PATHWAY HUDs: ARE THEY VIABLE?

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Abstract

We describe two experiments that examine the concept of 3D pathway displays in a head-up location for aircraft approach, landing and taxi. In both experiments, our interests focus on both guidance performance and pilot strategies in dividing, focusing and allocating attention between flight path information, to monitor for discrete events on the instrument panel (near domain) and in the world beyond (far domain). In Experiment 1, the 3D pathway HUD is compared with a conventional 2D ILS flight director HUD, and the former was found to produce substantially better flight path performance, with few or no costs to the detection of expected discrete events. Some evidence was provided for attentional tunneling of the pathway HUD inhibiting the detection of unexpected events. In Experiment 2, the pathway display was compared in a head-up and head-down location. A high level of guidance performance was maintained in both locations. There was a slight HUD cost for vertical tracking in the air, which was offset by a HUD benefit for event detection and for lateral tracking during taxi (i.e., on the ground). The collective results of both experiments are interpreted within the framework of object and space-based theories of visual attention, and point to the conclusion that pathway HUDs combine the independent advantages of both pathways and HUDs, particularly during ground operations.
INTRODUCTION

Three concepts in aviation display technology which have the potential to support pilot performance in navigating through a crowded airspace are examined in the experiments we report here. The most mature of these concepts is the head-up display or HUD, which has a history in military aviation (see Newman, 1995; Weintraub and Ensing, 1992). HUDs have also become fixtures in many commercial airlines within the last decade (Scott, 1999), and are beginning to appear in corporate and general aviation aircraft. The second concept is the “highway in the sky,” sometimes referred to as a tunnel or pathway, which provides both prediction and preview of a flight path in a forward-looking “3D format.” While pathway displays have been evaluated since the 1970s, (Wilckens, 1973), and have received some recent flight tests (Theunissen, 1997; Flohr and Huisman, 1997; Sachs, Dobler, and Hermle, 1998; Kubbat, Lenhart, and von Viebahn, 1998; von Viebahn, 1998), they have yet to appear as a commercial product. The third concept is that of “phase adaptive displays,” which can automatically reconfigure to conform to the pilot’s changing information needs in different phases of flight (Hammer, 1999). In particular, our interest here is in reconfiguration during the transition from air to ground navigation during a low visibility landing.

In two experiments we report the effects of these three display concepts as they are relevant to a design concept that has great potential but has not yet been subject to controlled experimental evaluation: the pathway HUD. Given the demonstrated value of both pathways and HUDs as they have been examined independently, the potential value of the pathway HUD to aviation is self-evident. Furthermore, the investigation of these two concepts also joins two important issues in the theory of attention, establishing the relevance of these issues to applied design. These are object-based theories of visual attention (Kramer and Jacobson, 1991; Wickens and Long, 1995) and the concept of “attentional tunneling.” In the following paper, we first overview the most relevant findings relating head-up displays to visual attention; we then review the benefits of pathway displays, and then report two experiments that address the interaction between these two concepts as pilots transition from the air to the ground in a simulated low visibility landing task.

HUDs. The literature regarding the strengths and weaknesses of head-up displays compared to head-down presentation of flight information has been extensively reviewed elsewhere (Weintraub and Ensing, 1992; Wickens and Long, 1995; Wickens, 1997; Fadden, Ververs, and Wickens 1998; Ververs and Wickens, 1998a). In general, HUDs appear to offer several benefits, relative to the head-down counterpart of instruments conveying equivalent information. The causes of such benefits can be classified into four general categories.

1. Because HUDs are usually collimated at optical infinity, they reduce (although they do not always eliminate) the problems of visual reaccommodation between instrument viewing, and viewing of the “far domain” or outside world beyond the cockpit, necessary for such tasks as traffic monitoring or assuring an open runway.

2. Because HUDs are superimposed over the outside world, they reduce the amount of visual scanning that must be accomplished to monitor both domains for events that may occur. With traditional head-down instrumentation, there is a likelihood that an event may occur in one
domain (instrument panel or outside world), while the eyes are fixated on the other, thereby leaving the event to be detected in peripheral vision (poorly done if the event is not salient), or to be undetected altogether until the scan visits the previously unattended domain. The HUD can reduce this problem, although it may not eliminate it, since simultaneous viewing of two overlaid scenes does not guarantee simultaneous detection of events in both scenes (Fischer, Haines, and Price, 1980; Neisser and Becklen, 1975; Tufano, 1997; Wickens and Long, 1995).

3. When piloting tasks require the specific integration of information between the two domains, added benefits are obtained when the HUD information can be configured such that it overlays its far domain counterpart. This imagery is sometimes referred to as conformal imagery, examples being a horizon line that overlays the true horizon, or a runway overlay that will overlay the trapezoid formed by a true runway (Weintraub and Ensing, 1992; Wickens and Long, 1995). Foyle et al. (1996) have referred to this form of imagery as “scene-linking” because the common form of the two images (on the HUD and in the world beyond), and their common motion, as the aircraft moves through space, serves to “link” the two together.

4. A characteristic of many HUDs is that their image representations of the aircraft moving through space is based upon inertial guidance or satellite navigational information rather than the air-referenced characteristics of most conventional head-down instruments. As a consequence, the HUD can better present information that is referenced to ground topography and landmarks. One class of such information, mentioned above, is the conformal symbology which overlays a far domain counterpart. However, the HUD can also depict information that overlays relevant regions in air space over the ground, even if these regions do not correspond to physically viewable parts of the outside world. An example might be a desired flight path “pathway in the sky.” We refer to such aspects of the symbology as “virtually conformal.”

Against this considerable array of human factors benefits there is one important cost of HUDs: the cost of the clutter of overlapping images, potentially masking events or relevant information in either domain (Ververs and Wickens, 1998a; Martin-Emerson and Wickens, 1997; Hofer et al., 2000). Such clutter costs may not only result from the physical masking of the far domain by the near domain, but also from perceptual or cognitive masking, whereby objects become difficult to detect in a visual scene with many overlapping images, even if these objects are not totally obscured. These clutter costs are greater with non-conformal imagery than with conformal imagery, since in the latter case, the imagery adds few additional “marks” to the display beyond that which already exists in the far domain. As a result of this difference, the clutter costs will partially offset or negate the “reduced scanning benefits” of non-conformal imagery, but will not offset those benefits of conformal imagery. Indeed Wickens and Long (1995), Foyle et al. (1996), and Levy et al. (1998) have found that the advantages of HUDs are greater, when conformal or scene-linked imagery is employed.

