. No effect was found for intensity, regardless of weather, leading the authors to conclude, "none of the three intensities provided sufficient contrast to disrupt the pilot's scan of the environment in the head-up location" (p.387). However, the HUD was found to significantly reduce reaction time to aircraft detection events compared to HDD.

Ververs and Wickens (1998) noted that, despite the conflicting support for the scanning benefits but not performance benefits of HUDs, "when the combination of weather and symbology intensity provided the most favorable HUD contrast ratio, the level of flight performance was, in fact, statistically equivalent to that in the head-down condition." Therefore, experiment two was designed to eliminate the confound between location and contrast observed in experiment one. Another objective was to examine the effect of clutter in greater detail and to do so in a higher fidelity simulation. The design of experiment two was a repeated 2 x 2 x 3 x 2 factorial design and included two locations of the symbology, two levels of instrumentation information (i.e., clutter), three intensity variations, and two weather conditions (i.e.,

background luminance). The low-clutter condition presented only minimal information needed to complete the task whereas the high-clutter condition also presented task-irrelevant, but commercially available information that may be shown on current HUDs. There was also a third clutter condition that low-lighted (deintensified) the task-irrelevant symbology; that is, it was still presented but not shown in the same intensity as the task-relevant symbology (Ververs & Wickens, 1998).

Ververs and Wickens (1998; experiment 2) reported a significant 3-way interaction for intensity, location, and weather for lateral and vertical performance. They observed that, in clear weather and the horizon is in view, symbology intensity has no effect on flight technical error. However, as the weather deteriorates and the pilot has to increasingly rely on instruments, the benefits of intensity and location are not as clear. Overall, however, they concluded that “detection of commanded changes and traffic was better in the HUD condition” and was a result different than found in experiment one. They went on to state there were three factors present in experiment two that were absent in experiment one that may have led to the result. First, the contrast ratios were equated between HDD and HUD. Second, the result may have been due to the need for visual reaccommodation in the HUD and HDD locations sequentially that may have led to the increased reaction times in the HDD condition. Both the environment and HUD were presented “optically far” at 3.2 meters whereas the HDD instruments were presented 65 cm as found in a typical cockpit. Finally, the location of a HUD, and a chief advantage of HUDs, reduced scanning area and time for detecting symbology changes (0.71 seconds faster) and aircraft (0.66 seconds faster); this can result in an additional 560 feet for making evasive maneuvers to avoid aircraft when flying at 250 knots. Another result was that the high-clutter condition significantly reduced detection in both the HUD and HDD conditions. Low-lighting the task-irrelevant information did benefit traffic detection but made no difference for detection of commanded changes. Ververs and Wickens interpreted the lowlighting result to show that, “when the task involves visual search and the information needed to be accessed is head down, separating the task-relevant information from the irrelevant information using lowlighting can be advantageous. In effect, lowlighting made extracting the relevant information from the symbology less effortful, thereby allowing more reserve attentional resources to be used for environmental scanning (e.g., more head-up time)” (p. 398).

Taken together, experiments one and two made a significant contribution to the HUD literature. First, the research used licensed pilots rather than university students, which substantially increased the validity of the studies. Second, the formats of the HDD and HUD instruments were consistent allowing comparisons between them. Next, the research used closed-loop low and high fidelity simulation allowing dynamic presentation of the variables of interest. Past research tended to rely heavily on static images (e.g., Weintraub et al., 1984; 1985). Fourth, the experiments expanded the knowledge of attention capture through the investigation of the construct in cruise phases of flight. Fifth, the research employed a “see and avoid” task using realistic midair targets that had not been used in previous experiments. Finally, the results show the need for caution in avoiding clutter on HUDs, which are fast becoming commonplace in the aviation community.

