THE INTERNATIONAL JOURNAL OF AVIATION PSYCHOLOGY, *16*(1), 1–19

FORMAL ARTICLES

A Review of the Perceptual and Cognitive Issues Associated With the Use of Head-Up Displays in Commercial Aviation

Jennifer Crawford and Andrew Neal
ARC Key Centre for Human Factors and Applied Cognitive Psychology
The University of Queensland

A head-up display (HUD) is a projection of symbology into the pilot's forward field of view that enables the pilot to monitor the instrumentation while, theoretically, also viewing the external domain. Although the HUD has been shown to improve flight performance, there are perceptual and cognitive issues that need to be addressed. This article reviews selected literature that investigates these issues and the possible solutions posed and identifies areas that remain in doubt.

A major review of head-up display (HUD) literature is timely and necessary as it has been 10 years since HUDs have been closely examined as a whole (Newman, 1995). Many airlines around the world now use HUDs. In some cases their use for the most critical phase of flight, approach, and landing, is mandatory. However, there are still issues that have been investigated but for which tested solutions have not been provided. This article examines the perceptual and cognitive issues associated with HUDs based on the studies that have been performed to date. It also looks at the advantages and disadvantages of HUDs. Finally, emerging issues and applications are identified in brief.

Correspondence should be sent to Andrew Neal, ARC Key Centre for Human Factors and Applied Cognitive Psychology, McElwain Building, University of Queensland, QLD 4072 Australia. Email: andrew@psy.uq.edu.au

BACKGROUND

An HUD is a projected display of symbology on a transparent screen. As can be seen in Figure 1, the symbology is superimposed over the pilot's forward field of view, enabling him or her to monitor primary flight information while maintaining a view of the outside world. The result is an opportunity for less time "head down" looking at instrumentation approximately 10° below the line of sight, and more time maintaining visual contact with the outside environment.

The first use of an HUD was for gun sights in the 1950s. These early HUDs were used for aiming and not as a flight instrument. In 1960, the Hawker Siddeley Buccaneer included the first operational HUD designed for use as a piloting instrument (Weintraub & Ensing, 1992). This HUD consisted of a horizon and a reference symbol of an aircraft. Altitude and speed values were digitally displayed, with the Flight Director providing rough flight path guidance information. The HUD symbology of the Buccaneer provides the basis for that used in most HUDs today.

HUDs are currently used as a visual aid to assist during two main landing situations, namely the visual approach and the transition from instrument meteorological conditions to a visual landing. The use of HUD during the various phases of flight is mandated by the airline company operating the aircraft in which the HUD is installed. The four advantages for the incorporation of HUDs into modern aircraft that have been proposed are a reduction of head-down time during critical stages of flight, a potential reduc-

FIGURE 1 The standard presentation used in a Rockwell Collins Flight Dynamics head-up display (photo courtesy of the Royal Australian Air Force).

tion in the need to refocus the eyes from the near to the far domain (from instrumentation to the external world), an improvement in awareness of the external domain, and an improvement in the quality of the instrumentation display by comparison to conventional displays based on dials and gauges (May & Wickens, 1995).

Studies of flight performance have shown advantages for HUDs over traditional head-down displays (HDDs), including superior flight path maintenance and higher precision landings (see Fischer, Haines, & Price, 1980; Naish, 1964). Furthermore, for some airports and aircraft types, HUDs enable lower visibility takeoffs and landings than previously possible. This can provide significant cost savings for airlines. However, potential problems have also emerged. Some of the early problems relating to design appear to have been resolved, but there are a number of cognitive issues that are still a matter of debate and research. These include the effects of divided attention and cognitive tunneling, and spatial disorientation and unusual attitude recovery. These issues are reviewed in later sections.

PERCEPTUAL AND COGNITIVE ISSUES

The majority of HUD research in the last decade has dealt with perceptual and cognitive issues. One of the main areas of interest is whether pilots can view the HUD and the external scene concurrently. It would appear that this is not the case (for reasons outlined in the sections that follow) and that pilots need to switch attention back and forth between the HUD and the external scene. Attempts have been made to overcome these problems by using new forms of technology, such as conformal symbology. However, there is still debate regarding the effectiveness of these measures. These issues are described in the following sections.

Misaccommodation

Misaccommodation of the eye occurs when the focus is drawn inward by something close. This is considered to be a problem because it impairs pilots' ability to detect targets and to judge their distance and size (Weintraub & Ensing, 1992). HUDs are collimated to appear at optical infinity to overcome the problem of misaccommodation. Collimation is intended to put the HUD symbology at the same optical depth as the external world, which in principle should assist with accommodation and reduce the time necessary to refocus (Naish, 1964). The effectiveness of collimation and whether HUDs should be collimated has been extensively debated. This debate has been covered in previous reviews (Newman, 1995; Weintraub & Ensing, 1992). Given that no new studies have addressed this issue in the past 10 years, we provide only a relatively brief summary of the issues here.

A number of studies suggest that collimation does not pull the pilot's focus outward to optical infinity, or that collimated HUDs may even exacerbate misaccommodation (Hull, Gill, & Roscoe, 1982; Iavecchia, Iavecchia, & Roscoe, 1988; Norman & Ehrlich, 1986). Weintraub and Ensing (1992), on the other hand, argued that the bulk of evidence suggests that collimated HUDs do pull the pilot's focus outward, even if it is not always to optical infinity. They argued that the earlier results were an artefact of the optical quality of the HUD image and the external scenes used in these studies. High-quality images, whether generated by the HUD or from the external environment, draw focus outward. Iavecchia et al. (1988) used a relatively poor-quality HUD image superimposed over a high-quality image of terrain, causing focus to be drawn inward. In contrast, Weintraub and Ensing (1992) argued that if the external image is of poor quality (e.g., because of fog or rain) high-quality HUD images will actually pull the pilots' focus outward, partially offsetting the tendency for the resting point of accommodation to be closer than the objects in the external environment. Similar arguments were made by Newman (1987), who argued on the basis of subjective experience that HUDs give the pilot a clearer view when flying through rain. To our knowledge, the question of whether collimated HUDs produce misaccommodation or whether they reduce it has not been resolved.