While the clutter of non-conformal imagery may mask all far domain objects (or such imagery may be perceptually degraded by the far domain imagery itself), there is a further concern with HUD imagery that relates to the detection of truly unexpected events. In a classic
study involving a landing simulation, Fischer, Haines, and Price (1980) found that an unexpected runway incursion was less detectable when viewed through the HUD, than when pilots were simulating head-down flying with conventional flight instruments. Although their results were not subjected to statistical testing because of the low power, Wickens and Long (1995) found a similar phenomenon to be statistically reliable, even when the format of instrumentation was identical between the two locations. Hofer, Braune, Boucek, and Pfaff (2000) have recently replicated this effect. Such a phenomenon may be labeled as “attentional tunneling,” suggesting an unwanted or undesirable tendency to keep attending to information in one domain (the near domain instrumentation), even when important signals are present in the other (the far domain world). A meta-analysis of HUD studies suggests other examples of attentional tunneling inhibiting the detection of unexpected events to a greater extent when they are viewed through a HUD than when information is displayed head-down.

Prior data have therefore suggested that HUD presentation of imagery conformal with ground features will provide an advantage over HUD presentation of non-conformal imagery. But such findings have only been observed when truly conformal imagery is used to support flight guidance (e.g. overlapping runway symbology or a horizon line), but not when such imagery is virtually conformal, as it is the pathway display. It may be that the pathway, containing more displayed elements, creates additional clutter to offset the benefits. Furthermore, it is possible that in the absence of a far domain counterpart with which to “link,” the benefits to divided attention between the near and far domain, offered by object-based theories of attention will be diminished, if not eliminated. Before presenting the specific hypotheses to be examined in the experiments however, we will now review some of the specific benefits of the pathway display, as it has been evaluated in a head-down location.

Pathway displays. The tunnel or pathway in the sky display essentially consists of three elements: a tunnel or command display, which presents preview of where the aircraft should be in the future, a predictor symbol (velocity vector) which predicts where the aircraft will be given some assumptions about future flight path control, and a 3-dimensional perspective, which represents this information in depth along the pilot’s forward viewing axis. (Whether this is referred to as a “tunnel” or as a “highway” generally refers to whether it portrays boxes to fly through (e.g., Theunissen, 1997) or a 2D surface in depth, to fly along (e.g., Reising et al., 1995). We use the more generic term “pathway” to characterize both.) Tracking research has long ago established the independent benefits of both prediction and preview (e.g., Lintern, Roscoe, and Sivier, 1990; see Wickens, 1986 for a review); while the added benefits to flight path guidance of presenting such information in 3D perspective has been conclusively established more recently (Haskell and Wickens, 1993; Wickens and Prevett, 1995; Theunissen, 1997). The three dimensionality of the pathway display is potentially valuable because it offers the opportunity to express the flight path in the same ego-referenced format as the pilot’s forward field of view; that is, as a virtually conformal image of a hypothetical tunnel seen forward of the aircraft. Furthermore, if presented while the pilot were on the ground taxiing, a pathway representation of the desired ground track (e.g., runway or taxiway) would be a truly conformal display; as has been examined by McCann et al. (1996), Foyle et al. (1996), and Lasswell and Wickens (1995), and found to support effective tracking.
While truly conformal displays have thus been evaluated, and in some experiments found to be superior to head-down representation of the same information (Lasswell and Wickens, 1995; Wickens and Long, 1995), few corresponding evaluations of virtually conformal HUDs appear to have been carried out. Reising, Liggett, Solz, and Hartsock (1995) did examine the pathway as a HUD. However, their simulation presented no far domain imagery behind the HUD, so that the view was essentially the same as a head-down presentation of the tunnel (presented at a slightly higher location in the cockpit); thus there was no opportunity to examine attentional distribution between near and far domains, as there was no far domain imagery to be processed. In particular, the critical issue of traffic detection through the HUD was not examined.

In one study that is a precursor to the experiments we report here, Fadden and Wickens (1997) compared flight path performance with a pathway display in the head-up and head-down location. Pilots flew a winding path in cruise flight, and were responsible for detecting events in both the near domain (command airspeed changes) and far domain (traffic). The results revealed few differences in flight path control as a function of display location, but some influence on attentional strategies, such that the head-up location induced more careful monitoring of the far domain (air traffic detection) while the head-down location induced more accurate monitoring of the instrument panel (airspeed change detection). The results of this study warrant caution in generalizing to a wider range of flight environments, in part because the pathway HUD was “minimalist” with less than the full complement of accepted HUD symbology, and in part because the simulation was only carried out in cruise flight, and did not examine the landing phase, where HUDs are assumed to be of greatest value.

In the two experiments to be reported here, we evaluate the effectiveness of a 3D pathway HUD when contrasted with more conventional 2D HUD symbology (Experiment 1), and when contrasted with the same pathway presented head-down (Experiment 2). Thus in Experiment 1, we are able to assess if the same benefits of 3D pathways relative to 2D displays that have been observed head-down, are preserved when the imagery is superimposed against a cluttered background, and when far domain traffic must be monitored behind the complex imagery of the pathway. In Experiment 2, we are able to assess if the benefits of the head-up over head-down location for flight path guidance and event (e.g., traffic) monitoring which have been observed in prior research, are preserved when the imagery is the more complex imagery of the pathway.

Both experiments simulate a full approach-landing-taxi scenario. The inclusion of this multi-phase scenario in each experiment is of both practical and theoretical importance. Of practical importance is the establishment of how HUD symbology can adapt or change between the air and the ground environment, given that the two environments impose different task demands, and somewhat different relevant information sources (Fadden, 1999; Ververs and Wickens, 1998b). The theoretical importance of the distinction between ground and air is offered in the context of the object-based models of visual attention discussed above (Kramer and Jacobson, 1991; Martin-Emerson and Wickens, 1997; Wickens and Long, 1995). According to the premise of such models, parallel processing of all parts of a single object will be improved. Hence, as applied to conformal imagery that can be “scene-linked” to a far domain counterpart, such scene-linking should support not only the tracking, guided by the symbology, but also the
division of attention as a whole between the near and far domain, supporting more effective monitoring and event detection in both domains. This scene-linking can take place during the taxi phase on the ground, since a pathway overlays a physical counterpart on the ground (the runway outline; McCann et al., 1996; Lasswell and Wickens, 1995). However in the air, the pathway does not overlay any visible, physical object on the ground; it is not “scene-linked” to anything, and hence it is only virtually conformal. Our question is whether this virtual conformal property will also facilitate the division of attention between the near and far domain (and hence facilitate event monitoring), or whether instead, in the absence of a far domain entity with which to conform or overlay, the divided attention benefits of the pathway may be diminished in the air relative to the ground.