Eye Accommodation and Attention Capture

Because so many studies found that pilots were unable to detect a runway incursion with a superimposed HUD, research has been directed at determining the reason for this phenomenon. For example, Brickner (1989) and Foyle, Sanford, and McCann (1991) both reported experiments where participants performed a ground track and altitude maintenance task using a graphic flight simulation tasks (overlaid HUD symbology with heading information presented on the virtual terrain). In both experiments, altitude performance was better but ground track performance was poorer than participants performing both tasks head-down. Roscoe (1984) posited that misaccommodation could be the etiology of why pilots take longer for obstacle detection with superimposed symbology on the HUD. Sanford, Foyle, McCann, and Jordan (1993) confirmed the hypothesis although others have suggested that no shift in accommodation occurs when HUD symbology is used (Sheehy & Gish, 1991).

In the Sanford et al. (1993) study, the location of altitude information relative to path information was varied. The design was a two-way within subjects repeated measure with HUD location and replication as independent variables. There were three levels of HUD symbology distance relative to the pyramids: proximal, intermediate, and distal. Additionally, a control condition was used in which HUD symbology was absent. Each of the four conditions went through 20 replications with the first four replications serving as practice trials. The task required the 14 participants to fly directly over each of nine segment paths (with 60°, 90°, and 120° degree turns) and maintain an altitude of 100ft with the emphasis of instruction on accuracy. The display showed a virtual environment with blue sky that met with green ground at the horizon with a white grid superimposed on the ground. The eight paths were each marked by brown pyramids that were 12 X 12 ft at the base and 6 ft high and located 33 ft apart on the ground. The result was significantly better altitude maintenance performance ($p < .0001$) for all three locations relative to baseline condition (i.e., location of HUD symbology did not predict altitude performance). An omega-squared analysis showed that 67% of the variance for altitude maintenance and 44% of variance in heading performance was accounted for by HUD symbology location ($p < .0001$). Overall, heading performance was equal for baseline, intermediate, and distal but significantly worse for proximal location --- proximal RMSE > (baseline = intermediate = distal). However, altitude performance was significantly better when located in the proximal location ($p < .0001$). Therefore, unlike predicted by the Proximal Compatibility Principle, heading performance, altitude maintenance was better when HUD symbology and terrain information were co-located. Rather, the results suggest that the two pieces of information were processed as separate objects and participants had difficulty processing them concurrently. However, as the sources of information became less proximal there was a breakup of the attention capture seen in the proximal condition possibly due to eye movement / scanning. The importance of these results are noted in the authors' conclusions that, "...superimposing digital flight information as a separate perceptual object from terrain information may not cause performance problems unless the HUD symbology, relevant to the task being performed, is located near the task-relevant information in the external terrain. However, this situation may occur [and does] in aviation situations, especially during runway approaches [when attention capture is particularly acute] when the runway should be located near the center of the pilots' field of view along with some superimposed symbology. Therefore, this study reaffirms the need to investigate methods of alleviating attentional tunneling" (p.86).

Redundancy

Another reason for attention capture may be the redundancy of the HUD symbology with the outside world information. Pilots may voluntarily choose to fly instruments without reference to the out-the-window scene because the information is redundant. As Fisher, Haines, and Prince (1980) described, "pilots prefer to use the HUD for the primary control of the flightpath, and to use the outside scene for monitoring purposes only, for the HUD provides more accurate guidance." Weintraub and Ensing (1992) discuss the use of the virtual runway of the HUD as an example of how conformal symbology makes it difficult to determine whether attention is being directed at all to the real runway. Another concern is that pilots may learn that there is no need to reference the outside world since the HUD provides adequate guidance leading to the potential for complacency on the part of the pilot. Over time, the pilot may fail to scan the far domain leaving open the opportunity to miss critical events that are not present in the near domain, such as an aircraft taxiing onto the active runway.

Perceptual Load

Several researchers (Fisher et al., 1980; Wickens, Martin-Emerson, & Larish, 1983; May & Wickens, 1995; Stuart, McAnally, & Meehan, 2001) have argued that attention capture can be exacerbated when the taskload is sufficiently demanding. Pilots have described tunneling on certain

instruments during periods of high workload (e.g., approach with turbulence), and stress has been documented to significantly limit the ability to process other stimuli (Hancock & Desmond, 2001). Therefore, increased workload and/or stress can serve to increase the potential of attention capture in reducing the scan of the pilot and filtering secondary information because of increased demand for cognitive resources (Wickens, 1984).