Another issue of concern is whether the HUD combiner glass itself, including its frame and lack of movement compared with the external world, are a source of misaccommodation. These items may provide perceptual clues that the HUD is closer than the outside scene (Larish & Wickens, 1991; Roscoe, 1987). However, the same is true of dirt, rain, and glare on the windshield (Weintraub, 1987). There is currently no strong evidence available to assess whether the HUD combiner glass significantly increases the risk of misaccommodation, over the risk posed by the contaminated windscreen itself.

ATTENTION AND COGNITIVE TUNNELING

Intuitively, one might expect that HUDs would enhance a pilot's ability to detect events in the external world because the pilot does not have to switch attention back and forth between an HDD and the external environment. However, there is strong evidence to suggest that HUD symbology can capture a pilot's attention, and impair the pilot's ability to detect events in the external environment. This effect is referred to as *cognitive tunneling*. In the following sections, we briefly examine the nature of attention, and review available studies that have assessed the issue of cognitive tunneling and the reasons why it may occur.

Attention

Information processing is critically dependent on attention. Research has demonstrated that, in general, people are much better at detecting events in the environment if their attention is focused on the area in which those events occur (Wickens & Hollands, 2000). However, attention is a resource with limited capacity. Under some circumstances, a single task or aspect of the environment will capture all of the individual's attention. If the individual focuses attention in this way then he or she will filter out unattended information and may not detect task-critical information. In other situations, people can divide attention across tasks or aspects of the environment. Factors that influence an individual's ability to divide attention include the nature of the tasks (e.g., whether the information is perceived via visual or auditory channels, and encoded verbally or spatially), and the nature of the display (Ververs & Wickens, 1998).

Display features that encourage divided attention may inhibit people's ability to focus attention on specific aspects of the display and vice versa (Ververs & Wickens, 1998). For example, putting similar objects together may support divided attention, but make it difficult to focus attention on one particular object within the display. Similarly, an element of a domain that has dynamic properties, such as motion, may capture attention and be so compelling that it consumes the majority of the attentional resource, so that there is not sufficient attentional capacity to view other visual elements concurrently.

Perceptual aspects of the visual field such as motion, color, and frame of reference distinguish the HUD from the external world. For this reason, the HUD and external world may not be processed or visually attended to at the same time. This results in aspects of the unattended domain being perceived only after some delay. If the HUD is the more salient of the two domains, these elements of the external world, especially those that are unexpected, may be more difficult to detect (McCann, Lynch, Foyle, & Johnston, 1993; Moodi, 1995). For example McCann et al. found that response times for events occurring within the domain to which the pilot was currently attending were faster than response times to events that occurred outside that domain. It was suggested that the HUD may act as an attentional trap and that the ability to concentrate attention on the HUD was more robust than the ability to concentrate attention on the outside world, interfering with the ability to focus externally.

Detection of Expected and Unexpected Events

Most research addressing the effects of cognitive tunneling has focused on the detection of unexpected events. An initial study comparing HUDs with HDDs found that landings were more accurate using HUDs for commercial airline pilots flying a fixed-based simulator. However, there was a longer response time to an aircraft that was located on the duty runway that was being approached (Fischer et al., 1980). A similar study was conducted by Weintraub, Haines, and Randle (1985), who found, in the final trial of their study, that there was a runway incursion that was only noted by 2 of the 8 participants. Naturally, this was cause for concern and many studies have subsequently addressed this issue and the reasons behind it.

Larish and Wickens (1991) examined instrument-rated pilots' ability to detect expected and unexpected events on the flight display and in the external scene, when using an HUD and an HDD. Both display formats contained the same instrumentation and were collimated to optical infinity to ensure that any observed differences could be attributed to display position. Many of the early HUD studies had confounded instrumentation, collimation, and display position. Therefore it is possible that the superior flight performance that had previously been observed with HUDs could be attributable to the quality of instrumentation, or the fact that the image was collimated, rather than the position of the image. The key outcome measure was the response time to the detection of expected and unexpected events in the external scene and on the display. General flight performance, in terms of vertical and lateral tracking ability and speed and heading control, was also measured. The results showed that pilots took longer to detect unexpected events in the near and far domain when the HUD was used. On the other hand, the pilots did detect expected events on their display more quickly when the HUD was used. Unlike many earlier studies, there was no advantage for the HUD in terms of flight performance. Larish and Wickens concluded that the advantages observed for HUDs may be due to the symbology that is used, and the collimation of the image, rather than the physical location (head up or head down) of the image.