Because prior research has shown differential effects of display location (HUD vs head-down) on event monitoring, as a function of whether the event was relatively routine (showing HUD benefits), or completely surprising (the runway incursion showing HUD costs), both types of events were included in the scenarios, enabling us to examine the possible influence of pathway HUDs on attentional tunneling. Finally, in both experiments we examined the effectiveness of different kinds of phase adaptive transitions between the air symbology and the ground (taxiway) symbology; a “seamless” transition, in which the former gradually changed to the latter, and a “seamed” or abrupt transition. The effects of these differences were found to be muted, and will not be discussed in the current article, but can be found in the detailed reports of each experiment (Experiment 1: Ververs and Wickens, 1998b; Experiment 2: Fadden, 1999).

In Experiment 1 (HUD symbology effect), pilots flew a series of simulated approach-landing-taxi cycles, with either a conventional HUD, designed to approximate the properties of a commercially available product, or a pathway HUD. Flight performance and traffic detection were compared when the far domain was either visible, or was obscured by clouds. On three separate trials, a truly unexpected event was presented.

Experiment 2 (pathway location effect) used a similar paradigm, with minor changes that will be described. However, the major difference from Experiment 1 is that head-up and head-down locations of the pathway (tunnel) display only were compared.

EXPERIMENT 1

Method

Design and participants. A fully crossed 2 (partially conformal vs. conformal) x 2 (seamed vs. seamless transition) design was used to investigate the effects on flight path performance and detection tasks. Twenty certificated flight instructors were recruited from the University of Illinois Institute of Aviation. The pilots averaged 869 flight hours ranging between 280 and 2140 hours. They were paid for their participation in the three-session study.

Apparatus and symbology. The pilots viewed the HUD symbology while seated in a low fidelity simulator. The environment consisted of two 3.0 x 2.2 meter screens on which the out-the-window (OTW) scenery and the HUD symbology were presented. An Evans and Sutherland SPX500 System generated the OTW scene, while a Silicon Graphics IRIS workstation generated
the instrumentation and aerodynamic model of a general aviation aircraft. The OTW scene consisted of generic terrain typical of the Midwestern United States and a single airport with three runways, taxiways, and a terminal building. The only available instrumentation was the projected head-up symbology that overlaid the far domain scene. The head-up display covered a visual angle of approximately 33.5 degrees across and 28.0 degrees down.

The pilots controlled the simulation using a two-axis joystick. In flight, moving the joystick forward and back controlled pitch while left and right enabled roll. Thrust was input using a hat on the back of the joystick. On the ground, control was limited to two dimensions with left and right controlling lateral movement (rate of turn) and the hat controlling ground speed with a lag.

There were two instrumentation sets representing the 3D pathway and 2D symbology for both air and ground operations. Both symbology sets provided a full set of instrumentation including a heading scale, altimeter, airspeed indicator, DME, horizon line, bank indicator, wind velocity and direction, and a radio altimeter below 1000 feet. The air-referenced 3D pathway symbology shown in Figure 1 was a perspective flight path that provided preview of upcoming turns and altitude changes. To reduce the amount of clutter imposed by the tunnel, a limited preview of 3 frames ahead was provided. The 2D set provided flight guidance using a more traditional flight director similar to ILS approach symbology (see Figure 2). The lateral and vertical lines forming across in the middle of Figure 2 represented the lateral (localizer) and vertical (glide slope) deviation away from the assigned course. Since the needles were conformal with the direction of the path, if the needle appeared off-center to the left then the flight path was located to the left. The horizon line was conformal with the true horizon.

Figure 1. Virtually conformal flight path symbology depicting the tunnel-in-the-sky. In this rendering the plane is flying straight ahead, so the aircraft symbol directly overlaps the predictor symbol. The round airspeed gauge to be tracked is shown at the left. Airspeed is redundantly coded digitally, with the command value at the top of the round dial (140) and the momentary actual value in the middle (142).
Pathway and 2D symbology sets were also created for the ground navigation tasks. The landing symbology group contained information needed by the pilot to direct the aircraft to touchdown onto the runway and to quickly exit off the runway in a high speed roll out and turnoff (ROTO). The instrumentation included a heading scale, ground speed, horizon line and the aircraft position along the assigned path. The 3D conformal pathway set was truly conformal since the symbology elements included scene-linked perspective cones that lined the assigned path and became part of the environment. The symbology was modeled after McCann et al. (1996) T-NASA symbology (see Figure 3). The 2D set was a plan-view depiction of the runway and turnoff with the pilot’s aircraft superimposed on the diagram (see Figure 4).
The 3D pathway and 2D symbology types were never paired together. In other words, the pathway air-referenced symbology set only transitioned into the pathway ground-referenced symbology set, while the 2D ILS set only transitioned into the 2D ground set. The transition took place around 200 feet agl, which was also the decision height the pilots were given. In addition to the two symbology sets, pilots also landed with either an abrupt transition between air and ground symbology, or a graduate “seamless” transition. As noted, we will not discuss these differences due to transition type here (they had only a small impact on the results; see Ververs and Wickens for details).

Procedure

The experimental session began with a training period during which the pilots became familiar with the symbology sets and the aerodynamics of the aircraft. They flew a minimum of four practice trials with each of the two display symbology sets for a minimum of eight practice trials. The pilots flew six different curved approaches to one of six runways. Pilots were given a missed approach procedure before each approach and on two of the eight practice trials they were required to fly a missed approach due to a wind shear warning or conditions reducing the visibility below decision height.

In the experimental session, the pilots flew 51 curved approaches of 4 different blocks of 12 or 13 trials using one of the two display symbology sets. Three of these trials, distributed unpredictably, presented truly unexpected events that required the pilot to fly a missed approach; the data from these trials were separated from the rest to be analyzed individually. These unexpected events were included since the element of surprise often has distinct, unanticipated
effects on performance. The unsuspecting nature of these events offered the best opportunity to investigate the availability of spare resources and the expression of attentional tunneling.

