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Cognitive Issues in Head-Up Displays

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COGNITIVE ISSUES IN HEAD-UP DISPLAYS

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The ability of pilots to recognize and act upon unexpected information, presented in either the outside world or in a head-up display (HUD), was evaluated. Eight commercial airline pilots flew 18 approaches with a flightpath-type HUD and 13 approaches with conventional instruments in a fixed-base 727 simulator. The approaches were flown under conditions of low visibility, turbulence, and wind shear. Vertical and lateral flight performance was measured for five cognitive variables: an unexpected obstacle on runway; vertical and lateral boresight-type offset of the HUD; lateral ILS beam bend-type offset; and no anomaly. Mean response time to the runway obstacle was longer with HUD than without it (4.12 vs 1.75 sec), and two of the pilots did not see the obstacle at all with the HUD. None of the offsets caused any deterioration in lateral flight performance, but all caused some change in vertical tracking; all offsets seemed to magnify the environmental effects. In all conditions, both vertical and lateral tracking was better with the HUD than with the conventional instruments.

INTRODUCTION

To execute a successful CAT II approach and landing, the pilot uses both instrument information and visual cues from the outside scene. In the conventional cockpit these two sets of information are obtained in a sequential manner. The pilot monitors the instrument panel in a "head-down" position, and then at some point looks up and lands visually. With the head-up display (HUD), instrument information is superimposed on the outside scene, so that the pilot can see both sets of information while looking out at the external scene; thus the name, the "head-up display."

Fischer (ref. 1) made an extensive literature search on attention and cognitive switching in which the ability of pilots to extract information from superimposed visual fields was explored. The cognitive issue with the HUD was addressed by Naish (ref. 2) in a series of laboratory, simulator, and flight tests, by Fischer (ref. 1) in the laboratory, and again by Naish (ref. 3) in a simulator. These studies have shown that within the framework of the respective experiments, pilots were capable of perceiving and evaluating information from both sources quickly and efficiently. However, none of these studies was conclusive enough to put the cognitive issue to rest. Two important questions remained: (1) At each point in the approach, which information source is used for primary control of the flightpath, and which for monitoring? and (2) If the display draws the primary attention of the pilot, to what extent does this impede the transmission of possibly vital information from the outside scene? The present study directly addressed these questions by exposing the pilot to various conflicts between the conformal symbology and the outside scene, and to an unexpected obstacle on the runway.

OBJECTIVE

The objective of the present study was to determine pilots' ability to perceive and act upon unexpected information presented in either the outside world or in the HUD symbology. Perception is defined here as detecting and identifying a stimulus (which may be an object or a problem). "Acting upon" requires an understanding of the perceived stimulus.

The scope of the study was limited to the following selected approach and landing phase issues, using a single conformal, flightpath-type HUD (described later) in the precision approach mode:

1. Vertical boresight offset of the HUD under conditions of high and low visibility, with and without wind shear.
2. Lateral boresight offset of the HUD under conditions of high and low visibility, with and without wind shear.

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3. Wrong information presented in the HUD and in the instrument panel typical of an instrument-landing-system (ILS) beam-bend situation, under conditions of high and low visibility, with and without wind shear.

4. Obstacle on runway under conditions of low visibility and low ceiling.

The present cognitive study fulfilled one part of a threefold objective. The second objective was to quantify head-down to head-up transition behavior with and without HUD and is presented elsewhere (ref. 4). The third objective was to monitor eye movement during approach and landing with and without HUD.[1]

METHOD

Subjects

The eight pilots who took part in this study – five captains and three first officers – were rated for and currently flying the Boeing 727-type aircraft for two major airlines. The first officers had flown an average of 1,113 hr, and the captains an average of 2,350 hr in their respective seats in the 727 aircraft. Each pilot was administered vision tests to ensure that all subjects had 20/20 distance acuity, normal color and depth perception, and no visual dysfunction that might affect performance. Seven of the pilots passed all vision tests without glasses. The eighth pilot passed only with glasses; he wore the glasses during the experiment, as he does while flying.

Apparatus

The study was conducted in a fixed-base simulator configured to simulate a 727-type aircraft. A full-color, 900:1 scale (Redifon) model board background scene, including electronic fog, was used. The HUD symbology was optically superimposed on the visual scene monitor and was carefully aligned daily with the external scene. The electronic fog was also calibrated daily; nevertheless, there were slight variations in the fog ceiling from day to day.

[1]Price, T. A.; Haines, R. F.; and Fischer, E.: Pilot eye-scan behavior with and without HUD. NASA Technical Paper (in preparation).

HUD Symbology

A conformal flightpath-type symbology was used in the present study. The phosphor in the monitor produced white symbols at a constant brightness giving an approximate 10% contrast with the background.

The information was presented in a field of view subtending 24° horizontally and 21° vertically. The display was "conformal" in that it moved in a one-to-one manner with the real world both in pitch and roll, and that certain elements, such as the runway symbol and the horizon line, were designed to overlay their real-world counterparts. Optimal use of the HUD information during approach and landing required that the primary attention of the pilot be on the flightpath symbol – that he attempt to overlay it on the glide slope and localizer lines in a tight tracking task, while monitoring speed or speed error or both. To further aid the pilot in his approach task, a conformal runway symbol was also provided. At a wheel height of about 80-90 ft, the flare bars became visible, rising from the bottom of the display to the center. The pilot was to note them; at a wheel height of about 30 ft he could track them in order to flare. Although this HUD was used only down to CAT II minima in the present study, it was designed to give sufficient information even to zero-zero visibility, including rollout guidance. A detailed description of the HUD symbology is given in reference 5; and the symbology elements are described in figure 1.

Environmental Variables

Environment 1 (E1) was used to simulate very low visibility conditions, close to CAT II minimums. The cloud ceiling was 120 ft, runway visual range (RVR) was 1,600 ft, light turbulence was included, and there was no wind. A 100-ft decision height (DH) always applied to this condition.

Environment 2 (E2) tested flight performance under fairly strong headwind shear. Breakout altitude was 380 ft, RVR was greater than 8,000 ft, there was moderate turbulence, and a shear consisting of 30-knot headwind at starting altitude of 1,500 ft to 150 ft altitude, decaying to 18 knots at 50 ft, followed by an exponential decay to 15 knots at the runway. A 200-ft DH applied.

Environment 3 (E3) was moderately difficult to operate in. The cloud ceiling was 615 ft, RVR was 10,000 ft, there was moderate turbulence, and a shear

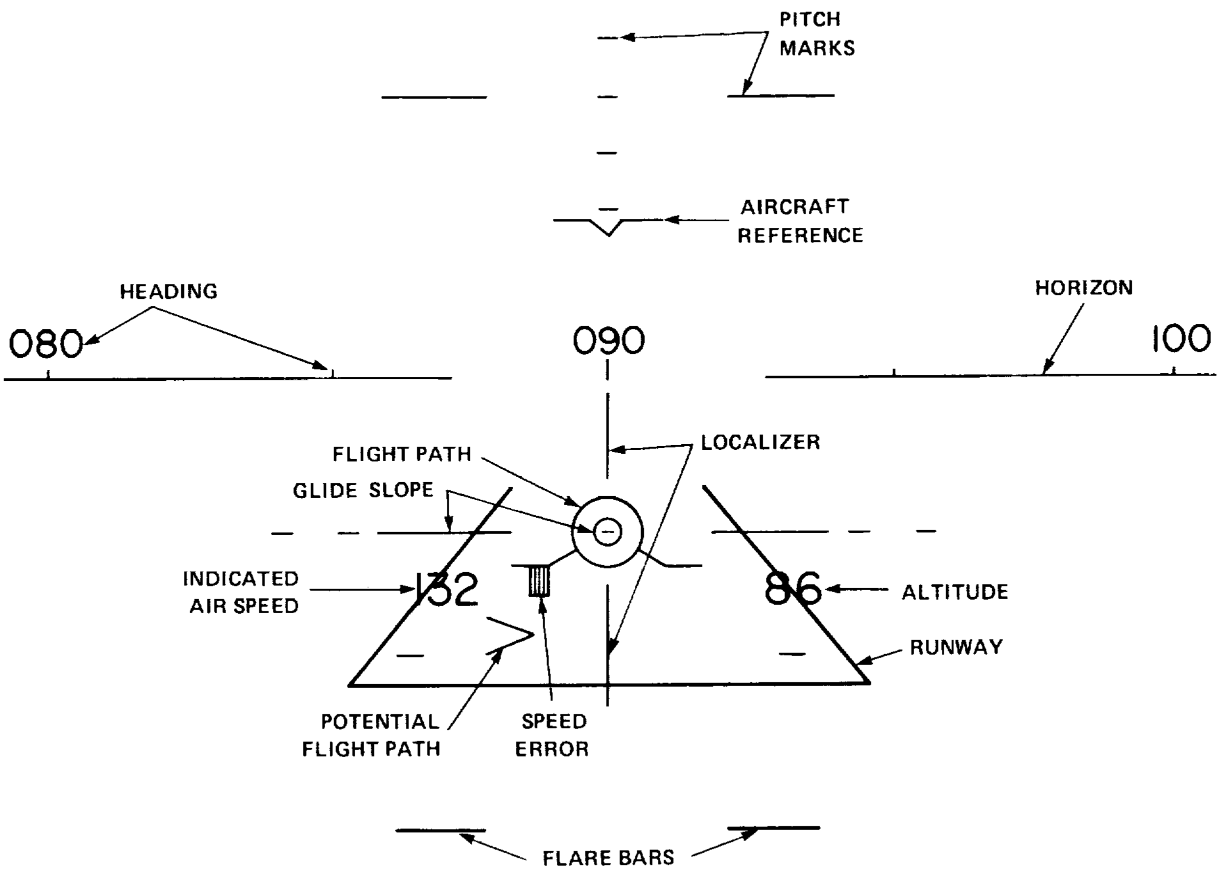

Figure 1.– Flightpath-type HUD format used.

consisting of a 25-knot headwind at starting altitude, decreasing exponentially to zero at the runway. A 200-ft DH applied.