A recent study conducted at Boeing's Integrated Airplane Systems Laboratory investigated attention switching between an HUD and the far domain, and an HDD and the far domain (Hofer, Braune, Boucek, & Pfaff, 2001). Twelve pilots flew four takeoffs and four approach and landings in each of the HUD and HDD conditions, resulting in 16 runs for each pilot. Each run included an expected event. These were display events (a frozen instrument), scene events (truck or aircraft incursion), or a combination of display and scene events. Six events per pilot (three HUD and three HDD) were serious enough that an accident could result without an appropriate response. The symbology set for the HUD in this study was reduced. The intention was to ensure that there was no hindrance of event detection due to symbology obstruction. Furthermore, the HUD and the far domain information were presented at the same visual distance, reducing accommodation bias. The workload was considered realistic, but not excessively high. The pilots were informed that there would be an event during each run in either the symbology layer or the outside scene to reduce learning effects and increase detection. The pilots were not informed what the particular events would be. However even knowing there would be an event, 36.5% of the events were missed in the HUD condition and 26% in the HDD condition. Across all pilots, 9 out of 36 accident events were missed in the HUD condition and these were all in the approach and landing phase. None of the accident events were missed in the HDD condition. These differences were statistically significant.

The finding that pilots can fail to detect unexpected events, such as a runway incursion, is consistent with results that have been reported within the broader psychological literature. Inattentional blindness is a phenomenon in which people fail to notice unexpected objects directly in their field of view (Simons, 2000). For example, studies have shown that although participants may be looking directly at a scene in which a ball game is being played, when a gorilla or a woman with an umbrella appears they do not notice these out-of-context objects (Becklen & Cervone, 1983; Simons & Chabris, 1999).

Conformal Symbology

FIGURE 2 Use of conformal symbology during the landing phase (photo courtesy of the Royal Australian Air Force).

A *conformal display* is defined as one “in which the symbols appear to overlie the objects they represent” (Newman, 1995, p. 234). An example of conformal symbology is shown in Figure 2. It is thought that by overlaying the images, they can be viewed concurrently, thereby overcoming the cognitive tunneling effect (Naish, 1964; Wickens, 1997).

A number of studies have shown that the use of conformal symbology produces benefits such as a reduction in scanning (Martin-Emerson & Wickens, 1993; Ververs & Wickens, 2000; Wickens & Long, 1994). In addition, conformal displays have been found to be less distracting and require less effort to attend to the environment (Boston & Braun, 1996). When investigating flight path tracking and event detection, benefits of a conformal HUD were shown to be faster detection of changes in symbology and traffic and an increase in flight path tracking accuracy (Fadden, Ververs, & Wickens, 1998). However, when unexpected events were introduced, the probability of detection was still degraded when using the HUD.

Wickens and Long (1995) examined flight performance and event detection using conformal and nonconformal symbology sets in either an HUD or an HDD condition. The flight performance measures included flight path control and airspeed tracking. Benefits for flight path control were found for the HUD condition when conformal symbology was used. These results suggest that the performance benefits from HUDs stem not only from the reduction in scanning that is required when the image is positioned head-up, but also from the use of conformal imagery. However, a slower response to the unexpected event in the far domain occurred with HUD use. The cognitive tunneling effect was attenuated by the use of conformal imagery. The authors cautioned against cluttering the HUD with too much nonconformal imagery as this may lead to slow detection rates for unexpected events.

Location of Symbology

A few studies have investigated whether changing the location of nonconformal symbology alleviates the cognitive tunneling effect (Foyle, McCann, Sanford, & Schwirzke, 1993; Martin-Emerson & Wickens, 1992). In an assessment of the effect of positioning altitude information in three locations on the HUD, Foyle et al. investigated ground path performance, altitude maintenance, and the concurrent processing of the display and external scene. The results indicated that when altitude and path information were superimposed, participants were unable to attend to both the HUD and the outside world. Furthermore, when the altitude information was over the path, there was a trade-off between altitude and path performance, with an increase in altitude performance and a decrease in path performance. Foyle et al. suggested that the results may have been due to attention being focused on the altitude information and hence, the inefficient processing of the path information. When the altitude information was placed higher up in the HUD, away from the ground path, the trade-off was not apparent.

Foyle, Dowell, and Hooey (2001) found that when HUD altitude symbology was placed at least 8° above the external ground path, the cognitive tunneling reported by Foyle et al. (1993) was eliminated. When the symbology was displaced in this manner, ground path performance was unaffected. A subsequent study carried out by Dowell, Foyle, Hooey, and Williams (2002) demonstrated that moving the altitude information in this way not only eliminated cognitive tunneling, but improved tracking performance and enhanced the processing of the HUD symbology and the external scene. It was suggested when the nonconformal altitude symbology was superimposed on the ground path, the compellingness of the altimeter was responsible for the tunneling, regardless of the relevance to the task.

Clutter and Intensity

It has been suggested that some of the benefits associated with the use of HUDs may be canceled out by clutter (Ververs & Wickens, 1996). Clutter is thought to be one of the causes of cognitive tunneling and may interfere with the processing of information in both the near and far domains. A number of incident reports have highlighted the problem of clutter. For example, May and Wickens (1995) described a military incident in which a pilot failed to detect a barrier on a runway. It appears that the level of brightness of the HUD and the amount of symbology led the pilot to fixate on the display and, hence, miss the barrier. In the case of a similar incident, the United Kingdom’s Air Accidents Investigations Branch (2000) concluded that the pilot of a Tornado that collided midair with a Cessna 152 may not have seen the Cessna due to the clutter of the Tornado’s HUD. It was reported that “it is possible that the effects of clutter in the HUD reduced the probability of detection at a critical moment” (Air Accidents Investigation Branch, 2000, pp. 4–5).

Some studies have shown that conformal displays can help reduce the effects of clutter. For example, Boston and Braun (1996) found that in high-clutter situations, a conformal display reduces the time it takes for a pilot to detect an obstacle in the far domain.