The trials began with the pilot enroute to the airport about 5 miles away, at a final approach fix. The sequence of events was equivalent for both display types. The pilots were positioned above a cloud layer, which they flew through and broke out of between 900 and 100 feet above the ground. Pilots were explicitly instructed about particularly unsafe conditions that would preclude a safe landing such as visibility too low to see the runway at the decision height, or wind shear or wake vortex warnings presented on the symbology. These conditions were presented twice in each block of trials. The pilots were informed that any time they determined that the conditions were unsafe they should fly a missed approach. On two occasions the pilots were confronted with conditions for which they were not previously warned, but which required them to fly a missed approach. These conditions were truly unexpected aircraft incursions; in one case an aircraft unexpectedly taxied onto the active runway and in the other case the aircraft on the parallel approach intruded into the path of the aircraft on final approach. The runway incursion was indicated by an aircraft crossing the “hold short” line on the runway. The parallel traffic incursion was first noted by the parallel traffic symbol on the instrumentation siding closer the flight director. If the pilot did not notice this incursion when he or she broke out of the clouds, the traffic was then visible in the far domain. The third truly unexpected event was the positioning of an aircraft on the pilot’s assigned high speed turnoff from the active runway. The presentation order of these unexpected events was counterbalanced across pilots.

The main task of the pilots was to closely track the approach path as commanded by the instrumentation and as shown on an approach plate that was provided to them. While on the approach, three airspeed commands were issued by changing the commanded value, located above the airspeed indicator. The pilots needed to detect this change and respond by reducing thrust to obtain the newly assigned speed. When the pilot broke out of the clouds, he or she needed to call out ‘runway in sight’ and the time was recorded. If the runway was not visible by the 200-foot decision height, pilots were instructed to fly a missed approach. An additional task required the pilot to scan the environment for traffic. Twice per trial a jet trainer aircraft appeared in the pilot’s airspace; each pilot was instructed to respond by pressing the trigger on the joystick.

Results: Experiment 1

Repeated measures of analyses of variance (ANOVAs) were used to analyze much of the data in these experiments. Throughout the Results Section the graphs are plotted with averages and error bars, which represent 95% confidence intervals. As noted, the (small) effects of transition type will not be reported here. These do not influence the conclusions drawn regarding the influences of display symbology.

Flight path tracking. Mean Absolute Error (MAE) was computed for the tracking of the assigned altitude, heading, and airspeed. The samples were recorded and averaged by the nine flight phases: (1) curved approach, (2) long final approach from approximately 1100 to 400 feet, (3) – (6) transition periods lasting 8 seconds each from 400 through 100 feet, (7) short final approach (approximately 100 feet to landing), (8) landing and roll out, and finally (9) the turnoff.
Altitude and heading tracking. Figure 5 depicts the altitude tracking error while the pilots were flying with either the tunnel-in-the-sky or the ILS symbology set in each of the 7 flight phases. There were main effects of symbology $F(1,19)=111.00, p < 0.01$ and phase $F(6,114) = 67.52, p < 0.01$, and a symbology by phase interaction ($F(6, 114) = 93.28, p < 0.01$). The graph indicates that for all the phases except the two just preceding the landing, the tunnel provided a significantly superior display format for maintaining vertical tracking relative to the ILS symbology. As the pilots approached the runway, the error associated with flying with the ILS symbology set was reduced. Similar findings were indicated for the heading tracking error, as shown in Figure 6. Again, there were main effects of symbology ($F(1,19) = 280.05, p < .01$) and phase ($F(6,114) = 124.55, p < 0.01$), and significant interaction between them ($F(6,114) = 198.04, p < 0.01$). It is important to note that all of the curves in the approach occurred in the first phase of flight, and after this phase the pilots were lining up for the approach to the runway on a stable glide slope localizer.

![Altitude Tracking](image)

Figure 5. Altitude tracking with the ILS and tunnel-in-the-sky symbology, as a function of phase of flight.
The phases of flight were broken down further to understand how weather (affecting visibility of the far domain in the air) modulated performance. Altitude and heading tracking were examined during both cloudy (prebreakout) and clear (post breakout) conditions. Identical results were found for altitude and heading tracking so we will only discuss one (heading tracking). There was a main effect of breakout ($F(1,19) = 171.79, p < .01$) and an interaction of symbology type with breakout ($F(1,19) = 262.37, p < 0.01$). Figure 7 indicates that only when the pilots were flying with the 2D ILS symbology was their performance hurt by the lack of a far domain reference (i.e., prebreakout). We inferred that pilots flying with the pathway relied less on the environmental cues and therefore their performance was not modulated by the weather conditions. This result may also indicate that the pilots flying with the pathway may have been overly reliant on the tunnel for flight path guidance because of its intuitive yet precise flight direction, thereby circumventing the need for them to reference the far domain, a valuable resource for situation awareness information.

Figure 6. Heading tracking with the ILS symbology and tunnel-in-the-sky symbology, as a function of phase of flight.

Figure 7. Heading tracking error with the ILS symbology and the tunnel before and after breakout from the clouds. One standard error is represented by the brackets.
Airspeed tracking. Airspeed tracking was analyzed slightly differently from altitude and heading tracking since pilot performance was not expected to be directly assisted by reference to the outside environment because visual cues to maintain airspeed were not available. Of interest is the fact that the airspeed is represented identically on both symbology sets, so differences in performance would be based solely on the difference in availability of spare resources and the distribution of attention, and not necessarily on direct features of the display design. As shown in Figure 8, airspeed tracking was better when the pilots were flying with the 3D pathway than with the ILS symbology (F(1,19) = 10.84, p < 0.01), an advantage that was amplified during the earlier flight phases (interaction F(6,114) = 2.82, p < 0.05). Thus, the pilots flying with the pathway had more spare resources to track symbology changes.

![Airspeed Tracking](image)

**Figure 8.** Airspeed tracking error with the ILS and tunnel symbology as a function of the seven flight phases.

Final approach and landing performance. Several measures of performance were used to assess differences in the symbology type during the final approach and landing. For sake of brevity, only a few measures are discussed here. More complete details may be found in Ververs and Wickens (1998b). The results yielded no significant difference between displays in the quality of landing (segment 8) or of taxi performance (lateral deviations or speed), although there was a non-significant trend favoring smaller deviations from the center of the taxiway with the 3D pathway HUD (F(1,19) = 4.00; p = 0.06).