In Environment 7 (E7), a variation of E1, the cloud ceiling was 180 ft and the RVR 2,000 ft. A DH of 150 ft applied. This condition was always used for the runway obstruction conditions.

Note that none of the environments included crosswinds, so that any effects of the lateral offsets could be more easily interpreted. Also, as part of the larger overall design, there were three other environmental variables (E4-E6), but since data collected under those conditions are not analyzed in this study they are not described here (see ref. 4).

Cognitive Variables

1. Vertical boresight offset (VBO). In this condition the entire symbology set was raised 2° above its correct referenced position (fig. 2). Internally the symbology was correct and gave the proper information, but physically the conformal symbols did not overlay their real-world counterparts. This mismatch condition was tested under environmental conditions E1, E2, and E3, but since this kind of offset is a result of the HUD hardware misalignment, it was tested only with HUD. The mismatch caused the pilot to have the illusion or feeling of being too high. Should the pilot follow his "feeling" and pitch down, he would land short of the aiming point. If, however, he followed either the symbology or the outside scene exclusively, he would land properly.

2. Lateral boresight offset (LBO). In this condition there was a random 3° shift of the symbology to either the left or right (fig. 3). Again, the symbology was internally consistent and gave correct information, but was out of spatial registration with the real world. That is, if the pilot attempted to fly the flightpath symbol onto the real runway centerline, he would land on the edge of the runway (or possibly on the grass). If, however, he flew the HUD only, or the

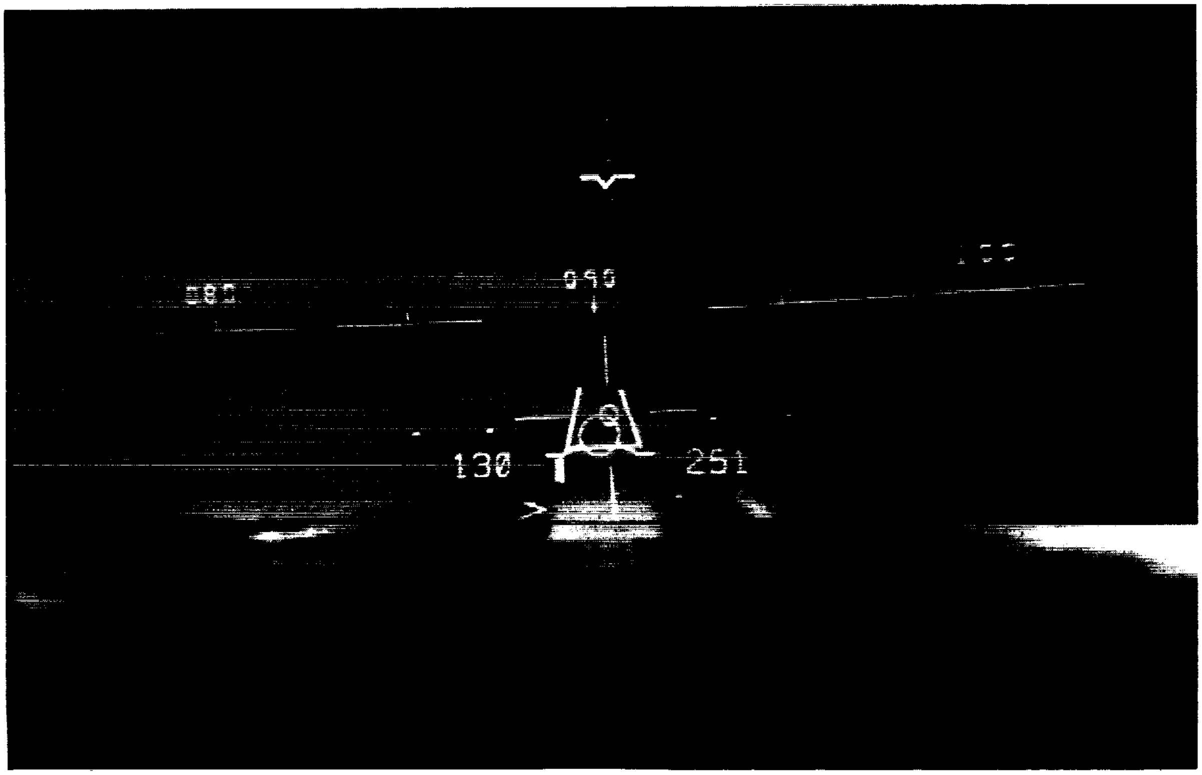

Figure 2.– Vertical boresight offset.

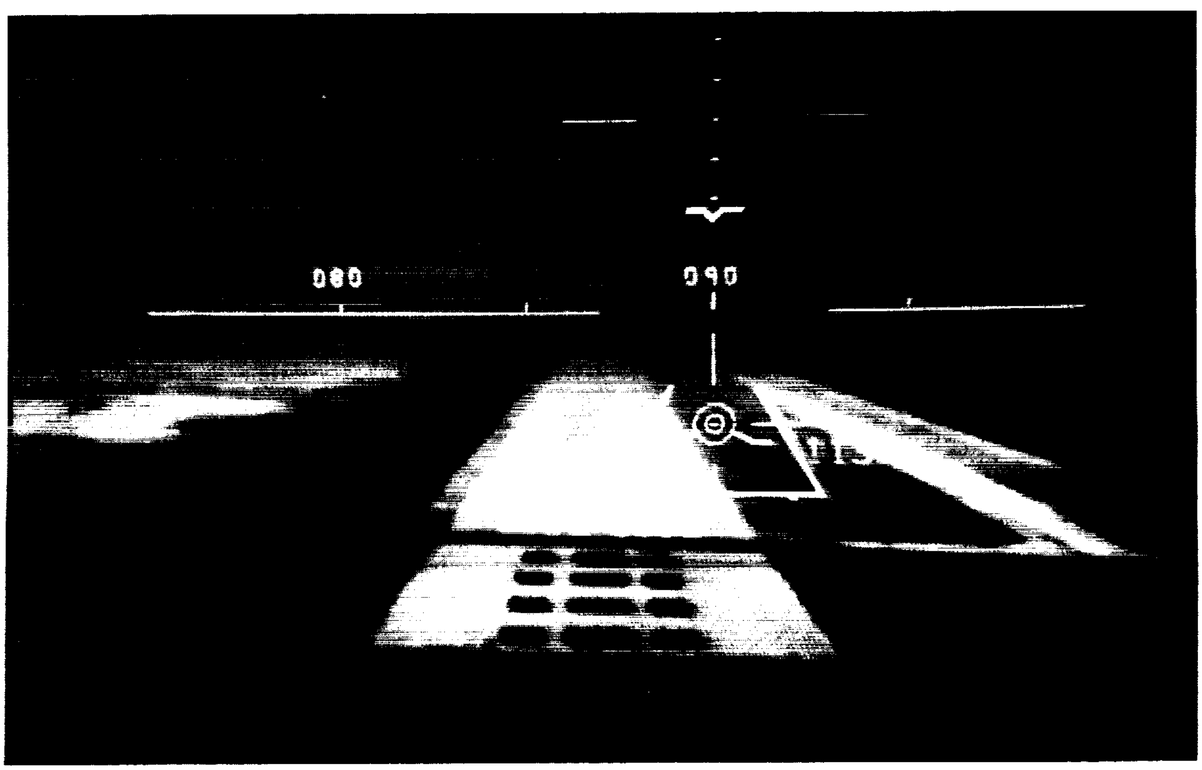

Figure 3.– Lateral boresight offset.

outside scene only, he would have landed properly. This offset condition occurred under environmental conditions E1 and E2 only. As with the vertical boresight offset the anomaly was symbology specific, and was tested only with the HUD.

For both types of boresight error the magnitude and the direction of the offset were selected so that the offset would be clearly perceivable at the lowest visibility condition tested (E1). Because the degree of the offset was constant, the closer the aircraft approached the runway, the smaller was the perceived discrepancy.

3. Lateral ILS offset (LIO). In this condition a 90-ft bias, introduced into the localizer (fig. 4) randomly to the right or to the left, resulted in erroneous information in both the Sperry flight director (vertical) bar and the HUD. This condition can occur as a result of a bend in the ILS beam; therefore, it is referred to as an ILS offset. In the real world, of course, such a condition probably would be reported by the tower or would likely exist for only a short time; moreover, typically it would be a changing condition, not a constant offset. The condition was selected as a worst case representing wrong lateral information. With this type of offset (as with the boresight offsets), the problem was not perceivable while the pilot was flying in clouds. Only after breakout could the pilot detect that he was not lined up with the runway (although he expected to be). Since this type of error could occur while flying with instruments or with HUD, it was tested both ways under conditions E1, E2, and E3. It must be noted that the angular scaling of the flight director is 1:6, and the angular scaling of the HUD is 1:1 with the real world. Consequently, a small discrepancy would not likely be very obvious on the flight director, but would be on the HUD. In addition, once the pilot comes head-up, he is likely to make lateral corrections based on his external visual information only;