Another way to decrease clutter may be to highlight salient information and reduce the luminance of information that may be less important and distracting (May & Wickens, 1995). Ververs and Wickens (1996) found that an increase in contrast ratio assisted pilots in cruise flight in responding faster to changes in heading, airspeed, and altitude indicators in the HUD condition. Furthermore, when the contrast ratio of the HUD was the same as that of the HDD, the detection of events in both the near and far domain was superior in the HUD condition. Including additional information in the display hindered event detection. Lowlighting the additional information, however, provided pilots with a sense of what was important on the display and distraction from far domain elements was less likely. The results from this study suggest that putting symbology into an appropriate location on the HUD, and ensuring an appropriate level of symbology intensity and contrast with the environment, improve HUD performance. However, both of the studies just described were conducted to reflect cruise flight and not the landing phase. Therefore, these results may not generalize to other phases of flight.

In a study examining HUDs and HDDs, Wickens (1997) found that clutter effects appeared to be mediated more by the number of elements than by the overlapping of symbology on the far domain. Furthermore, the benefits of a reduction in scanning in the HUD condition outweighed the costs of clutter, even though the high-clutter displays did result in a delay in the detection of events in the near and far domains. The poor detection of events with high clutter was found in both the HUD and HDD conditions.

Workload

High workload seems to be associated with an increase in cognitive tunneling. If cognitive tunneling is caused by limitations in attentional capacity, increasing workload should further reduce a pilot's available capacity, thereby exacerbating the tunneling effect. However, there are very few studies comparing the workload of HUD and HDD in the civilian domain. Although there have been some recent studies investigating pilot workload while taxiing, high-fidelity investigations into workload during commercial flight operations need to be conducted. The results from military studies cannot easily be applied to the commercial aviation sector because of the differing nature of equipment and flight situations. For example, there are differences in currency and recency, the number of airport movements, fatigue levels, and schedules. These factors are likely to confound comparisons across the two sectors.

Some evidence to support the assumption that workload will exacerbate cognitive tunneling was provided by Larish and Wickens (1991). Two levels of turbulence (high and low) were used to vary the workload for instrument-rated pilots in a flight simulator. The differences in response latency to unexpected events between the HUD and HDD conditions were greater under high levels of workload, suggesting that workload does increase cognitive tunneling. Interestingly, the opposite effect was found for the detection of expected events. Pilots using the HUD were faster at detecting expected events in the near domain than pilots using HDD, and this difference was stronger under high-workload conditions. The authors argued that in a high-workload situation, the HUD may induce a narrowing of attention to avoid distraction from the superimposed images, or a change to the pilot's scan pattern, due to the superimposed images. They concluded that dividing attention between the two overlapping sources is a difficult and unnatural cognitive task that may exhaust resources in high-workload situations (Larish & Wickens, 1991).

Pilots, on the other hand, appear to believe that HUDs reduce their workload. In the Boeing study described earlier, the pilots reported that the HUD reduced their workload. Furthermore, the pilots reported that they found it easier to switch attention from the HUD to the external scene, compared with the HDD, and that the HUD was easier to use. The positive evaluations of the HUD provided by the pilots occurred despite the fact that the HUD produced an increased number of missed events. These results suggest that the cognitive tunneling effect is counterintuitive, and that many pilots are not aware of its existence. Hofer et al. (2001) concluded that "Pilots think they are seeing everything because all the information is being presented in their visual field when in fact they are not attending and processing everything" (p. 2). Additional studies into the effects of workload on cognitive tunneling, and pilots' awareness of these effects, need to be carried out.

Spatial Disorientation and Unusual Attitude Recovery

The use of HUDs in instrument meteorological conditions has raised concerns that they may contribute to spatial disorientation (Zenyuh, Reising, McClain, Barbato, & Hartsock, 1987). Barnette (1976) found that 30% of pilots reported that the use of HUDs was associated with an increased risk of spatial disorientation (see also Newman, 1980). Newman (2000) argued that this problem was caused by the symbology used at the time. Because the early HUDs were designed to be used as gun sights and not as a primary flight instrument, their symbology may not have been adequate to support the pilot in instrument meteorological conditions. This would be particularly important for recovery from unusual attitudes. Changes to the symbology, including the use of a compression pitch ladder, appear to have alleviated the problems (Newman, 2000).

Roscoe (1987) argued that the change in focus from the HUD to the external world produces spatial disorientation. As pointed out by Newman (2000), none of the studies conducted to date have supported this concern, although improvement of some features would assist in unusual attitude recovery (see below). Furthermore, Newman argued that the distance of the HUD would be at least that of the conventional HDD, so the change in accommodation from the HUD to the external world should not cause spatial disorientation. Newman concluded that modern HUDs do not cause spatial disorientation and that their advantages far outweigh any disadvantages.

There is potentially some difficulty in recognizing unusual attitude and then determining the appropriate maneuver to recover when using an HUD (Newman, 2000; Zuschlag, 2001). Newman noted eight HUD characteristics that may produce difficulty in interpreting orientation cues, which in turn makes unusual attitude recovery difficult. Three of these characteristics (clutter, framing, and accommodation traps) have all been mentioned previously in this article. The other five are poor upright compared with inverted cues, digital data and rate information, full-scale pitch angles, pitch ladder precession passing zenith or nadir, and velocity vector control.

In the case of poor upright and inverted cues, traditional attitude indicators include color to show sky and ground, which cannot be matched with today's monochromatic HUD design. Hence sky–ground discrimination may be difficult. When airspeed and altitude are presented digitally, there may be difficulties in interpretation. However, there is also concern that HDD analog formats such as tapes and pointers may increase clutter on an HUD (Zuschlag, 2003).