Solutions to Attention Capture

Superimposed and Scene-Linked Symbolology

The results of Wickens and Long (1995) and Foyle, McCann, and Shelden (1995) have been discussed as reflecting perceptual limitations in our information processing – it is difficult to divide attention across disparate perceptual groupings leading to a near/far domain disconnect. Wickens and Long found that pilots had difficulty detecting an unexpected runway incursion and Foyle and his colleagues reported that the presence of altitude superimposed symbolology facilitated altitude maintenance, as expected, but significantly increases lateral path error. These results have been interpreted to reflect limitations in human visual/spatial attention, and considerable evidence exists to show the difficulty of dividing attention across stimuli that belong to separate perceptual groupings (Kahneman & Henik, 1981). Because most HUD symbolology in the near domain appears stationary whereas objects in the far domain appear to be in continuous motion with respect to the pilot, there is often grouping of the near and far domain that occurs. Therefore, pilots have difficulty dividing attention between the near and far domain because they each belong to separate perceptual groupings which explains why unexpected events in far domain are difficult to detect (e.g., Wickens & Long, 1995) and why lateral path error takes longer to detect and be corrected (e.g., Foyle, McCann, & Shelden, 1995).

Because the problem of attention capture may be due to near and far domain perceptual grouping, Foyle, McCann, and Shelden (1995) suggested that “scene-linked symbolology” may be a potential solution to the problem. Scene-linked symbolology is projected at a specific location in the scene so it appears to move with the scene allowing it to undergo the same optical transformations as far domain objects; it essentially makes the symbolology appear as a real-world object itself. Levy, Foyle, and McCann (1998) investigated the possibility, in a follow-up to the 1995 research, using four conditions: superimposed symbolology, scene-linked symbolology (on path), scene-linked symbolology (fixed distance from path), and scene-linked symbolology (variable distance from path). Each of the 14 participants was instructed to fly a series of short, winding path flights using a Silicon Graphics-based flight simulation. The task required the pilot to fly over a series of equally spaced ground markers while maintaining a target altitude. Overall, it was reported that altitude performance and path performance was better in the scene-linked symbolology conditions although not statistically significant for altitude performance. The superimposed, on-path scene-linked, fixed-distance scene-linked, and variable-distance scene-linked display conditions were within 2 ft. RMSE altitude error of each other ($p > .05$). However, for path performance, there was a significant main effect ($p < .05$) and each of the scene-linked conditions was significantly better than the superimposed symbolology condition, which was also significantly poorer than a baseline, no-gauge condition. The average RMSE was 70 ft for baseline, 73.5 ft for superimposed symbolology and an average of 64 ft for the three scene-linked symbolology conditions. Levy, Foyle, and McCann interpreted these results to show that “...scene-linked altitude gauges support efficient joint processing of the altitude information and the far domain even when the gauges are not located directly along the path” (p. 15). The authors also offered explanations for the reported findings and suggested that “...scene-linking only encourages a partial division of attention between altitude gauges and the far domain, which yields a more efficient serial extraction of path-related and altitude-related information than in the superimposed condition...”; “...that scene-linking produces a complete division of attention, enabling fully parallel perceptual processing of task-relevant information in the scene-linked symbols and the far domain; or “

that scene-linked performance benefits reflect more than just an increase in the efficiency of perceptual processing...” but may “...also support a cognitive integration of the two tasks so that they become, in effect, one task rather than two.” Levy, Foyle, and McCann noted that these explanations are speculative but are supported by other research outside the HUD literature (e.g., Fagot & Pashler, 1992), and may alleviate attention capture through a merging of the near and far domain into one perceptual grouping. However, the theory requires further research.

Peripheral Symbology

Another potential solution to attention capture is to segment perception into separate perceptual modes. For example, peripheral symbology can facilitate concurrent attention directed to visual and auditory modes or, within vision, to foveal and peripheral vision. Because of the significant number of auditory alarms and annunciations, the latter may offer a possible avenue for reducing clutter and enhancing event detection.