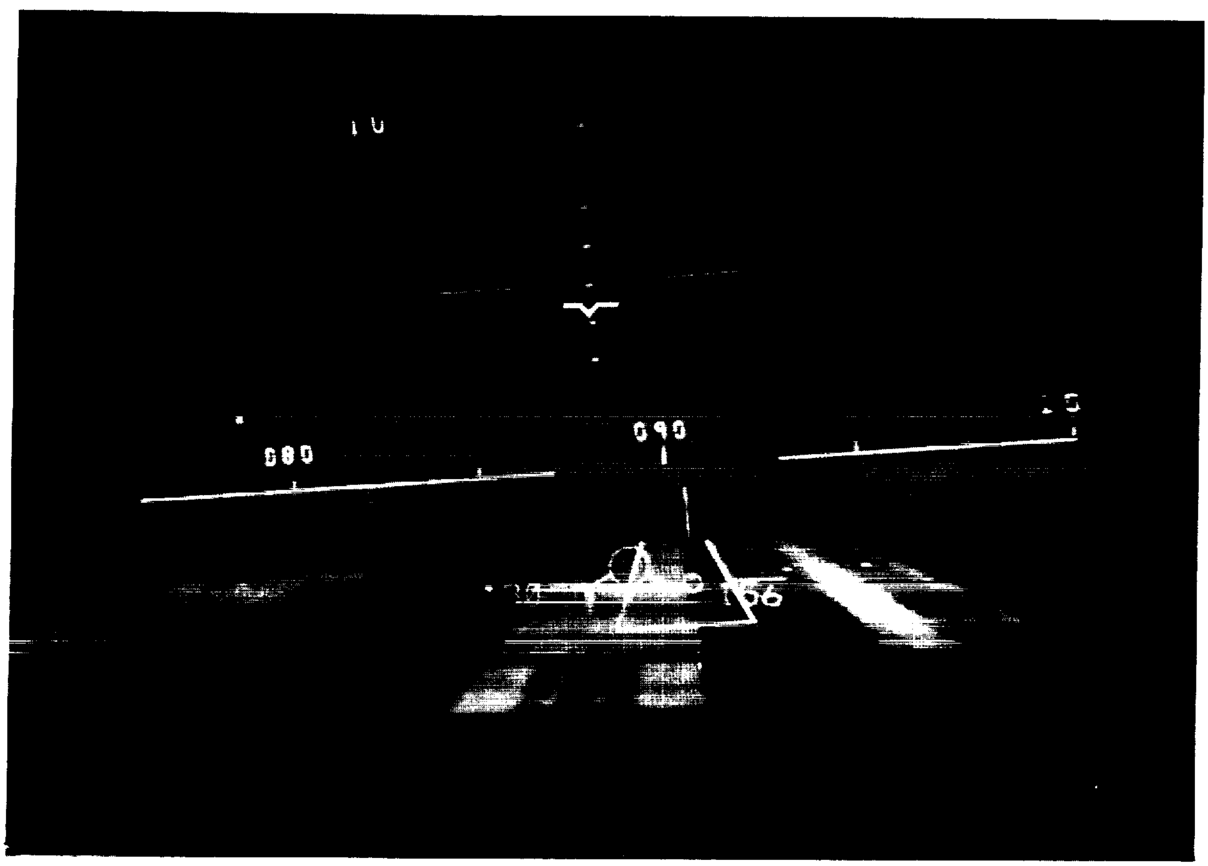

Figure 4.– Lateral ILS offset.

thus, he might not become aware of the localizer offset from his flight director. With the HUD, however, if the pilot flew only the flightpath symbol (which did not depend on localizer input) onto the real runway, he could land the aircraft properly. Of course, while flying with HUD the pilot could also ignore all symbology and just land visually.

4. Obstruction on runway (OB). A scale model of a current wide-body aircraft was placed halfway onto the runway at a 45° angle, as if it was turning from an adjoining taxiway near the runway threshold (fig. 5). Each pilot encountered this condition once with the HUD and once without it during the 31 data runs – four pilots being first exposed to the incursion while using HUD, the other four being first exposed when not using HUD. Since the presentation order of all test run conditions was randomized, the first obstacle runs were encountered anywhere between data run 5 and data run 22; there were from 5 to 21 runs between the first and the second exposures.

The objective was to test the pilot's ability to critically perceive the outside world under conditions of low visibility while using HUD; as mentioned, only E7 was used. This visibility condition was selected to give the pilot sufficient time, following the initial appearance of the obstacle, so that he could execute a missed approach. The runway obstruction became visible as something dark on the runway, but not necessarily identifiable, about 4-5 sec after breakout, depending on the aircraft's position at the time. The pilot then had about 7-8 sec to execute a missed approach, depending on the position and speed of the aircraft.

5. No offset (NO). Each pilot had one run each in conditions E1, E2, and E3, with and without HUD, in which the symbology was correctly aligned with the runway. These runs provided baseline performance data and made it possible to compare flight performance with and without the "cognitive anomalies."

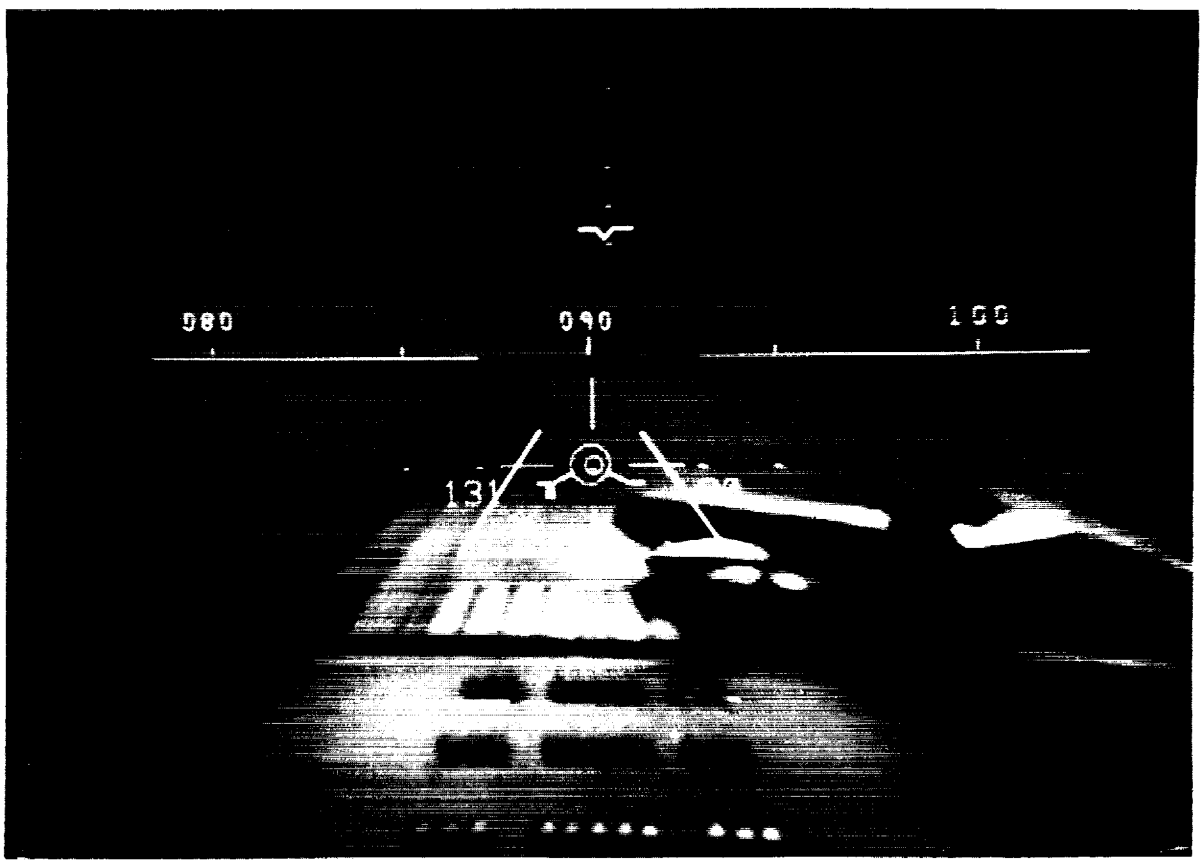

Figure 5.– Runway obstruction.

Experimental Design and Performance Measures

The 31 data runs that each pilot flew included 18 with HUD and 13 without HUD, 7 environmental variables, and 5 cognitive variables. In this report only 19 of the 31 runs that pertain to the cognitive variables (under E1, E2, E3, and E7) are analyzed and discussed; 11 of these runs had one of the offset conditions, 2 had runway obstructions, and 6 were control runs with no offset. A summary of the experimental variables is presented in table 1. All pilots encountered each combination once; therefore, every cell includes 8 data points.

All runs were videotaped. The resulting video image included the outside scene and the superimposed HUD, just as the pilot saw it. A moving white dot was visible whenever eye-movement data were recorded (see footnote 1). In addition, a picture of the pilot's face was inset in the screen to permit quantification of head-up transition behavior (see ref. 4). All communications between pilot and experimenters were recorded. These tapes provided useful backup information and helped in interpreting the data.

Flight performance measures included localizer and glide-slope deviations expressed in feet, which were sampled at every 100-ft altitude down to 200 ft, then at 150, 100, 75, 50, and 25 ft, and at landing. Root mean square (rms) values in degrees (indicating the mean deviation from the desired values, regardless of the direction of the deviation) for the above variables were also recorded for various segments of the flight.

A flight performance measure obtained in all conditions was whether the pilot landed or executed a missed approach. Pilot comments were recorded during and between runs, from the voice tape and from the post-test debriefing questionnaires.

Procedure

Each pilot underwent training, data collection, and debriefing, as described below. The entire procedure took about 8-10 hr, including breaks whenever necessary. Pilots were initially scheduled for 4-hr sessions on two consecutive days, and were brought back for additional sessions as necessary.

Training– The pilots received a detailed description of the display symbology – and familiarized themselves with it – before they reported for testing. At the first session a battery of eye tests was administered. The actual training started with showing the pilot a 20-min narrated videotape explaining and demonstrating the various features of the HUD in flight. A question and answer period (and occasionally a second viewing of the tape) followed, until both the pilot and the experimenter were satisfied that the pilot conceptually understood the symbology. At that point training in the simulator began.