Full-scale pitch angles make the symbols move very quickly across the pilot's field of view and therefore become hard to interpret. The compression of the pitch scale will slow the movement of the symbology so it can be read and may also alert the pilot to an unusual attitude (Newman, 1995). The precessing of the pitch ladder to simulate an attitude director indicator avoiding gimbal lock (when the velocity vector passes 90° nose up or down), is no longer a feature of HUDs. Finally, pilots using the HUD velocity vector as a control parameter may have trouble during unusual attitudes because they pull instead of push on the stick during high angle of attack conditions.

The Federal Aviation Administration (FAA) of the United States suggested that HUD designers should avoid confusion between input guidance and orientation symbology. This is necessary if the HUD is intended to provide orientation only during upsets or unusual attitudes. Cues must be designed to prevent them from being mistaken as flight control input commands. For example, "a cue for left stick input should not be confused with a cue indicating direction to the nearest horizon. Guidance should be removed if cues become invalid at extreme attitudes, such as zenith, nadir, or inverted" (FAA, 2001, p. 31).

Additional Areas of Research

There are a number of outstanding issues that require further research. For example, there does not appear to have been any research conducted into the use of vision aids and correction in pilots that may use HUDs. In addition, research is warranted into the use of HUDs in single and multicrew environments; the effects of pilot qualifications, training, and experience; and the training practices and experience of operators.

Research is currently being conducted at the FAA/Volpe National Transportation Safety Center to provide the FAA with guidelines for certifying HUDs for civilian use (FAA, 2002). Twenty-two HUD design issues have been identified by FAA experts while certifying HUDs. Further research is being conducted to determine how pilot performance is affected by each of the design issues. The 22 issues are broken down into the following categories: location and format design of flight information, display effectiveness to support the intended task, HUD effectiveness in displaying and guiding recovery from unusual attitudes, consistency, and discriminability of HUD symbology, and pilot physiological stress associated with HUD optical design.

A further area of investigation might include HUDs and the proximity principle, which is a principle of perception that was first identified by the Gestalt psychologists. The central idea of this principle is that the smaller the gap between stimuli, the more likely those stimuli are to be seen as belonging together. The gap can be in terms of space or in terms of time. Although this principle has been investigated by putting similar items together in the HUD visual field to ease processing, the HUD could also break down the external field stimuli, making them hard to interpret. Flight Lieutenant Robert Woodbury at RAAF Richmond demonstrated this effect to the first author by showing a photographic image of an HUD plus three lights visible in the external domain. It was not until the HUD was removed from the field of view that it was easy to see that the three lights were part of a preceding aircraft. To our knowledge, no studies have investigated this issue.

Summary: The Advantages and Disadvantages of HUDs

Fadden et al. (1998) conducted a meta-analysis assessing the costs and benefits of HUDs. They included data from 18 studies comparing HUDs, HDDs, and conformal displays. The results showed that the use of an HUD was associated with improved tracking performance for all tasks except cruise flight. Tracking performance during cruise flight was actually worse when using an HUD. Fadden at al. concluded that this may be caused by the lower level of contrast that is present when an HUD is used, compared to an HDD.

Furthermore, the use of an HUD was associated with improved event detection for all tasks except approach and landing. The use of an HUD was associated with improved event detection when the event was expected, but impaired event detection when the event was unexpected. Most studies presented expected events during cruise flight, and unexpected events during approach and landing, possibly accounting for differential effects of HUDs on event detection across phases of flight. The use of conformal symbology was associated with improved tracking performance and event detection for all tasks.

One of the issues that needs to be considered when interpreting the findings from this literature is the extent to which findings from laboratory studies will generalize to operational environments. It is possible that effects observed in the laboratory may not generalize to the real world. For example, many of the laboratory studies have used general aviation rather than commercial airline pilots as participants (Larish & Wickens, 1991). General aviation and commercial operations differ in a number of respects, such as the number of crew and their level of experience. Other potential problems include the use of low-fidelity simulations, small sample sizes, and unrealistic displays. However, several studies have used high-fidelity simulations. The fact that the results replicate when high-fidelity simulations are used (e.g., Hofer et al., 2001), and when highly experienced airline pilots are used (e.g., Atkins, Foyle, Hooey, & McCann, 1999), suggests that we can have some confidence in the generality of the effects. Furthermore, the fact that these findings have been replicated across different research laboratories overcomes the problems of small sample sizes within individual studies, and further strengthens the argument for generalizability.

Finally, it is important to note that there is currently no evidence to suggest that the use of HUDs is associated with accident or incident rates in flight operations. LeBlaye, Roumes, Fornette, and Valot (2002) carried out a review of accident and incident databases to assess whether HUDs have been involved in incidents. Sources that were examined included the Aviation Safety Reporting System (ASRS), which is managed by the National Aeronautics and Space Administration (NASA); Vortex, which is managed by the Flight Safety Office of the French Air Force; Baseac, which collects human factors analyses of all accidents within the French Air Force; and the flight analysis office at Air France. ASRS was the only database to contain incident or accident reports involving HUDs. Of the 100,000 reports collected since 1990, only 16 related to HUDs. Of the 16 reports mentioning HUDs, only 5 actually identified problems with HUDs. The problems that were identified involved a delay in the pilot noticing that the symbology did not match the actual situation, a symbol disappearing during a flight phase, and overfocalization on the HUD symbology.

LeBlaye et al. (2002) argued that there are a number of potential explanations for the extremely small number of incidents involving HUDs. One obvious explanation is that HUDs do in fact provide a high level of safety. However, trying to draw conclusions from null effects is problematic. Other possibilities are that HUDs were rarely used in this period, that incidents involving HUDs were rarely reported, or that investigators misattributed the causes of accidents. Furthermore, the cognitive tunneling effects reported in the literature relate primarily to the detection of unusual events during approach and landing. By definition, these events are rare, so we would not expect to see many incidents. It is, therefore, difficult to draw any firm conclusions from these data on incidents and accidents involving HUDs.