Expected detection tasks. There were three types of expected detection tasks, those requiring focused attention on the symbology to detect airspeed command changes, and those requiring focused attention on the far domain environment for runway and traffic detection. As shown in Figure 9, the analysis of the airspeed detection accuracy and response time indicated a performance advantage for the pilots flying with the pathway display (F(1,19) = 11.58, p < 0.01) and F(1,19) = 53.19, p < 0.01, respectively).
The time in which pilots reported “runway in sight” did not differ significantly between the two formats. Both the accuracy and the average response time to detect traffic revealed main effects of symbology. There was a speed accuracy tradeoff with the pilots flying the tunnel having 11% higher accuracy in detecting traffic ($F(1,19) = 9.70, p < 0.01$) but a 1.34 second slower mean response time ($F(1,19) = 30.97, p < 0.01$). This tradeoff can be explained by considering the distribution of visual attention while flying with the tunnel. All traffic initially appeared near the middle of the pilot’s forward field of view beyond the symbology. As the pilot flew toward the (non-conflicting) traffic, its relative location would move toward the periphery of the display. If the pilot’s attention was distributed over a larger portion of X-Y space (as inferred to be the case when they were flying with the tunnel; see Figure 1), then the pilot would be able to detect more traffic in the periphery; however, this wider attention distribution would also lead to longer response times because of the added time required for the plane to reach the more peripheral regions of the display.

In contrast, with the 2D ILS display, in which critical guidance information was centralized at the intersection of the glideslope to localizer needles (see Figure 2), a plane not detected early would be more likely to be missed once its relative motion brought it to the periphery of the display.

**Unexpected detection tasks.** We employed two types of unexpected detection tasks that had a low probability: the occurrence of a wind shear or wake vortex warning on the symbology.
and the presence of low visibility conditions below decision height. Each of these tasks occurred once per block of trials. There were also three truly unexpected or surprising tasks: the parallel traffic incursion, the runway incursion, and the presence of traffic in the pilots’ assigned turnoff. Each of these events occurred only once in the entire three-day experiment.

None of the low-probability unexpected events showed a reliable difference in detection latency or accuracy between the two display types. For the truly surprising events, no significant differences were found in the time to acknowledge the parallel traffic or runway incursions. However, the time to resolve the runway incursion (i.e., initiate the missed approach) was delayed by four seconds with the pathway display (15.2 sec) relative to the ILS display (11.0 sec), a non-significant trend ($t(18) = 1.58, p = 0.07$). This trend with the low power comparison (one data point per pilot) is of importance both because it is in the opposite direction from the display effects on expected event detection, and because it is consistent with the pattern of previous results revealing that HUD display features may have opposite effects on the detection of expected versus surprising events (Wickens and Long, 1995; Fadden, Ververs, and Wickens, 1998). These previous studies have compared display locations, rather than HUD formats.

The third unexpected event occurred during ground operations. Half the pilots witnessed the unexpected traffic blocking the high speed turnoff while taxiing with the pathway scene-linked symbology set and the other half while using the plan-view symbology set. Due to an error in the data collection procedure, data were only collected from eight pilots, therefore, formal analyses were not performed. It is important to reserve judgment about the data because of its limited scope, however as shown in Table 1, the findings indicate an advantage for the perspective pathway view with a substantial savings in time before the impact (26.08 seconds) and distance (381.5 feet), relative to the nonconformal ground symbology set. The greater separation between ownship and the other aircraft provides some indication that the pilots may have been more keenly aware of the turnoff traffic in the scene-linked (pathway) viewing condition.

Table 1

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<tr>
<th>Event</th>
<th>Measurement</th>
<th>Symbology</th>
<th>Average Responses</th>
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<td>Time before impact</td>
<td>Perspective</td>
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<td>Plan view</td>
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<td></td>
<td>Distance between ownship and traffic</td>
<td>Perspective</td>
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<td></td>
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<td>Plan view</td>
<td>277.29 feet</td>
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Discussion: Experiment 1

The results of Experiment 1 were fairly conclusive in revealing the benefits of the 3D pathway over the 2D ILS display, when both were presented in a head-up location. These benefits were pronounced in flight path control, as anticipated given previous demonstrations of the benefits of both prediction and preview in tracking (Jensen, 1981; Wickens, 1986). Furthermore, not only did the pathway offer more precise tracking than the ILS display, but the absolute level of flight path deviations with the pathway, around 20 feet RMS, was small and sustained at this level through all phases of the approach.

The data offered some evidence that the effect of HUD format was revealed not just in flight control performance, but also in terms of changed attentional strategies, in a manner similar to that reported by Martin-Emerson and Wickens (1997). That is, those pilots flying with the ILS, both here and in the previous study, showed evidence for a discrete attention switching strategy between the near and far domain as well as a focus of attention on the middle of the display. However, those flying with the tunnel showed a greater tendency to maintain attention on the near domain instrumentation, also showing faster RT to the airspeed changes but slightly (4 sec) slower responses in resolving the unexpected runway incursion and calling runway in sight. Martin-Emerson and Wickens (1997) had also observed that pilots flying with a 3D perspective HUD imagery were slower in calling out “runway in sight.” It should be noted that the runway incursion RT was quite long for pilots in both HUD conditions, consistent with earlier observations by Fischer, Haines, and Price (1980) and by Wickens and Long (1995).

The longer delay for incursion detection with the pathway display might be attributed to the “compellingness” or attention tunneling/capture characteristics of a 3D tunnel display, an effect that has been both inferred from detection data (Olmos, Chudy, and Wickens, 2000) and directly observed from visual scanning data (Flemisch and Onken, 2000).

Results regarding the detection of the more expected far domain aircraft were partially consistent with this attention allocation strategy; those flying the tunnel were slower in detecting such traffic. However, they were considerably more accurate (detecting more aircraft), presumably a benefit of a wider “breadth” of attention fostered by the tunnel which occupied a wider area as compared with the more narrow focus on the glideslope-localizer intersection of the ILS.

Fewer overall differences between the pathway and the non-conformal instrumentation were observed on the ground than in the air. The small non-significant trend for more accurate tracking with the pathway is not considered to be of practical importance. However, it is noteworthy that the four-second conformal symbology cost for truly surprising event detection in the air (the runway incursion) was eliminated on the ground, with a tendency for a reversed effect (better performance with the conformal pathway), an effect that will be seen to have importance in interpreting the results of Experiment 2.
Thus on the whole, Experiment 1 reveals major benefits (to flight path tracking) with the tunnel or pathway HUD, with only relatively minor costs, when contrasted with the a HUD using conventional symbology. Such benefits are consistent with those benefits observed when the pathway is situated head-down (Wickens and Prevett, 1995) and are related to its 3D representation (Haskell and Wickens, 1993) as well as the preview and prediction that are offered (Theunissen, 1997; Wickens, Haskell, and Harte, 1989; Jensen, 1981). These results clearly extend those of Wickens and Long (1995) and Martin-Emerson and Wickens (1997) whose conformal HUD only involved a runway overlay. Yet the design of Experiment 1 was unable to reveal any possible advantages or costs of presenting the pathway in the head-up versus head-down location. This comparison was the explicit goal of Experiment 2, which has many features in common with Experiment 1. The same fundamental pathway display used in Experiment 1, with some modifications, was presented in either a head-up or head-down location, during an approach, final landing and taxiway scenario.