Each pilot flew a minimum of five increasingly difficult approaches without HUD to become familiar with the simulator environment and the aircraft's flying qualities. When the pilot was satisfied with his level of proficiency, training with the HUD began. Each pilot flew at least eight training approaches with the HUD. These runs started out with simple maneuvers in clear visibility and calm winds and gradually included turbulence, crosswind, wind shear, and low visibility, as well as the checklist, callout, and missed approach cockpit procedures. Each pilot was asked to indicate his preference for callouts, and these calls were then used in the data collection phase. If the

TABLE 1.– SUMMARY OF EXPERIMENTAL CONDITIONS

Environment[a]	Cognitive variables[a]									
	HUD					No HUD				
	OB	VBO	LBO	LIO	NO	OB	VBO	LBO	LIO	NO
E1		*	*	*	*				*	*
E2		*	*	*	*				*	*
E3		*		*	*				*	*
E7	*					*				

[a]Defined in text.

pilot wanted more training runs he got them. On the second and succeeding days refresher training was provided by beginning the sessions with at least one no-HUD and two HUD runs. During all training runs there was a constant interaction and feedback between the pilot and the experimenter. When both the pilot and the experimenter were satisfied about the pilot's competence in handling the simulator and the HUD, data collection began. The flying part of the training averaged about 3 hr, about 2 hr of which were devoted to flying with the HUD.

Note that the training did not include exposure to any of the offset or obstacle conditions, nor was the possibility of the occurrence of such anomalies mentioned. The pilots were told only that the purpose of the study was to test the HUD under various environmental conditions.

Data runs– Once data collection began, one of the experimenters (R.F.H.) assumed the role of the first officer. Another experimenter (E.F.) stood behind the pilot to observe and control the procedures. Each trial started on autopilot (to ensure uniform initial conditions for all runs and all pilots) in level flight at an altitude of 1,500 ft and 8 miles from the runway; a run lasted about 4 min. For more realism a taped, air traffic control communication was played to the pilot's headset, down to about 400 ft. The procedure required the first officer to call for the weather report and landing clearance soon after the run started. After the tower's report the pilot was asked to disconnect the autopilot, unless it was a coupled approach. The pilot and copilot went through the appropriate checklist, that is, for HUD or for head-down flight, and usually completed it by the glide-slope capture. During the descent the first officer gave the desired callouts and in every way complied with the pilot's commands. The callout always included "ground in sight," "runway in sight," or some equivalent indication of visual contact with the ground. At this point the first officer pushed a button, thus recording the first perception of the outside world. The pilot was instructed to say "decision" when he had enough external visual cues to decide whether to land or to go around. This was also recorded by a button push. If there was an offset or an obstacle on the runway, the first officer did not call the pilot's attention to it; this was done in order to see the pilot's unbiased reaction. (However, at the beginning of the study the first officer did call attention to the obstacle twice by mistake, as will be discussed later.)

After rollout or, in the case of a missed approach, after stabilization of the flight, the run was terminated by the experimenter. To protect the external scene equipment, any run was terminated by the experimenter (E.F.) if there was an imminent danger of crashing (decided subjectively by the experimenter).

Debriefing– After all data runs were completed, the pilot was questioned about the various aspects of the study (see ref. 4). In addition to answering these specific questions he was encouraged to offer other information, observations, suggestions, etc., pertaining to the study.

RESULTS AND DISCUSSION

Results will be presented and discussed separately for each of the cognitive variables. The mean glide-slope and localizer deviation for the last 800 ft of descent and other pertinent information for each condition is presented in the appendix.

Vertical Boresight Offset

The vertical boresight offset required no corrective action by the pilot – only the position of the symbology was off, not the aircraft. It is reasonable to assume that a significant vertical deviation from the glide slope contributes to the illusion created by the mismatch.

Analysis of variance– To assess overall vertical flightpath performance, two separate analyses of variance were performed comparing the offset with the no-offset condition while flying with HUD. One used rms glide-slope deviation, the other rms control-column displacement as the relevant response measure. Each analysis was a 2-condition (offsett, no offset) × 3-environment (E1, E2, E3) × 2-segment (800-300 ft, 300-50 ft) × 8-pilot design. The analysis showed no statistically significant difference between offset and no-offset conditions for either measurement. However, since rms values show only magnitude, deviations above the glide slope in one environment and below the glide slope in another environment would cancel each other. There was a significant difference for both measurements between environments ($p < 0.005$). This was expected, because E2 and E3 contained wind shear that would influence glide-slope tracking; E1 had no wind shear. The difference for the glide-slope deviation between segments ($p < 0.001$) was also expected, because the last segment (300-50 ft) included a portion of the flare maneuver, while the 800-300-ft segment followed the flightpath. The interaction between environment and segment for the glide-slope deviation was also significant ($p < 0.005$), E3 producing almost twice as much increase in mean deviation from the 800-300-ft segment to the 300-50-ft segment as did E1; the deviation increase for E2 was between those for E3 and E1. This indicates that the longer the pilot assessed the offset, the more he deviated from the glide slope, suggesting that the longer the exposure to the offset, the stronger the illusion effect.

Glide-slope deviation– To take a closer look at flightpath performance after breakout (when the discrepancy is evident), raw glide-slope deviation in feet was plotted at altitude intervals from 800-25 ft for each environment, with and without offset (fig. 6); the deviation is described below.

In E1 the low breakout brought the aircraft so close to the runway that the offset was not very obvious; in fact, none of the pilots gave any indication of even being aware of the offset. However, the top graph in figure 6 shows that with the offset, pilots got above glide slope at an altitude of about 100 ft (breakout was at 120 ft). Landing data indicate that the pilots also overshot the 1,000-ft mark. Comparing the no-offset and offset conditions, the mean glide-slope deviation for 150-25-ft altitude was -4.6 ft versus +3.0 ft, and the mean touchdown distance from the runway threshold was 855 ft versus 1263 ft, respectively. Thus, in the offset condition the pilots flew about 8 ft higher and landed about 400 ft farther down the runway than they did without offset.

In the E2 condition the wind shear acted to place the aircraft below glide slope from an altitude of about 150 ft down, which usually resulted in landing short of the 1,000-ft mark. This effect was most pronounced in the no-HUD, no-offset control condition, where the mean glide-slope deviation between 150-25 ft was -12.4 ft and the mean touchdown distance was 106 ft past the runway threshold. Two of the pilots actually touched down short of the runway. With the HUD in the no-offset condition the effect was less. The mean glide-slope deviation for the same segment was -9.6 ft, still below glide slope, but the touchdown distance was 1,107 ft, indicating that the HUD enabled the pilots to compensate for the shear condition. For the vertical offset of the HUD (center graph in fig. 6), the mean glide-slope deviation for the 150-25-ft altitude segment was -19.6 ft, and the landing distance was 529 ft, about 10 ft lower and 600 ft shorter, respectively, than without the offset. It seems that the offset initially distracted the pilots from dealing with the shear, causing the aircraft to descend well below the glide slope; but some of this was compensated for before touchdown, as the landing distance indicates.

In E3, pilots tended to go above glide slope at an altitude of about 150 ft, but came back to, or even below, glide slope by touchdown (lower graph in fig. 6). Again, this effect was increased in the offset condition, as shown by both the mean glide-slope deviation (3.0 vs 11.4 ft), and touchdown distance (737 vs 1,025 ft) for the 150-25-ft segment.

No missed approaches were made in any of the vertical offset conditions.

The graphs indicate that the offset did influence vertical tracking performance to some degree; however, the pilots did not seem to be consciously aware of anything being wrong. None of the pilots made any comments about the symbology being in the wrong location, and only a couple of comments were made to the effect that "It seems farther out" than the information in the symbology (i.e., altitude, ground distance) suggests.

To sum up the results of the vertical boresight runs, none of the changes in performances noted above are significant from a practical point of view. In all cases the pilots landed as well or better with the HUD (even when there was an offset condition), than they did without HUD. It must be noted, however, that the vertical boresight offset did reduce the effectiveness of the HUD in aiding the pilot to cope with the environment, resulting in larger deviations from the glide slope and that the pilots were not aware of the additional problem (i.e., the offset). Should such an offset occur in combination with an extreme shear, it could become a potentially dangerous situation.

It should be remembered that in the present study pilots were not only unaware of what a mismatch looks like, but were not even informed of potential mismatch problems. The above results point out the necessity to train the pilots to readily recognize abnormalities that may occur while using the HUD.

Lateral Boresight Offset

Analysis of variance– As in the previous condition, two separate analyses of variance were conducted to compare the overall performance in offset and no-offset conditions while flying the HUD. The