EMERGING ISSUES AND APPLICATIONS

There is an abundance of new avionics available now and these are provided by a multitude of manufacturers. For example, in 2002 Boeing conducted demonstrator flights in a specially modified 737–900. The advanced avionics to be evaluated by representatives from a variety of airlines included synthetic vision system (SVS) displays; a head-up guidance system married to two infrared enhanced vision systems (EVS); highway-in-the-sky navigational cues; a virtual-traffic-cone surface guidance system; global positioning satellite (GPS) landing system; and a software upgrade to the enhanced ground proximity warning system (EGPWS). Other prevention technologies include NASA's Runway Incursion Prevention System, which alerts pilots on approach to other aircraft that pose a threat. In the following sections, we consider the implications of these types of emerging technologies for the use of HUDs.

Pathway HUDs

Pathway, tunnel, or highway-in-the-sky 3–D format flight path displays provide a prediction and preview of a flight path. Although these displays have been investigated for a few decades, combining the pathway display and HUD is a relatively new concept.

Pathway HUDs have been investigated by Ververs and Wickens (1998) and Fadden, Ververs, and Wickens (2000). The three elements that make up the new HUD are a preview tunnel of where the aircraft will be in the future, a predictor symbol, and a 3–D perspective. Preliminary tests with pilots showed positive performance results, in the form of more precise tracking with lateral and vertical error limited to approximately 10 ft. However, when an unexpected event arose for pilots who were truly naive to the study (in this case a runway incursion), the event was detected more slowly in the HUD condition than in the HDD condition. It should be noted that this finding was not statistically significant, possibly due to the insufficient power of the study. Nevertheless, the results are consistent with the cognitive tunneling effects reported previously, without pathway displays.

Taxi Performance

Advances in HUD technology have extended its use to taxi guidance. During taxiing, pilots rely heavily on visual navigation aids on the airport surface outside the cockpit. Helping pilots to taxi during times of low visibility could, therefore, increase the safety and efficiency of surface movements. However, as pointed out by M. Wiggins (personal communication, September 4, 2003), the effectiveness of using HUDs for taxi guidance depends on the accuracy and reliability of the route path programming. It would therefore be necessary to include safeguards to ensure that pilots do not blindly follow HUDs for example, onto an inactive runway.

A number of studies assess how effectively HUDs provide taxi guidance (Battiste, Downs, & McCann, 1996; Jones, Quach, & Young, 2001). In low-visibility conditions, poor taxi performance is dangerous, increases fuel costs to airlines, and affects passenger schedules. McCann, Andre, Begault, Foyle, and Wenzel (1997) examined taxi performance when pilots were using T–NASA's "Scene-Linked" HUDs and 3–D moving maps. The HUDs substantially improved taxi performance over performance seen with 3–D moving maps.

EVS/SVS

EVSs are designed to increase safety in low-visibility conditions. EVSs can be added to both HUDs and HDDs, providing the pilot with infrared-derived visual cues of the external scene, including terrain and traffic. The pilot sees the real-world runway even when it is obscured by poor weather conditions. The EVS also enables views of surrounding terrain in poor lighting and weather conditions. This may help to prevent controlled flight into terrain.

The use of EVS is limited during periods of heavy rain, fog, and dust. Furthermore, as infrared only shows thermal differences, the images can be confusing during certain conditions such as when objects within a scene are of an equal temperature.

SVS is a different flight display system developed by Rockwell Collins and NASA. It provides a conformal view of the world outside using the EGPWS database to portray a picture of terrain, obstructions, and airports. SVS uses highway-in-the-sky software, giving pilots visual cues and flight path guidance. As the images provided are database derived, it is possible that important information is not available when needed, such as a new construction. Furthermore, processing latency or database integrity issues may lead to confusion when the pilot breaks through cloud cover and the image from the HUD is not the same as that provided by the SVS.

Researchers are currently exploring the possibility of combining EVS and SVS to produce an enhanced synthetic vision system. With both systems used in combination, the images, which will include possible hazardous traffic, will give the pilot the same information as would be available for a daylight, clear weather visual flight. As both systems can be presented on an HUD together, human factor design principles, pilot performance, problems, and safety concerns will need to be investigated.

CONCLUSIONS

In summary, research suggests that there are a number of advantages in using HUDs. These include increases in flight path tracking accuracy, except during cruise flight; benefits for event detection, except in the approach and landing phase and for unexpected events; lower visibility takeoff and landing; more accurate approach and landing; the elimination of head-down time; a reduction in the time taken to refocus between instruments and the external scene; and the potential to use overlaid symbology for the external scene when it is not visible, hence enhancing situation awareness. The major disadvantages of HUDs are difficulties in switching attention between the internal and external scene and difficulties in detecting unexpected events. Despite this, there is currently no evidence to suggest that the use of HUDs is associated with an increased risk of accidents.

With the use of HUDs increasing throughout commercial aviation, more research is needed to identify ways to address the issues just noted. From a practical perspective, one of the most pressing issues concerns training. We do not yet know whether it is possible to train pilots to overcome the effects of cognitive tunneling, or how much training would be needed if it was possible to do so. One option is to train pilots to scan more effectively by teaching them to take their attention away from the HUD and into the far domain (Wickens, Helleberg, Goh, Xu, & Horrey, 2001). We could not find any studies in the public domain that have addressed this issue. Other issues that need to be examined include the use of HUDs in multicrew operations, and the effects of fatigue and experience on performance when using an HUD. Although HUDs offer significant benefits to airlines in both productivity and safety, an extensive program of research is needed to ensure that these gains are realized.