The theoretical justification for employing peripheral-vision displays is based upon the positing of two visual systems in the human eye: focal and ambient visual systems (Trevarthen, 1968). The human eye continuously samples both a large segment of the visual world (i.e., ambient field) and a much smaller segment (i.e., foveal field). These two visual systems are made up of specialized, parallel information channels, and principal among them are the parvocellular and magnocellular channels. The parvocellular channel makes up the foveal system and is located in the fovea and has small receptive fields and sustained synaptic responses. The channel is characterized as having a long integration time with a peak temporal modulation transfer function (MTF) of 10hz, high spatial frequency sensitivity, low contrast sensitivity (i.e., can see faint images), and sensitivity to color. In contrast, the magnocellular channel averages responses over large areas and is highly sensitive and has good temporal response. As part of the ambient visual system, this channel is made up of large neurons with short conduction times to higher cognitive centers (association centers). It responds phasically and provides transients at stimulus onset and offset. The magnocellular system has temporal MTF of 20 Hz (i.e., shorter integration time), and is contrast and low spatial frequency sensitive (Walrath, 1996). Generally, the focal system is best for central vision and fine details and is useful for object detection. The ambient or peripheral system, on the other hand, uses the entire field of vision and is less under conscious control of the pilot. It is useful for spatial awareness, self-orientation, and guidance of motion particularly in the peripheral field-of-view (Previc, 1998).

There have been several attempts to use the capabilities of peripheral vision to display flight information (Stuart, McAnally, & Meehan, 2001). Majendie (1960) introduced a “para-visual director”, which was a set of barber poles that presented bank and pitch information in the pilot’s periphery. Another promising peripheral display was the “Malcolm Horizon”. It consisted of a horizontal line that was presented virtually across the cockpit such that it was conformal with the real world. Although significant progress was made, including SR-71 flight research, it has yet to be adopted for civilian use. The reason is partly attributable to significant technical challenges. However, recent research has been focused on overcoming these difficulties and significant progress has been reported (Comstock, Jones, & Pope, 2003; Lentz, Turnipseed, & Hixson, 1987).

Prevention Technologies

Another potential solution would be to focus directly on the problem of attention capture. Several advancements in technologies have allowed for the introduction of prevention technologies that would orient the pilot to significant threats (e.g., TCAS, E-GPWS) and, therefore, mitigate the consequences of attention capture. An excellent example of this is runway incursion prevention technologies, such as NASA’s Runway Incursion Prevention System (RIPS), which alerts the pilot to other aircraft that present a danger while on approach.

A runway incursion occurs any time an airplane, vehicle, person or object on the ground creates a collision hazard with an airplane that is taking off or landing at an airport under the supervision of air traffic control (ATC). Despite the best efforts of the FAA, National Transportation Safety Board (NTSB) and others, runway incursions have continued to occur more frequently. The number of reported incursions rose from 186 in 1993 to 431 in 2000, an increase of 132 percent. Runway incursions continue to be a serious aviation safety hazard, and have been listed on the NTSB's ten most wanted list of transportation safety improvements every year since its inception in 1990.

The NASA RIPS technology has been developed in an attempt to reduce the number of runway incursions. RIPS integrates airborne and ground-based technologies, which include flight deck displays, incursion alerting algorithms, on-board position determination systems, airport surveillance systems, and controller-pilot data link communications. NASA flight research (e.g., Young & Jones, 2001) has shown the efficacy of the system to mitigate attention capture and reduce the potential for not detecting far domain traffic when using a HUD during approach and taxi (Figures 3 & 4).