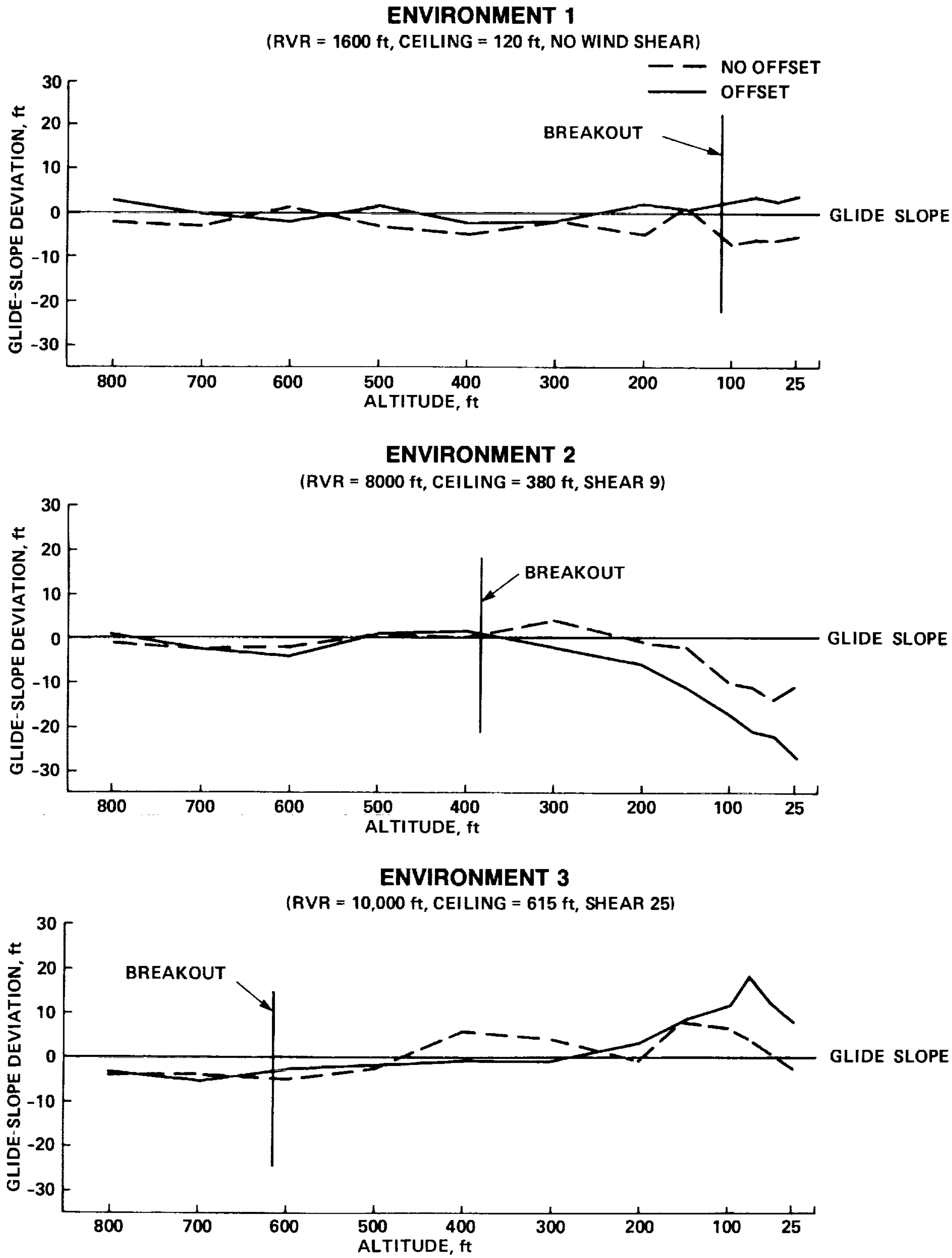

Figure 6.– Glide-slope deviation – with and without offset while flying with HUD.

design was the same as previously described, except there were only two environmental conditions, E1 and E2, and the performance measures were rms localizer deviation and rms control wheel displacement. The analysis of variance for the rms localizer deviation indicated no significant difference between the offset and no-offset condition. The rms wheel displacement was significantly different at the $p < 0.05$ level of confidence. Interestingly, more wheel movement was made in the no-offset than in the offset condition in the last segment (14.6° vs 12.8°), where the offset became evident. Obviously, the nonconformity of the symbology did not act to increase workload, at least as measured by wheel displacement. On the contrary, the offset seemed to draw the pilots' attention to lateral performance, resulting in smoother handling of the control wheel.

Localizer deviation– The raw localizer deviation data showed no meaningful difference or trend in the offset condition for either environment tested. For example, in E1 for the 150-25-ft altitude segment, the mean localizer deviation was 3.3 ft with offset and 2 ft without offset; in E2 it was 7.9 and 6 ft, respectively. In all cases the pilots tracked the centerline very closely.

To see if the lateral offset influenced vertical flight performance, glide-slope deviation was compared in the offset and no-offset conditions. It was found that in E1 for the 150-25-ft segment the mean glide-slope deviation was +4.2 ft with offset and -4.6 ft without offset; in E2 it was -7.2 ft versus -9.6 ft, respectively. Landing distances were 1,270 ft versus 855 ft in E1, and 690 ft versus 1,107 ft in E2 for the offset and no-offset conditions. It may be seen that in E1, pilots flew about 12 ft higher and landed about 400 ft farther with the offset; in E2, while their glide-slope tracking did not deteriorate, compared to the no-offset condition, they landed about 400 ft shorter with the offset.

The interesting phenomenon with the lateral boresight offset was the pilots' misinterpretation of it. In contrast with the vertical boresight offset runs, on these runs all pilots recognized that something was wrong with the symbology and made comments to that effect. However, most of them attributed the lateral offset position of the symbology as being the result of crosswind, and continued to use the information it provided. Some pilots even praised the way the symbology guided them in crosswind. (As mentioned earlier, none of the data runs contained crosswind.) This mistake is somewhat understandable, as the offset was a constant 3°, so the closer the pilot got to the runway the smaller the apparent discrepancy, thus suggesting that a correction was being made; moreover, the information in the HUD and in the outside world told him he was on centerline. In this condition the pilots made the right response for the wrong reason. It must be remembered, however, that during the training it was explained to all pilots that crosswind is indicated by a lateral separation between the aircraft and the flightpath symbols only. Each pilot had at least two runs with crosswind, so they could experience how the symbols behaved.

There were no missed approaches in the lateral boresight offset in either environmental condition tested.

In summary, the lateral boresight offset did not affect the pilots' lateral flight performance nor does this kind of offset seem to pose any serious potential problems; however, the results indicate that the offset did change vertical tracking and landing performance to some degree, and the pilots did not recognize the true nature of the problem. This again suggests the necessity of more thorough training, not only in flying the HUD, but in the potential problems that can arise.

Lateral ILS Offset

The lateral ILS offset, which placed the aircraft either to the left or to the right of the real runway at breakout, required recognition and corrective action by the pilot. Comparing pilot response time and the accuracy of his correction with and without HUD indicates whether the HUD had any effect on flight performance.

Response time– Pilot response time was measured for each environment for both HUD-offset and no-HUD-offset runs from breakout to the time the aircraft started (and continued on) a converging path to the real runway. It was found that response time to the offset was faster without HUD in all three environments tested: in E1 by 0.14 sec, in E2 by 0.51 sec, and in E3 by 2.12 sec. Thus, on the average, pilots responded to the offset 0.92 sec faster without HUD than with HUD. (For total response times see the appendix, tables 4-6.)

Analysis of variance– Two analyses of variance were performed, one using rms localizer error, the other rms control-wheel displacement as response measures. The design was similar to the one used in the boresight offset conditions, except that a "no-HUD, offset" and a "no-HUD, no-offset" condition was added.

The offset caused no significant difference in rms localizer deviation, and caused only a moderate difference in rms wheel displacement, there being 0.67° more displacement with offset, thus reflecting that a correction was being made. The difference due to segment (800-300 and 300-50 ft) was significant at the $p < 0.005$ level, there being 2.45° more wheel movement in the last segment, indicating that most of the correction was made during the 300-50-ft altitude segment. The interaction of offset and segment, significant at the $p < 0.05$ confidence level, also reflects this.

Whether the pilots were flying with or without HUD made a significant difference both in rms wheel displacement ($p < 0.05$) and in rms localizer deviation ($p < 0.005$). With the HUD the rms wheel displacement was 3.43° more for the 800-25-ft segment than it was for the no-HUD runs, but the localizer deviation was 3 times smaller (0.07° vs 0.21°) than without HUD.

The analysis of variance results show that the offset had no significant effect on lateral convergence; pilots flew more accurately with the HUD; they also worked harder for this increased accuracy, as the larger wheel displacement and their comments indicated.

Localizer deviation– To look closer at the lateral performance with the ILS offset, the absolute localizer deviation (i.e., irrespective of the direction of the error) is plotted for the last 800 ft of altitude (fig. 7). The figure shows mean localizer error and plus and minus one standard deviation with and without HUD under the offset condition for each environment tested. The figure also indicates the real runway centerline and the 90-ft offset line. The latter was the indicated runway centerline on both the HUD and the flight director localizer bar. While in the clouds, the pilots should have followed the indicated localizer, which in the real world would have placed them on a path parallel to the runway and 90 ft to one side of it. After the breakout the pilots were able to perceive the discrepancy, and should have converged to the real runway centerline; as can be seen, that is what happened.

The data in figure 7 reflect the main effects of the analysis of variance. With the HUD, localizer tracking was more accurate than it was with the instrument panel in all environments, including strong wind shear. This is indicated by the mean flightpath flown and by the magnitude of the standard deviation, which was considerably larger for the no-HUD conditions. The standard deviation includes both within trial differences (i.e., the pilot oscillates about the target line) and between subject differences (i.e., individual pilots were deviating in varying magnitude and direction from the target line).

An interesting phenomenon is the "ballooning out" of the standard deviation with the HUD after breakout. It is not evident in E1, probably because at breakout the pilots were so close to the runway – the runway was such a strong stimulus that seven of the eight pilots reported abandoning the HUD for (external) visual information and making the substantial lateral correction necessary to land. One of the pilots continued to rely on the HUD guidance information and soon realized that it would not guide him back, so he executed a missed approach. The "ballooning out" may be observed in both E2 and E3, where the visibility conditions allowed the pilot sufficient time to observe and evaluate the discrepancy. The offset seemed to create an uncertainty in the pilots. All of the pilots tracked the HUD tightly in the clouds, but after being confronted by the mismatch they took different actions. In E2, four of the pilots continued to follow the HUD for a while longer, even though they made verbal comments about the symbology being off. Two of these resulted in missed approaches. The other four pilots abandoned the HUD guidance soon after they became aware of the discrepancy, reported that they were going "visual," and started converging. The same four pilots who in E2 chose to follow HUD longer, also elected to stay with it longer in E3. Two other pilots started to converge immediately, and two tried to figure out what was wrong with the HUD and oscillated back and forth between the wrong HUD information and the real runway, as indicated by their comments and by the localizer deviation on the strip-chart records. There were no missed approaches in E3 in the ILS offset condition.

There was no strong trend in vertical tracking in E1 and E2; however, in E3 pilots exhibited the same tendency of going above glide slope more with the offset than without it (14 ft vs 3 ft) as they did in the boresight offsets.

Altogether there were six missed approaches (12.5% of the total) with the ILS offset, three of them with the HUD and three with instruments. In comparison, in the no-offset control condition there were four missed approaches (8.3%), one with and three without HUD.