ACKNOWLEDGMENTS

This research was funded by the Civil Aviation Safety Authority of Australia. We thank Michael Rodgers, Mark Wiggins and David O'Hare for their helpful comments on an earlier draft of this article.

REFERENCES

Air Accidents Investigation Branch. (2000). RAF Tornado GR1, ZA 330 and Cessna 152, G–BPZX: Main document (Aircraft Accident Rep. No, 3/2000; EW/C99/1/4). Retrieved May 2, 2003 from http://www.dft.gov.uk/stellent/groups/dft_avsafety/documents/page/dft_avsafety_502737.hcsp

Atkins, M. L., Foyle, D. C., Hooey, B. L., & McCann, R. S. (1999). Head-up display symbology for surface operations: Comparisons among scene-linked symbology sets for optimum turn navigation. In R. S. Jensen, B. Cox, J. D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth International Symposium on Aviation Psychology* (Vol. 2, pp. 784–790). Columbus: Ohio State University.

Barnette, J. F. (1976). *Role of head-up display in instrument flight* (Rep. No. AFIFC–LR–76–2). Randolf AFB, TX: Air Force Instrument Flight Center.

Battiste, V., Downs, M., & McCann, R. S. (1996). Advanced taxi map display design for low-visibility operations. In *Proceedings of the Human Factors and Ergonomics Society 40th annual meeting* (pp. 997–1001). Santa Monica, CA: HFES.

Becklen, R., & Cervone, D. (1983). Selective looking and the noticing of unexpected events. *Memory and Cognition, 11,* 601–608.

Boston, B. N., & Braun, C. C. (1996). Clutter and display conformality: Changes in cognitive capture. In *Proceedings of the Human Factors and Ergonomics Society 40th annual meeting* (pp. 57–61). Santa Monica, CA: HFES.

Dowell, S. R., Foyle, D. C., Hooey, B. L., & Williams, J. L. (2002). The effect of visual location on cognitive tunneling with superimposed HUD symbology. In *Proceedings of the 46th annual meeting of the Human Factors and Ergonomic Society* (pp. 121–125). Santa Monica, CA: HFES.

Fadden, S., Ververs, P. M., & Wickens, C. D. (1998). Costs and benefits of head-up display use: A meta-analytic approach. In *Proceedings of the Human Factors and Ergonomics Society 42nd annual meeting* (pp. 16–20). Santa Monica, CA: HFES.

Fadden, S., Ververs, P. M., & Wickens, C. D. (2000). *Pathway HUDS: Are they viable?* (Tech. Rep. ARL–00–13/NASA–00–3) Savoy: University of Illinois Institute of Aviation.

Federal Aviation Administration. (2001). *Joint advisory circular: Flight guidance system approval* (No. AC/ACJ 25.1329). Washington, DC: Author.

Federal Aviation Administration. (2002). *Human factors research and engineering division annual report.* Retrieved September 2003, from http://www.hf.faa.gov/report.htm

Fischer, E., Haines, R. F., & Price, T. A. (1980). *Cognitive issues in head-up displays* (NASA Tech. Paper No. 1711). Moffett Field, CA: NASA Ames Research Center.

Foyle, D. C., Dowell, S. R., & Hooey, B. L. (2001). Cognitive tunneling inhead-display (HUD) superimposed symbology: Effects of information location. In R. S. Jensen, L. Chang, & K. Singleton (Eds.), *Proceedings of the Eleventh International Symposium on Aviation Psychology* (pp. 143:1–143:6). Columbus: Ohio State University.

Foyle, D. C., McCann, R. S., Sanford, B. D., & Schwirzke, M. F. J. (1993). Attentional effects with sumperimposed symbology: Implications for head-up displays (HUD). In *Proceedings of the Human Factors and Ergonomics Society 37th annual meeting* (pp. 1340–1344). Santa Monica, CA: HFES.

Hofer, E. F., Braune, R. J., Boucek, G. P., & Pfaff, T. A. (2001). *Attention-switching between near and far display domains: An exploratory study of pilots' attention switching ability with head-up and head-down tactical displays in simulated flight operations* (Boeing IR&D Document No. D6–36668). Chicago: Boeing.

Hull, J. C., Gill, R. T., & Roscoe, S. N. (1982). Locus of the stimulus to visual accommodation: Where in the world, or where in the eye? *Human Factors, 24,* 311–319.

Iavecchia, J. H., Iavecchia, H. P., & Roscoe, S. N. (1988). Eye accommodation to head-up virtual images. *Human Factors, 30,* 689–702.

Jones, D. R., Quach, C. C., & Young, S. D. (2001). Runway Incursion Prevention System (RIPS): Demonstration and testing at the Dallas/Fort Worth International Airport. In T. Rosetti (Ed.), *Proceedings of the 20th Digital Avionics Systems Conference* (pp. 2D2/1–2D/11). Madison, WI: Omnipress.

Larish, I., & Wickens, C. D. (1991). *Divided attention with superimposed and separated imagery: Implications for head-up displays* (Tech. Rep. ARL–91–4/NASA HUD–91–1). Savoy: University of Illinois Institute of Aviation.