EXPERIMENT 2

Method

Design and participants. A fully crossed 2 (head-up versus head-down) x 2 (seamed vs. seamless transition) factorial design was used to explore differences in performance related to display location and transition type. Twenty-six pilots were recruited from the University of Illinois community, and the number of flight hours averaged 1017 (ranging from 160 to 12,500 hours). All pilots held at least an instrument rating, and 21 were certificated flight instructors. Each pilot was paid for participating in the three-hour experimental session.

Apparatus and symbology. The apparatus and setup were the same as in Experiment 1, although a 3D pathway instrumentation set was presented to pilots in both display locations. The displays used for flight, landing, and taxi are presented in Figures 10, 11 and 12, respectively. The displays were modified from those used in the first experiment, with the most notable difference being the implementation of scene-linked digital instrumentation. In-flight, airspeed and altitude readings were attached to the pathway (see Figure 10) to encourage pilots to divide attention between the pathway and the outside scene (McCann et al., 1996). The landing display (see Figure 11) consisted of a simplified pathway view, including aircraft position, actual and commanded speed, and the distance to the runway turnoff. The taxi display (see Figure 12) was similar to that used in Experiment 1.
Figure 10. Symbology set used for cruise flight and final approach (Experiment 2). The printed words are for explanation to the reader and were not part of the symbology viewed by the pilots.

Figure 11. Symbology set used for landing operations (Experiment 2).
Figure 12. Symbology set used for taxi operations (Experiment 2).

As in Experiment 1, the display was changed in accordance with flight phase transitions. The flight display was replaced with the landing display when the aircraft was about to touch down at a considerably lower altitude (50 ft) than the 200 ft level used to define the transition in Experiment 1.

Procedure

Pilots first completed eight practice trials (taking about 3.5 minutes to complete) that included all of the normal flight and ground-based tasks. Missed approach procedures were described and explained in detail, but were not practiced so that missed approach events remained relatively unexpected. After training, pilots flew 21 experimental trials (each taking about 5 minutes to complete), with half performed with the HUD, and half with the HDD (the extra trial was flown with either the HUD or HDD to assess the pilot’s ability to respond to a truly surprising runway incursion). The order of display location (up versus down) was randomized for each subject. Missed approaches were required for five trials, with two trials imposing low visibility below decision height, two trials presenting wind shear, and 1 trial presenting an aircraft taxiing onto the active runway. As in Experiment 1, the latter was defined as “truly surprising.”

As in Experiment 1, in addition to tracking heading and altitude, pilots had to respond to several events that were presented to assess allocation of attention to the near and far domain. In flight, other aircraft traffic was encountered as in Experiment 1, first appearing approximately 2000 feet in front of the pilot, within a region corresponding to a circle with a radius of 10 degrees of visual angle. These were flying in such a way that they never became a conflict (i.e., they did not require an evasive maneuver). Once an aircraft was detected, pilots had to pull the trigger to indicate detection, and the aircraft would disappear from view. Pilots also responded to “data” icons (see bottom of Figure 11), which could appear in a central display location once per flight phase, and disappeared once pilots pulled the trigger. These simulated the visual alert for a data link message. Speed changes were periodically commanded by a change in the digital command speed box located above the airspeed readout (see Figure 12), with new speeds
presented in a pseudo-random fashion, and an interval of at least 10 seconds elapsing in between each commanded airspeed change. During the taxi phase, however, specified speeds were treated as speed limits, and pilots were not required to match the indicated speed. Also during the taxi phase, pilots were sometimes issued a “stop” command (see Figure 12), and were required to decrease speed immediately. These events simulated a “hold short” command at a runway intersection.

Response time to detect runway-in-sight was also measured as in Experiment 1. For each pilot, a truly surprising event (consisting of an aircraft taxiing on to the active runway) was presented in the last quarter of trials. Visibility was always high during this trial to ensure that the taxiing aircraft was clearly visible. The incursion event was timed to be evident by the time the pilot was 250 feet above ground, before the decision height was reached (see Figure 13). Because pilots were not informed that the runway incursion was possible, this event was presented after both the wind shear trials and visibility below decision height trials in which a missed approach procedure was flown, in order to ensure that pilots understood this procedure.

![Figure 13. Sequence of possible events experienced in Experiment 2.](image)

On another trial, the pilot was guided to taxi past a truck waiting on a crossing taxiway. As the pilot approached the truck, the truck crossed in front of the pilot, requiring the pilot to swerve, stop, or collide with it. The pilot was also not told that the taxiway incursion was possible, thus increasing the surprising nature of this event. However, the taxiway incursion trial was always presented some time after the runway incursion trial had been presented, so pilots may not have been truly surprised by the taxiway incursion.

Each trial began in the cruise flight phase, and several turns were required for the pilot to become established on the final approach to the cleared runway. Half of the landings were in high visibility, while half were in low visibility. In low visibility conditions, pilots flew in the presence of haze that obscured the far domain view beyond approximately 3000 feet. (Note that this would not disrupt visibility of the other air traffic, which initially appeared at a shorter distance). When haze was present, the terrain and airport features in the far domain were generally invisible, until the pilot was relatively close to the ground. Once the pilot was about 400 feet above ground, the airport and runway features gradually came into view, and the
runway was clearly visible by the time the pilot was about 380 feet above ground. Upon landing, the pilot was required to maintain the commanded speed and heading for a normal or high speed turnoff. If low visibility weather was present, the view was obscured beyond a range of about 700 feet. After turning off of the runway, the pilot taxied across runways and taxiways for at least one minute, guided by the pathway display.

Results: Experiment 2

Data for the analysis were broken down into four phases: cruise phase (before line up on the runway for a straight in approach), final approach phase (from line up until the ground symbology was fully visible in both visibility conditions, at 50 feet), landing phase (from 50 feet until wheels down), and the taxi phase. For the taxi phase of course, altitude error was not a relevant variable.

Flight path tracking. Phase of operation was found to have a reliable influence on lateral tracking \((F(3,23) = 75.342, p < 0.01)\). Tracking error decreased as pilots approached the runway and landed, and then increased slightly during taxi. Display location and visibility did not have a reliable influence on tracking, although there was a marginal three-way interaction between phase, location, and visibility \((F(3,23) = 2.969, p = 0.05)\) (see Figure 14). The interaction is due to the performance seen in the taxi phase, with the HUD associated with a 5-foot tracking benefit relative to the HDD during high visibility taxi, but not different during taxi in low visibility. In low visibility, pilots could focus on the display regardless of its location, but in high visibility, the conformal elements of the taxi display could fuse or “scene-link” with their outside counterparts, apparently facilitating the division of attention between the near and far domain.