In summary, the lateral ILS offset did not affect lateral performance with the HUD any differently than it did without HUD; however, pilots did respond

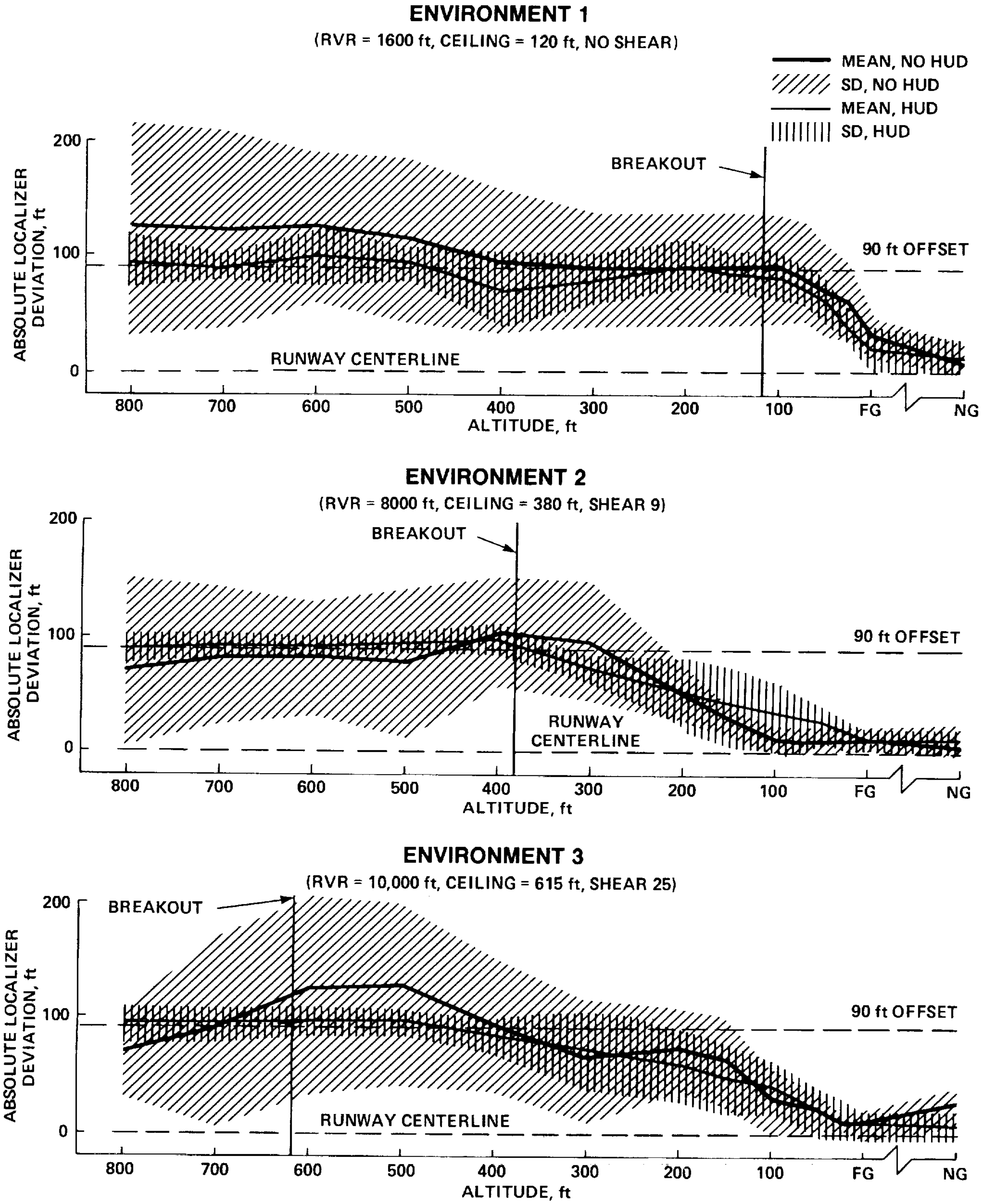

Figure 7.– Absolute localizer deviation – with ILS offset with and without HUD.

to the offset a little sooner without the HUD. Localizer tracking was generally more accurate with the HUD, but when confronted with the ILS offset, it deteriorated to the level of visual tracking, suggesting that the pilots critically evaluated the display, found it useless, and switched to visual guidance.

Regarding all the offset conditions in general, pilots said that the offset was a nuisance, although it did not interfere with their performance. They also indicated that they would prefer to fly with the HUD even if it was offset, because "the HUD provided some reference to go by."

Obstacle on Runway

Because of the small sample size and the somewhat irregular application of this test variable, no statistical analysis was attempted.

As noted earlier, four of the pilots first encountered the runway obstacle (airplane) with HUD and four first encountered it without HUD. The first pilot who was tested experienced his initial encounter of the obstacle without HUD; however, the environment was the higher visibility E2, instead of E7. In addition, the first officer called attention to it as soon as he saw it, at about 350 ft altitude, saying "There is something on the runway." The pilot responded with "Let's go down and take a look at it," which he did and then executed a missed approach at an altitude of 190 ft. The first officer inadvertently called attention to the obstacle one more time with pilot No. 4, also in a first-encounter, no-HUD condition. Because of these irregularities, data for these two runs are not reported; however, they are considered as the first exposures to the obstacle for these two pilots. All other runs were made in E7, and with no advance warning.

In the actual simulation it was about 4-5 sec after breakout before the "airplane" became detectable as an obstacle. During the first 1-2 sec of visibility (after descent below clouds in which visibility was zero) the retinal size of the airplane image was still relatively small, allowing the HUD symbology to partially obscure it. Nevertheless, with the HUD the pilot was head-up at the first opportunity to perceive the obstacle. In contrast to this, when flying with head-down instruments, most of the pilots glanced up quickly when the first officer called out "ground in sight" and went back to the instruments again. Some pilots took one or two more quick glances up but all would come head-up permanently only after the first officer indicated the runway was in sight. By this time the airplane was always clearly visible. The interested reader is referred to a companion paper for more details (ref. 4).

Table 2 is a summary of the pilot's response time to the airplane on the runway. For the HUD flights it represents the time from the first opportunity to see the airplane to the first response of the pilot, which most often was a verbal exclamation. For the no-HUD runs, response time represents the time from the final look-up to the response, for this was the available time for perceiving the obstacle. The table also includes the particular response made, which was either an executed missed approach (MA) or an intended missed approach (IMA). The IMA resulted when the pilot saw the airplane and called for the MA, but the experimenter terminated the run (sometimes simultaneously with the pilot's call) before the MA was actually carried out, in order to prevent damage to camera equipment.

As may be seen in table 2, two pilots did not see the airplane at all. Both of these runs were with HUD and were the pilots' first exposures to the obstruction. Pilot D was a first officer with approximately 2,000 hr in the 727; his performance with both the head-down instruments and the HUD was considered good; he flew 21 data runs prior to the first obstacle encounter. The airplane became increasingly visible about 4 sec after breakout, but the pilot gave no indication of seeing it. He was pleased with his approach "setup," as indicated by his comments: ". . . oh, it looks good (110 ft) . . . the HUD looks good (90 ft) . . . ." The experimenter terminated the run at an altitude of about 67 ft. ". . .Oh, wait a minute! It looked good, the flare bars were coming up . . . then the picture disappeared." The subsequent exchange between first officer and pilot: "I saw an airplane. Did you see it?" "No." "You didn't see it?" "No, sir."

Pilot F was a high-flight-time captain who demonstrated exceptionally good performance, both with and without HUD. The runway obstruction run was his seventh data run. He indicated his "Decision (140 ft) . . . to land (110 ft)," and proceeded to do so. The experimenter terminated the run at an altitude of 50 ft – the pilot was surprised. Pilot: "Didn't get to flare on this one." First officer: "No you didn't . . . I was just looking up as it (the picture) disappeared and I thought I saw something on the runway. Did you see anything?" Pilot: "No, I did not." The experimenters suggested that an equipment failure was probably to blame.

TABLE 2.– RESPONSE TIME AND TYPE OF RESPONSE TO AIRPLANE ON THE RUNWAY

Pilot	First exposure		Second Exposure	
	Response time, sec	Type of response[a]	Response time, sec	Type of response[a]
	No HUD		HUD	
A	---	MA, E2, warned	2	MA
B	1	MA	3	MA
C	---	MA, warned	3	MA
G	3	IMA	3	IMA
Mean	2.0		2.75	
	HUD		No HUD	
D	6[b]	Never saw	2	MA
E	5	IMA	2	MA
F	6[b]	Never saw	1	MA
H	5	IMA	1	IMA
Mean	5.5[b]		1.5	

[a]MA = missed approach; IMA = intended missed approach.

[b]These values are not response times, since the pilot never saw the airplane – rather, they denote the available time in which the airplane could have been seen; the mean also includes these values.

Both of these pilots saw the airplane on the second exposure without the HUD (13 runs and 21 runs later, respectively) and executed missed approaches. Upon seeing the tapes during their individual debriefing session, both expressed surprise and concern that they missed such an obvious stimulus. Pilot D said that "If I didn't see it (the tape), I wouldn't believe it. I honestly didn't see anything on that runway." It may be argued that if these pilots had been allowed to continue the run to a lower altitude (as some of the other pilots had been, see table 3), they would have seen the obstacle in time.

On the remainder of the trials all of the pilots did see and react to the obstacle. Table 2 shows that mean response time was longer with the HUD than without it (4.13 sec vs 1.75 sec) and was longer on the first exposure than on the second one (3.75 sec vs 2.13 sec). It seemed reasonable to expect some order effect. Most pilots were impressed by their first encounter with the runway obstacle, and, although they did not know if there was going to be more of the same, they were on the alert and were more cautious about calling out "decision."

Table 3 shows the aircraft's position in terms of radio altitude in feet (ALT) representing wheel height, and ground distance from the runway threshold (DIS) in feet. These data are shown at the time the first reaction (RT) to the obstacle was made, and at the lowest altitude (LOW) achieved (this occurred either where the airplane "bottomed out" on a go-around, or where the experimenter terminated the run).