LeBlaye, P., Roumes, C., Fornette, M. P., & Valot, C. (2002). *Head up displays symbology (HUD): Prenormative study for DGAC/SFACT* (DCSD Tech. Rep. 2/05007). Toulouse, France: DCSD

Martin-Emerson, R., & Wickens, C. D. (1992). The vertical visual field and implications for the head-up display. In *Proceedings of the Human Factors Society 36th annual meeting* (pp. 1408–1412). Santa Monica, CA: HFS.

Martin-Emerson, R., & Wickens, C. D. (1993). Conformal symbology and the head-up display. *SID International Symposium Digest of Technical Papers, 24,* 191–194.

May, P. A., & Wickens, C. D. (1995). The role of visual attention in head-up displays: Design implications for varying symbol intensity. In *Proceedings of the Human Factors and Ergonomics Society 39th annual meeting* (pp. 50–54). Santa Monica, CA: HFES.

McCann, R. S., Andre, A. D., Begault, D. R., Foyle, D. C., & Wenzel, E. M. (1997). Enhancing taxi performance under low visibility: Are moving maps enough? In *Proceedings of the Human Factors and Ergonomics Society 41st annual meeting* (pp. 37–41). Santa Monica, CA: HFES

McCann, R. S., Lynch, J., Foyle, D. C., & Johnston, J. C. (1993). Modelling attentional effects with head-up displays. In *Proceedings of the Human Factors and Ergonomics Society 37th annual meeting* (pp. 1345–1349). Santa Monica, CA: HFES.

Moodi, M. (1995). *Head-up display supplemental information package* (Boeing Document No. D6–81703). Chicago: Boeing.

Naish, J. M. (1964). Combination of information in superimposed visual fields. *Nature, 202,* 641–646.

Newman, R. L. (1980). *Operational problems with head-up displays during instrument flight* (Rep. No. AFAMRL–TR–80–116). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory.

Newman, R. L. (1987). Response to Roscoe, "The trouble with HUDs and HMDs". *Human Factors Society Bulletin, 30*(11), 3–5.

Newman, R. L. (1995). *Head-up displays: Designing the way ahead.* Aldershot, England: Ashgate.

Newman, R. L. (2000). HUDs, HMDs, and SDO: A problem or a bad reputation. (Report). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory.

Norman, J., & Ehrlich, S., (1986). Visual accommodation and virtual image displays: Target detection and recognition. *Human Factors, 28,* 131–151.

Roscoe, S. N. (1987). The trouble with virtual images revisited. *Human Factors Society Bulletin, 30*(11), 3–5.

Simons, D. J. (2000). Attentional capture and inattentional blindness. *Trends in Cognitive Sciences, 4,* 147–155.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28,* 1059–1074.

Ververs, P. M., & Wickens, C. D. (1996). *Allocation of attention with head-up displays* (Tech. Rep. ARL–96–1/FAA–96–1). Savoy: University of Illinois Institute of Aviation.

Ververs, P. M., & Wickens, C. D. (1998). *Conformal flight path symbology for head-up displays: Defining the distribution of visual attention in three-dimensional space*. (Tech. Rep. ARL–9–5/FAA–98–1). Savoy: University of Illinois Institute of Aviation.

Ververs, P. M., & Wickens, C. D. (2000). Designing head-up displays (HUDs) to support flight path guidance while minimizing effects of cognitive tunneling. In *Proceedings of the IEA 2000/HFES 2000 Congress*. Santa Monica, CA: HFES.

Weintraub, D. J. (1987). HUDs, HMDs, and common sense: Polishing virtual images. *Human Factors Bulletin, 30*(10), 1–6.

Weintraub, D. J., & Ensing, M. (1992). *Human factors issues in head-up display design: The book of HUD* (SOAR, CSERIAC 92–2). Wright-Patterson Air Force Base, OH: Crew Station Ergonomics Information Analysis Center.

Weintraub, D. J., Haines, R. F., & Randle, R. J. (1985). Head-up display (HUD) utility: 2. Runway to HUD transition monitoring eye focus and decision times. In *Proceedings of the Human Factors Society 29th annual meeting* (pp. 615–619). Santa Monica, CA: HFS.

Wickens, C. D. (1997). *Attentional processes in GA head-up display design* (Tech. Rep. ARL–97–8/FAA–97–3). Savoy: University of Illinois Institute of Aviation Research Lab.

Wickens, C. D., Helleberg, J., Goh, J., Xu, X., & Horrey, W. J. (2001). *Pilot task management: Testing an attentional expected value model of visual scanning* (Tech. Rep. ARL–01–14/NASA–01–7). Savoy: University of Illinois Aviation Research Lab.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.

Wickens, C. D., & Long, J. (1994). Conformal symbology, attention shifts, and the head-up display. In *Proceedings of the Human Factors and Ergonomics Society 38th annual meeting* (pp. 6–10). Santa Monica, CA: HFES.

Wickens, C. D., & Long, J. (1995). Object versus space-based models of visual attention: Implication for the design of head-up displays. *Journal of Experimental Psychology: Applied, 1,* 179–194.

Zenyuh, J. P., Reising, J. M., McClain, J. E., Barbato, D. J., & Hartsock, D. C. (1987). Advanced head-up display symbology: Aiding unusual attitude recovery. In *Proceedings of the Human*

Factors and Ergonomics Society 31st annual meeting (pp. 1067–1071). Santa Monica, CA: HFES.

Zuschlag, M. (2001). Issues and research needs concerning the use of head-up displays in air transports. In T. Rosetti (Ed.), *Proceedings of the 20th Digital Avionic Systems Conference* (pp. 2A4/1–2A4/8). Madison, WI: Omnipress

Zuschlag, M. (2003). Certifying head-up displays. *Human Factors Newsletter,* 02–22.

Manuscript First Received: July 2004