Figure 3. Runway Incursion Prevention System Incursion Alert on Approach

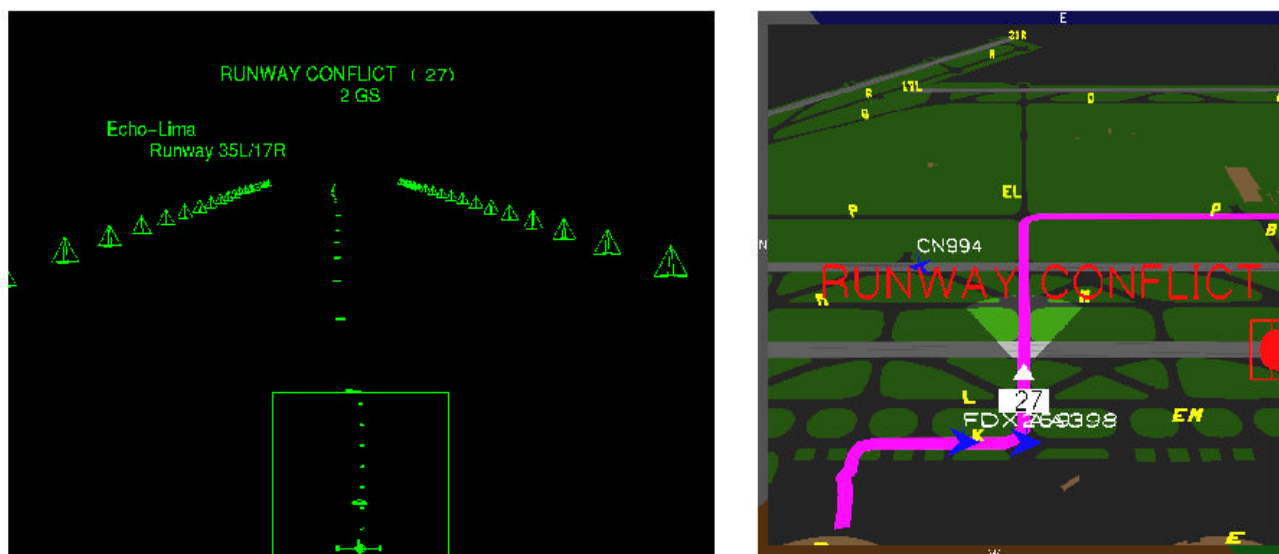


Figure 4. Runway Incursion Prevention System Incursion Alert During Taxi

Synthetic Vision

The NASA runway incursion prevention system was developed in parallel to another NASA technology solution designed to enhance aviation safety, called “synthetic vision.” RIPS has since been integrated as part of the NASA’s Synthetic Vision System (SVS). SVS emphasizes the cost-effective use of synthetic vision tactical and strategic displays; worldwide navigation, terrain, obstruction and airport databases; integrity monitoring and forward-looking sensors, and Global Positioning System (GPS)-derived navigation to eliminate “visibility-induced” aircraft accident precursors.

The objective of synthetic vision is to enhance a pilot’s situation awareness through the synthetic display of how the outside world would look to the pilot if visibility were not reduced. The SVS display would significantly augment hazard avoidance, including cooperative and uncooperative traffic, terrain, wildlife on runways and taxiways, weather, and cultural features (e.g., towers, buildings). Synthetic vision would present these hazards on the head-up display thereby minimizing the chance that the pilot may not perceive them in the far domain. A pilot would be able to de-clutter the HUD and remove the synthetic terrain and/or symbology thereby allowing him or her to better acquire the hazard in the real world. By alerting the pilot to potential threats in the near domain, it reduces the potential that attention capture, if it occurs, will result in not detecting important events in the far domain perceptual field. Several research studies have shown that pictorial displays (e.g., Busquets, Parrish, & Williams, 1991; Busquets, Williams, & Parrish, 1990; Parrish, Busquets, Williams, & Nold, 1994; Williams, Busquets, & Parrish, 1990; 1993) Williams & Parrish, 1990) and synthetic vision (Prinzel et al., 2002; 2003; in press) can significantly enhance situation awareness and prevent accidents. Figures 5 and 6 show the NASA SVS HUD concept.