If we look at the aircraft's position at the point where the first reaction (RT) to the obstacle was made, we find that it was closest to the runway threshold both in altitude and ground distance when the encounter was a first exposure with HUD. The rest of the time there was not much difference, although the order effect found for response time is suggested in the position data as well.

TABLE 3.– AIRCRAFT POSITIONS DURING OBSTACLE RUNS

Pilot	First exposure[a]				Second exposure[a]			
	RT		LOW		RT		LOW	
	ALT	DIS	ALT	DIS	ALT	DIS	ALT	DIS
	No HUD				HUD			
A	---	---	---	---	105	1295	57	375
B	72	960	45	480	71	550	60	330
C	---	---	---	---	51	550	40	320
G	63	505	50	250[b]	61	550	50	330[b]
Mean	68	733	48	365	72	736	52	339
	HUD				No HUD			
D	Never saw		67	450	95	590	82	345
E	61	360	61	360[b]	131	1280	107	830
F	Never saw		50	240	70	545	56	300
H	63	470	63	470[b]	61	495	50	270[b]
Mean	62	415	60	380	89	728	74	436

[a]RT = time of first reaction to obstacle; LOW = lowest altitude achieved; ALT = radio altitude in feet; DIS = ground distance from runway threshold in feet.

[b]These are intended missed approaches where the pilot called for go-around, but had no chance to actually initiate or fully execute the missed approach.

Tables 2 and 3 show that although pilots had a shorter response time without HUD (when they did respond), it was counteracted by the fact that they did come head-up later and thus saw the aircraft from about the same distance as with HUD and came to within the same distance of it.

In addition to the data runs reported here, two of the pilots received extra obstacle runs at the end of data collection. The results of these runs suggest that further exposure may not result in improved performance, possibly as a result of fatigue.

Interpretation of the obstacle data– The findings that response time was longer, and especially that two of the eight pilots did not see the obstacle at all with the HUD, indicated that the HUD may restrict or even inhibit the pilot in perceiving information from the outside world when flying a simulator. The question is, to what extent can these results be generalized to the real world? Several factors should be considered as they relate to generalizing these results to the real world. They are discussed in three groups: (1) those likely to occur in the real world with any HUD; (2) those that are likely a result of the properties of the specific type of HUD symbology used in this study; and (3) those that are likely to be an artifact of the present simulation.

First, let us consider five factors that are likely to occur in the real world with any HUD.

Factor 1 – obstacles on runways continue to be a safety problem. The NASA Aviation Safety Reporting System (ref. 6) cites 135 potentially hazardous runway incursions between July 1, 1976 and June 30, 1978. The report concludes that "Incursions of aircraft onto runways at controlled airports represent a significant safety problem."

Factor 2 – the last phase of the approach and landing is very stressful even with the HUD; that is, the pilot extends maximum effort. Several pilots in the present study noted that although they thought that they were controlling the aircraft better with HUD, their workload was just as high or higher than in the conventional approach, for there was more information to process. Because of the high stress the pilot is necessarily constraining his visual attention to the immediate task at hand, and may not be aware of information that is below the point of maximum attention. Without HUD, maximum attention is tightly held to the target point on the runway on late final. The 2- and 3-sec lag in responding to the obstacle in the no-HUD cases in the present study probably reflects this concentration. This single-mindedness is illustrated by the comment of one pilot (ref. 6) after a real runway obstacle encounter: "When I received clearance into position, I looked to my left. It may be difficult to believe that I looked and did not see an aircraft coming toward me . . . . I should have seen the other aircraft, and I bear the responsibility for not having seen it . . . ." This pilot was flying without HUD. However, the lack of response to (in fact the total blocking out of) the airplane on the runway by the two pilots in the present study was similar to this episode, although they were flying with HUD.

Factor 3 – it may be assumed that when it is available, pilots prefer to use the HUD for the primary control of the flightpath, and to use the outside scene for monitoring purposes only, for the HUD provides more accurate guidance in the last phase of the approach than is obtainable from visual cues. In the present study, pilots indicated a strong preference for flying with the HUD.

Factor 4 – the symbology is more compelling than the outside scene, because there is much more immediately perceivable change going on, calling for more attention.

Factor 5 – in addition, in the last phase of the flight the pilot is probably more fatigued, yet the workload is relatively high. Paying attention to two sets of information continuously and vigilantly in such a condition is demanding and stressful. The pilot may unwittingly lapse into paying attention to only one information source. Because the HUD information is more accurate and more compelling, it is likely to be the one followed. In the current study, several pilots admitted that from time to time they caught themselves totally fixating on the symbology, oblivious of anything else, and had to consciously force their attention to the outside scene.

Secondly, let us consider four factors that are likely due to the specific symbology used in this study.

Factor 1 – the HUD was designed to provide sufficient information even in zero-zero visibility conditions, that is, HUD guidance could be followed without direct use of the visual runway, although ideally it (also) should have been monitored. This redundancy of information may have created a conflict in the pilot, as he could use or ignore the outside cues at will. Not only could he ignore the outside world, but from about 150 ft and down (from about the time the obstacle became visible) the necessary tight control of the flightpath symbol in relation to the glide-slope symbol (and not the real runway) demanded maximum attention by the pilot. If the approach task had included aiming symbology at the "real" runway, thus forcing the pilot's attention to the outside world, the results might have been different.

Factor 2 – as may be seen in Fig. 5 the central symbols obscured the obstacle to a large degree at the time the obstacle first became visible, and by a decreasing amount all the way down. The airplane became clearly recognizable only about 2 sec after it became visible. It is interesting to note that the six pilots who did see the obstacle through the HUD believed that they detected it sooner with the HUD than without it. The typical explanation was that "The airplane was easier to see with the HUD because I was head-up."

Factor 3 – there were comments by some pilots that too many symbols were cluttering the center of the HUD's field of view. They recommended decluttering on final approach. In addition, the central symbols were too close together, inhibiting normal eye scanning.

Factor 4 – based on pilot comments, the flare bars were too compelling. Once they became visible, all pilots reported concentrating most of their visual or cognitive attention, or both, on them. It is interesting to note, however, that in all but one of the cases in which the obstacle was seen through the HUD, response occurred at about the time the eye scan had to be modified to take in the flare symbol (3° to 5° below the flightpath symbol, approximately overlaying the obstacle).

Thirdly, let us consider the possible influence of five factors related to the present simulation on the results.

Factor 1 – although all pilots agreed that the visual scene simulation was good, especially compared with the training simulators they were used to, the resolution was poorer, images were more "fuzzy," and the three-dimensional depth effect was not as good as in the real world. The relative deficiency of the outside visual cues may have been the cause of the apparently exaggerated attention on tracking the symbology in the present study. Still, it should be noted that none of the pilots, including the two who did not see the obstacle, believed that the quality of the visual simulation would inhibit them from seeing the airplane on the runway.

Factor 2 – as far as realism is concerned, in spite of all efforts to achieve the contrary, it was hard for the pilots to forget that they were flying a new approach every few minutes in a fixed-base simulator. Also, they tended to focus their attention on tracking the HUD closely, because it was new to them, rather than "landing the aircraft safely," as they would in the real world.

Factor 3 – in addition, all pilots have a set of expectancies when flying a simulator, none of which includes an obstacle on the runway. Human beings tend not to notice things they do not expect, especially in high stress situations. These pilots were not informed of the possible occurrence of such a stimulus. This is unrealistic, because in the real world they are far more aware of such a possibility. The generally shorter response time to the second encounter indicates that awareness of this possibility improves performance.

Factor 4 – the cockpit procedures used here were irregular in that the first officer did not report the obstacle, as he likely would have, if he followed the regular procedures these pilots were used to. The two times he did report it, the pilots had no difficulty executing a timely missed approach.

Factor 5 – it may also be argued that the results are reflecting insufficient training. Although the pilots did learn to correctly control the simulator so as to track the symbols after 8-10 trials, it is not the same as really understanding and "instantly knowing" how to use them in any situation. The pilots reported that they began to feel relaxed and confident in flying the HUD only toward the end of the experiment, after 25-30 runs with the HUD. This suggests that throughout the study the pilots were probably focusing mainly on how to fly the HUD, not how to fly the airplane.

In summary, due to the small sample size and the possible compounding effect of numerous factors, the present study cannot provide a clear-cut answer to whether the HUD will restrict or otherwise inhibit pilots from perceiving critical changes in the outside world. There are several factors that are likely to occur in the real world, as they did in the simulation: pilots will encounter obstacles on runways; their workload with the HUD will likely be just as high (or higher) as without HUD; the HUD is likely to demand their primary attention; and, if the HUD is totally self-sufficient and consistent, they may neglect to monitor the outside scene. These effects were probably magnified by the simulation effects; nevertheless, they should be taken into serious consideration by HUD users, until further studies clarify the issues.

SUMMARY AND CONCLUSIONS

The objective of the study was to assess pilots' ability to perceive and act upon unexpected information presented in either the outside world or in the HUD symbology.

In view of the objectives the results of the study are as follows:

1. None of the pilots reported perceiving the vertical boresight offset, and they did not act as if they understood it. Landing performance suggests that these pilots responded to some degree to the illusion the offset created. Nevertheless, pilots landed well within the acceptable region on the runway.
2. All pilots perceived the lateral offset. Although they did not understand the specific nature of it, their actions indicated that they understood the essence of the problem and responded appropriately. That is, in the case of the lateral boresight offset, the information was correct and usable; in the case of the ILS lateral offset, part of the information was wrong, and the rest of the symbology was usable. Pilots were not aware that offset influenced their flight performance in any way. The results show that offsets, especially in the vertical dimension, increased vertical error caused by environmental factors.
3. Two of the pilots did not perceive the obstacle on the runway while flying with the HUD. The rest of the pilots did, but they took longer to respond with the HUD than without it.
4. Pilots correctly assessed that their flight performance with the HUD was more accurate than it was with the conventional instruments.