![Figure 14. Lateral tracking by error as a function of phase of flight, and display location. Left panel: Low visibility; Right panel: High visibility.](image-url)
less accurate during landing. Thus, pilots were equally proficient at vertical tracking with both locations during cruise flight, when the far domain contained terrain features that were not relevant to the flight or detection tasks, but when the runway became visible in the far domain, vertical tracking with the HUD was slightly degraded relative to the head-down location.

An interaction between location and visibility ($F(1,25) = 7.960, p = 0.01$) revealed that in high visibility, tracking error was 2.3 feet greater with the HUD than with the HDD, while in low visibility there were no display location differences. Because pilots were presented with a clear view of both the display and the outside scene in high visibility, we may assume that visual clutter was increased for pilots using the HUD (i.e., far domain features interfered with parsing the HUD image). In contrast, low visibility conditions generally afforded the pilot a clear view of the HUD pathway against a featureless background, an image equivalent to that when the pathway was presented head-down.

**Speed tracking.** Since commanded speeds were not specified during the taxi phase, this phase was not included in the analysis. Speed tracking was not influenced by display location, nor did location interact with other variables of phase or visibility.

The average speed attained during the taxi phase was of interest because others (e.g., McCann et al., 1996) have reported that pilots using a HUD can attain higher taxi speeds than those using a HDD. No reliable differences in speed were found for the different location or visibility conditions, as pilots in all conditions attained an average speed of 24 knots while taxiing.

**Expected event detection data.** In the near domain, response time to the command airspeed changes was not influenced by display location, nor did location interact with variables of phase and visibility. In contrast, RT to the data icons was faster in the head up location ($F = 26.61, p < 0.01$). This HUD benefit was modified by phase ($F(3,23) = 2.94, p < 0.05$), such that the HUD benefit was greatest during final approach (0.25 sec, $F(1,25) = 4.87, p < 0.05$), and landing (0.3 sec, $F(1,25) = 11.17, p < 0.01$), while it was absent during cruise phase (well before
the outside world became directly relevant to landing). During taxi, the effect of location was
different in low and high visibility (the source of a significant three way interaction between
phase location and visibility: F(3,23) = 3.49; p < 0.05). The HUD location had no benefit on data
icon RT in low visibility conditions, but produced a substantial 0.8 sec benefit to RT when the
outside world was clearly visible. We hypothesize that this interaction reveals a benefit due to
the nature of the taxi display, enabling pilots to more effectively divide attention between the
near and far domain when the superimposed symbology is truly conformal. It is noteworthy that
the HUD benefit here (0.8 sec) is substantially greater than that which was observed in the air
(approximately 0.3 sec).

Concerning far domain events, when pilots were flying in low visibility, they indicated
when they first detected the runway, but due to software limitations, response times were not
usable for the analysis. However, the altitudes at which the runway was detected were available
(with higher altitudes corresponding to earlier detection). Pilots using the HUD reported the
detection of the runway at a later time (lower altitude: mean: 350.34 ft) than those using the
HDD (mean: 367.27 ft; F(1,25) = 8.525, p < 0.01).

Finally, response times for detecting aircraft during cruise flight revealed a strong benefit
of the head-up location, with aircraft being detected over 1.3 seconds faster (F(1,24) = 15.124, p
< 0.01) with the HUD (mean: 2.18 sec) than with the HDD (mean: 3.49 sec). In addition, pilots
detected about 23% more targets (F(1,25) = 42.006, p < 0.01) with the HUD (mean: 84%) than
with the HDD (61%).

Unexpected events. Because some of the pilots participated in previous flight simulation
studies at the University of Illinois, participants were split into two groups. Eighteen “naïve”
pilots had never participated in a flight simulation study, while eight “exposed” pilots had
recently participated in such a study (i.e., in Experiment 1, conducted approximately six months
before). While pilots did not receive practice with wind shear and low visibility missed
approaches, they were told that such events would occur on more than one occasion during the
experiment. Thus, these events are considered unexpected in the sense that they were not
frequent, but also not surprising. No differences due to location were found in response times for
low visibility missed approaches or for the wind shear warning. Correspondingly, during the taxi
phase no significant differences were found in the stop sign response for display location or
visibility.

Truly surprising events. Results from the runway incursion during landing did not
provide statistical evidence (F<1) for a difference in response time between the two display
locations, but due to the low power of this comparison (one data point per subject), it is possible
that differences due to location exist, without sufficient power to generate a statistically reliable
finding. Therefore the data are presented here, to illustrate that the naïve pilots showed a pattern
consistent with attentional tunneling for the HUD, as has been reported by previous researchers.
Naïve pilots detected the incursion 1.27 seconds slower when the HUD was used, whereas
exposed pilots for whom we can assume that the runway incursion would have been less
surprising, detected the incursion 0.31 seconds faster when the HUD was used.
As with the runway incursion data, no evidence was found for a statistically reliable difference in response time between the two display locations in detecting the taxiway incursion. Again however, because of the low power associated with this analysis, the results are presented here to demonstrate that the data represent a consistent but non-reliable (F<1) .45 sec HUD benefit for pilots to detect taxiway incursions.

Subjective data: Pilot preferences. At the completion of the study, pilots were given a survey to assess their preferences and elicit comments regarding how the different displays were perceived and used. Pilots overwhelmingly preferred the HUD over the HDD, with only one pilot out of 26 stating a preference for the HDD. In general, pilots commented that the HUD allowed them to view both the instrumentation and outside scene simultaneously, reducing scanning demands and enhancing target detection.

Discussion: Experiment 2

The results of Experiment 2, like those of Experiment 1, offer a favorable prospective for the tunnel or pathway HUD. First, in both locations, the pathway supported very precise tracking. Lateral and vertical error in the air was approximately 10 feet, a precision even greater than that obtained with the tunnel display in Experiment 1 (see Figures 5, 6, and 7). However, there was some slight evidence for an airborne performance cost for the HUD relative to the head-down display, specific to altitude control in high visibility (i.e., when the runway was visible in the far domain). This cost was only about 3 feet of altitude error, and this HUD cost reversed itself to become a HUD benefit on the ground during taxi, in terms of lateral tracking error (approximately 12-foot lateral error benefit). Here again, this benefit emerged only during high visibility.