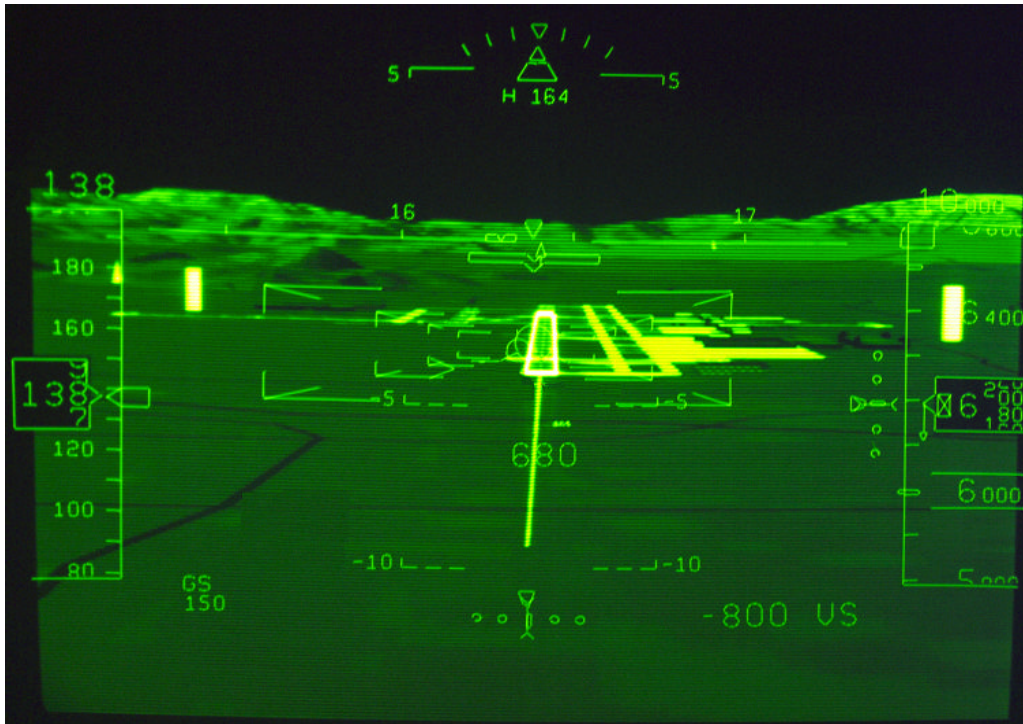


Figure 5. NASA SVS Concept During CAT IIIa Approach

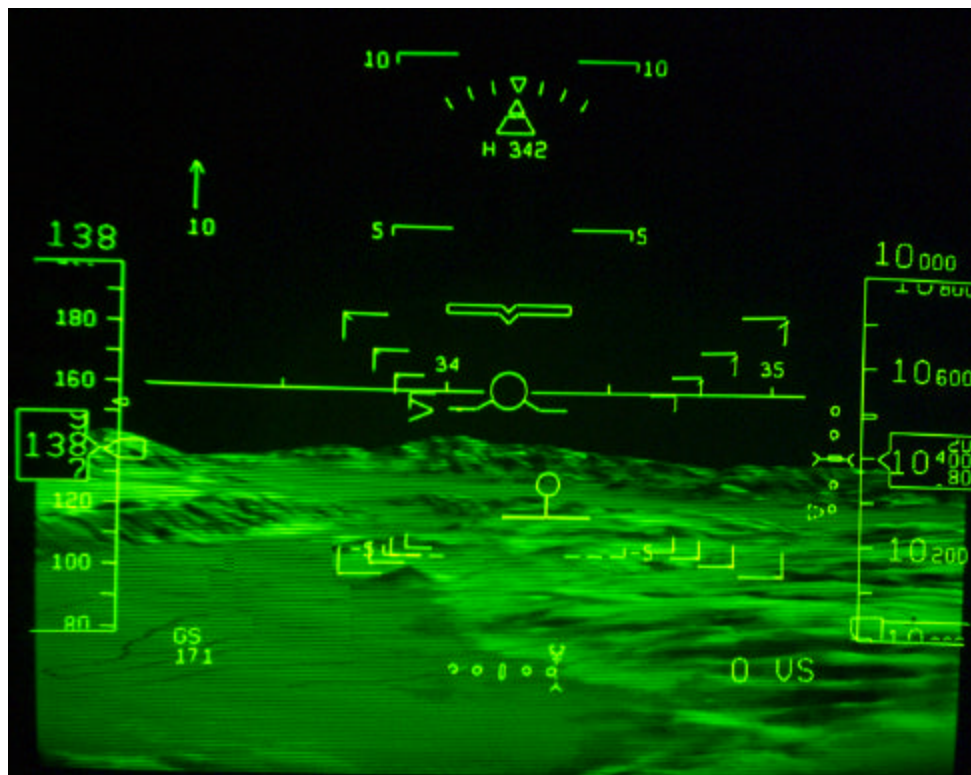


Figure 6. NASA SVS Concept During Initial Approach

Training And Practice

Fisher et al. (1980) observed that the reason for attention capture might have much to do with the training that pilots receive. Training is often suggested as a solution to human factors problems and must be cautioned against as a panacea for solving shortcomings of design. However, in the case of attention capture and HUD use, it is likely that training specific to ameliorating inattention to unexpected far domain events may have a significant impact on aviation safety. For example, Stoffregren and Becklen (1989) reported that several days of practice could significantly improve detection of unexpected events through the promotion of a state of implicit divided attention. Stuart, McNally, and Meehan (2001) concluded that the study showed that, “attention capture by HUDs is also likely to be minimized by promoting implicit divided attention through training in awareness of the non-redundancy of the environment, including the possibility of unexpected events.” Therefore, in addition to improvements in HUD design, another solution may be to focus training curricula to heighten awareness of the potential for attention capture and ways pilots may use to countermand its onset.

Conclusions

The present paper described the human factors issues of attention capture and head-up displays and laid the foundation for future human factors research, under the “hazardous states of awareness” (i.e., Human Measures & Performance; HM&P) element of the Airspace Systems program, Airspace Operations Systems (AOS) project. A survey of current HUD technology and an exhaustive literature survey traced the phenomenon of attention capture and the concomitant safety concerns it presents. To date, much is now known about the deleterious potential of attention capture and an appreciation of this is often echoed in training curriculum designed for HUD-equipped aircraft (e.g., B-737-800). However, few solutions are available. Some prescriptions described include scene-linked symbology, training, peripheral displays, prevention technologies and synthetic vision, as well as minimizing clutter (e.g., better de-clutter options).

Weintraub and Ensing (1992) noted that, “the questions having to do with attention capture and cognitive switching are empirical, and must be answered via evidence. Precious little evidence exists.” (p. 105). Since then, significant progress has been made in our understanding of attention capture. Furthermore, the success of these displays in commercial operations has been documented (e.g., Kaiser, 1993), and there have been no reported accidents directly attributable to human-HUD interaction. Despite this, the phenomenon of attention capture is well known both to the research and pilot community and, therefore, it is important for us not to become complacent. HUDs are now being considered for general aviation use and advanced HUDs (e.g., color) are being developed. Unfortunately, there is still much that remains unanswered with regard to its etiology. We should, therefore, be careful not to allow these successes to “capture” our research “attention”. Rather, because of the minimal training that GA pilots are likely to receive and the potential increased “compellingness” of advanced HUDs, the need to study attention capture may be greater than ever. Future research in the HM&P element will focus on the study of these issues and seek to further understand the nature and causes of attention capture.

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14. ABSTRACT The primary role of head-up displays (HUDs) is to provide primary flight, navigation, and guidance information to the pilot in a forward field-of-view on a head-up transparent screen. Therefore, this theoretically allows for optimal control of an aircraft through the simultaneous scanning of both instrument data and the out-the-window scene. However, despite significant aviation safety benefits afforded by HUDs, a number of accidents have shown that their use does not come without costs. The human factors community has identified significant issues related to the pilot distribution of near and far domain attentional resources because of the compellingness of symbology elements on the HUD; a concern termed, attention or cognitive capture. ¹ The paper describes the phenomena of attention capture and presents a selected survey of the literature on the etiology and potential prescriptions.						
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