The equivocal costs and benefits of pathway HUDs, relative to head-down pathways, that were observed in flight path control gave way to a more consistent HUD benefit when detection performance was considered. While airspeed tracking (and change detection) did not reflect such a benefit, there was a consistent advantage of the head-up display location for the detection of both near domain (data icon) and far domain (traffic) events. In the latter case, this benefit was realized in both speed and accuracy. Furthermore, there was a modest, but non-significant HUD benefit for detection of the unexpected taxiway incursions. Indeed the only detection measure that appeared to show a HUD cost was the "runway in sight" call out, and the runway incursion detection (for the naïve pilots). Each of these costs can be accounted for by different mechanisms, discussed below.

It is clear first, that the overall high quality of performance with the pathway in either location is consistent with prior research, as well as with the results of Experiment 1. Furthermore, it is apparent that some of the benefits of placing the pathway in a head-up location can be accounted for by the reduced scanning benefit of that location, and the fact that any clutter caused by those overlapping images was more than compensated by the reduction in scanning, results similar to those observed elsewhere (Martin-Emerson and Wickens, 1997; Ververs and Wickens, 1998a). Yet clutter did appear to impose some cost to vertical flight path tracking on the final approach and landing, an effect related to the fact that the tunnel source of guidance was not conformal with the runway beyond. Here any benefit of their overlay in space, was
presumably more than offset by the clutter of the overlapping, non-conformal image. HUD clutter may well have been responsible for the delayed report of runway in sight, because here the HUD image would have directly overlapped the runway.

One noteworthy feature of the present results speaks to the particular benefits of scene linking. This is the fact that the HUD benefits were either amplified (in the case of the data-icon detection) or emerged (in the case of lateral tracking and unexpected event detection), when the HUD was directly positioned over ground elements (the scene-linked taxi display) rather than being "virtually conformal" (the pathway in the sky). This emerging benefit on the ground may well reflect the benefits of linking the HUD imagery with conformal elements in the visual scene, in such a way that a single object-like representation is formed (Kramer and Jacobson, 1991; Wickens and Long, 1995; Martin-Emerson and Wickens, 1997; Levy et al., 1998). This linking is absent when the pathway does not conform with a ground domain counterpart (in the air), or when that counterpart is not visible (low visibility during taxi); but the linking is present during high visibility conditions on the ground, amplifying the benefits to both icon detection and lateral tracking, and turning the mild cost for unexpected event detection in the air, to a mild benefit on the ground.

Finally, the current results speak to the issue of cognitive tunneling. Certainly the HUD advantage to detecting expected traffic was eliminated when traffic was in an unexpected (truly surprising) location – on the runway threshold at landing. Furthermore, this elimination may be considered to be a full reversal to a HUD cost, if only data from the 18 "naïve" pilots are considered. (The remaining eight pilots may well have "expected the unexpected" given their experience that runway incursions had been imposed in Experiment 1, conducted some six months previously). A HUD cost for unexpected events then is consistent with the findings of Wickens and Long (1995), and more recently those of Hofer et al. (2000), both of which employed more conventional HUD symbology.

**General Discussion**

The thesis of this paper was represented as a question: Are pathway HUDs viable? And the answer provided by the data from both experiments appears to be a clear “yes.” A pathway HUD generally supports performance better than a conventional HUD (Experiment 1) and better than a pathway head-down display (Experiment 2) and does so both in the air and on the ground. These general trends were modified in some respects by the different aspects of “performance.” For example, it is evident that the greatest benefits of the pathway (over the conventional ILS) format were observed on flight path guidance, and the greatest benefit of the head-up (over head-down) location of the pathway was observed on event detection, particularly the detection of far domain traffic. The muted effects of display location on tracking observed in Experiment 2 (and slight cost to the HUD for vertical tracking) should be balanced against the fact that overall, at both locations tracking with the 3D pathway was quite good, and that the 3-foot cost to vertical precision was small and could be seen to be compensated by the consistent gains in detection of both near and far domain events that were supported by the head-up location.

The current data also suggest that, in some circumstances, the combined benefits of a pathway HUD may be greater than the independent benefits of the pathway, offering 3D
prediction and preview and of the head-up display location, offering reduced scanning. These additional benefits are revealed in the circumstances on the ground in which the pathway produces truly conformal imagery, scene-linked to the far domain, in such a way that clutter is reduced and divided attention between the two domains is enhanced (Levy et al., 1998). This is a similar benefit to that observed with the less elaborate runway overlay used on landing by Wickens and Long (1995) and Martin-Emerson and Wickens (1997). Thus, in Experiment 1, the pathway HUD on the ground eliminated a HUD cost to detecting unexpected events (blocked turnoff), a cost that had been observed in the air (runway incursion). In Experiment 2, the pathway HUD on the ground, erased a HUD tracking deficit that had been observed in the air (vertical tracking), and changed it into a HUD benefit (for lateral tracking), while also amplifying a HUD benefit for detecting near domain (data icon) events. Furthermore, in Experiment 2, these effects were only observed when the visibility was high, thereby allowing “scene linking” with HUD imagery to images on the ground, in a way that was not possible in the air.

The results of the two experiments therefore provide reason for optimism regarding the viability of the pathway HUD as a display concept. Such a design has already been tested as a prototype on the ground (T-NASA Taxiway display; McCann et al., 1996), and the benefits are consistent with the fact that much of the praise which has been offered of commercial HUDs relates to the predictive capabilities of the velocity vector (McClellan, 1999). The pathway HUD here couples that prediction with a preview of the flight path, a concept which has been shown to offer independent benefits to tracking (Wickens, 1986).

At the same time, however, a note of caution should be expressed about the potential costs of clutter, when the symbology necessary to construct a 3D pathway is considered. Increased HUD clutter can hinder event detection (Hofer et al., 2000; Ververs and Wickens, 1998a), and as found in Experiment 1, the compellingness of the pathway HUD can also inhibit the appropriate allocation of attention, sometimes to the detriment of detecting unexpected events. This conclusion is supported by the recent evaluation of HUDs in a high fidelity simulation (Hofer et al., 2000). Furthermore, the compellingness of pathways in a head-down location has also been found to inhibit the detection of out-the-window traffic (Flemisch and Onken, 2000). Thus, there will be need for designers to consider relatively “minimalist” tunnel symbology (Fadden and Wickens, 1997), with limited intensity (Ververs and Wickens, 1998a). These issues were not addressed in the two experiments reported here, nor was the potentially important issue of accommodation, since we did not use a collimated HUD. When such designs that are sensitive to the constraints of pilot attention and perception, are coupled with adequate training, it is likely that the pathway HUD can provide the best features of both its attributes.

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