The finding that the HUD may have some negative effect on flight performance is contrary to the findings of previous studies. This may be due to the combination of the runway obstacle – a factor not used in previous studies – and high workload. It may be hypothesized that the pilot constructs a cognitive model for the flight task, and that this model is dynamic and changes with changing needs. The information that goes into the model at any moment is arbitrarily selected by the pilot, based on what he deems necessary for the current task. Actual flight performance is then compared with the model on a continuing basis. At some point in the approach he is satisfied that the information on the instruments and from the outside world corresponds with the model in his head, and he makes the decision to land. The various information in the model is assigned priorities, probably based on how important it is to the successful execution of the task, or the probability of occurrence. As the workload increases, the amount of information the pilot is able to utilize is reduced; also, the less important or lower probability items would be the least likely to be attended to. During the final phase of the approach this model is likely narrowed down to the presence of the runway in proper lateral alignment, correct airspeed (or absence of speed error), correct aircraft attitude, and altitude.

The above model would explain why two of the pilots did not see the obstacle on the runway; it was simply not part of their model, and the low visibility and the pilots' relative unfamiliarity with the HUD created a high workload. It would also explain why pilots did not perceive the vertical offset; it did not violate their model. They were lined up with the runway, their altitude was within the acceptable range, and they felt in control of the aircraft. In fact, the offset had no practical significance. The ILS lateral offset, however, did violate the model; the runway was not where it was expected – therefore it was easy to perceive. The lateral boresight offset also raised a question about the position of the runway, so it was also recognized, if not understood. Workload was high in all cases, because of weather conditions and the fact that the HUD was still relatively new to the pilots. Individual differences between pilots would account for some of them responding better than others under similar circumstances.

It is not known to what extent, if any, the findings of this exercise apply to the real world. More work is needed to eliminate the possible simulation and specific symbology effects on performance with HUD, and to find out at what point the workload becomes a critical factor. In the meantime, it is recommended that users of HUD in commercial aviation train pilots thoroughly with every capability of the HUD, and develop crew procedures that would eliminate or counteract possible negative effects of the HUD.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035, June 6, 1980

APPENDIX

MEAN GLIDE-SLOPE AND LOCALIZER DEVIATION FOR EACH CONDITION

Notes for tables 4–10

Vertical dashed lines indicate breakout point

FG = first gear: designates data at time first gear touched the runway

NG = nose gear: designates data at time nose gear touched the runway

Hard landing: defined by $\dot{H} > 8$ ft sec^{-1} (first gear contact)

Short landing: defined by first gear touching ground in approach lights

Missed approach: an approach in which pilot elected to go around for any reason

Mean response time and standard deviations are given in seconds

Mean landing distance from threshold with standard deviation are given in feet

All deviations and altitude are in feet and are measured from the 3° glide slope or from runway centerline

Glide-slope deviations: "+" designates above; "–" designates below

Localizer deviations: "+" designates to the right; "–" designates to the left of runway centerline

Absolute glide-slope deviation does not reflect direction of offset

Response time to ILS offset is measured from breakout to beginning of convergence with the runway

Runway was not necessarily visible at breakout

TABLE 4.– FLIGHT PERFORMANCE WITH 90-FT ILS OFFSET – ENVIRONMENT
[RVR = 1,600 ft, ceiling = 120 ft, no wind shear]

Condition	Altitude, ft 800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
Glide-slope deviation, ft														
HUD														
Mean	-17	-7	-5	-5	-7	-4	-1	0	-2	-2	-1	0	---	---
SD	45	9	8	5	10	7	5	5	4	5	6	10		
No HUD														
Mean	29	15	-7	-20	-19	-8	-9	3	6	4	1	-4	---	---
SD	31	31	34	33	29	22	23	32	17	13	13	12		
Absolute localizer deviation, ft														
HUD														
Mean	93	90	99	93	71	80	96	86	82	78	63	41	23	18
SD	20	8	24	12	31	21	9	7	15	15	12	12	7	12
No HUD														
Mean	126	123	125	114	95	91	88	93	88	86	76	63	35	15
SD	90	85	63	68	63	51	52	48	49	43	41	36	20	14

Other pertinent flight information

Condition	Response time to offset (SD), sec	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
HUD	3.14 (0.90)	1	785 (258)	0	3
No HUD	3.00 (1.79)	2	859 (519)	0	1

TABLE 5.– FLIGHT PERFORMANCE WITH 90-FT ILS OFFSET – ENVIRONMENT
[RVR = 8,000 ft, ceiling = 380 ft, wind shear = 9]

Condition	Altitude, ft													
	800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
Glide-slope deviation, ft														
HUD														
Mean	-6	-2	-1	1	2	2	1	4	-2	-5	-11	-16	---	---
SD	11	13	13	9	10	7	10	11	10	10	8	5		
No HUD														
Mean	15	9	-1	-8	-6	18	18	8	-5	-11	-19	-28	---	---
SC	57	48	40	35	17	16	10	7	9	7	9	10		
Absolute localizer deviation, ft														
HUD														
Mean	91	93	91	95	95	77	57	43	39	32	27	19	12	12
SD	9	6	7	4	12	12	30	35	24	18	15	12	7	7
No HUD														
Mean	76	80	84	79	107	97	54	31	14	9	12	14	15	16
SC	74	64	52	65	47	50	24	13	10	10	8	8	12	18

Other pertinent flight information

Condition	Response time to offset (SD), sec	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
HUD	9.14 (7.45)	2	760 (568)	0	1
No HUD	8.63 (4.47)	1	312 (472)	1	4

TABLE 6.– FLIGHT PERFORMANCE WITH 90-FT ILS OFFSET – ENVIRONMENT
[RVR = 10,000 ft, ceiling = 615 ft, shear = 25]

Condition	Altitude, ft													
	800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
Glide-slope deviation, ft														
HUD														
Mean	-10	-5	-7	-7	-4	2	0	11	17	16	13	12	---	---
SD	29	16	13	13	13	24	11	19	14	12	13	18		
No HUD														
Mean	8	13	14	-1	-17	-16	-4	-1	7	6	1	-2	---	---
SD	21	17	17	16	19	28	21	22	8	5	7	13		
Absolute localizer deviation, ft														
HUD														
Mean	94	94	96	98	81	75	60	48	42	30	19	16	12	11
SD	14	11	6	8	13	27	29	30	18	19	22	17	14	10
No HUD														
Mean	71	95	134	136	97	62	73	62	28	23	19	15	16	23
SD	36	81	71	63	60	52	34	42	29	24	18	10	10	15

Other pertinent flight information

Condition	Response time to offset (SD), sec	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
HUD	43.00 (9.18)	0	1101 (616)	0	2
No HUD	40.88 (9.48)	0	977 (515)	0	0

TABLE 7.– FLIGHT PERFORMANCE WITH LATERAL BORESIGHT OFFSET IN HUD

Condition	Altitude, ft													
	800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
Environment 1														
Glide-slope deviation														
Mean	-18	-6	0	0	-1	2	-1	1	1	5	7	7	---	---
SD	12	10	8	5	2	4	5	5	8	8	8	8		
Localizer devation														
Mean	-2	-8	-9	-12	-2	4	-6	-3	-5	-7	-5	-2	-1	0
SD	37	38	21	13	15	15	11	11	10	8	7	10	19	17
Environment 2														
Glide-slope deviation														
Mean	-10	-2	-4	-4	-3	7	-1	6	-3	-8	-13	-18	---	---
SD	14	8	15	17	18	8	17	9	8	12	16	18		
Localizer deviation														
Mean	-5	-6	-4	-1	4	8	0	-12	-12	-10	-11	-7	-2	1
SD	14	18	15	12	10	14	20	15	18	17	13	11	8	11

Other pertinent flight information

Condition	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
E1	0	1270 (480)	0	1
E2	0	690 (910)	2	1

TABLE 8.– FLIGHT PERFORMANCE WITH VERTICAL BORESIGHT OFFSET IN HUD

Condition	800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
	Altitude, ft													
Environment 1														
Glide-slope deviation														
Mean	3	0	-2	2	-2	-2	2	1	3	4	3	4	---	---
SD	5	6	5	3	4	5	3	3	2	4	5	10		
Localizer deviation														
Mean	8	-1	-2	-2	3	-2	-1	1	-1	-2	-3	-3	-2	5
SD	55	29	8	20	9	4	8	7	4	7	10	13	12	18
Environment 2														
Glide-slope deviation														
Mean	1	-2	-4	1	2	-2	-6	-11	-17	-21	-22	-27	---	---
SD	10	9	12	6	5	8	11	10	16	16	18	17		
Localizer deviation														
Mean	3	-11	-19	0	2	-6	1	-4	-9	-9	-11	-11	0	5
SD	14	20	45	12	8	17	11	13	17	13	13	14	11	8
Environment 3														
Glide-slope deviation														
Mean	-3	5	3	-2	-1	-1	3	8	11	18	12	8	---	---
SD	13	14	7	5	11	11	25	10	14	19	18	22		
Localizer deviation														
Mean	-3	2	2	7	5	-1	-2	-8	-3	2	5	7	9	1
SD	21	11	6	6	17	11	21	21	16	18	16	14	15	16

Other pertinent flight information

Condition	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
E1	0	1263 (685)	0	1
E2	0	529 (377)	0	2
E3	0	1025 (487)	0	2

TABLE 9.– FLIGHT PERFORMANCE WITH HUD, NO OFFSET

Condition	Altitude, ft 800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
Environment 1														
Glide-slope deviation														
Mean	-2	-3	1	-3	-5	-2	-5	1	-7	-6	-6	-5	---	---
SD	9	5	5	7	6	3	7	11	9	9	8	9		
Localizer deviation														
Mean	3	2	3	8	1	5	5	5	1	-2	-2	-1	2	-1
SD	9	12	8	8	5	9	16	20	8	8	8	7	11	11
Environment 2														
Glide-slope deviation														
Mean	-1	-2	-2	1	0	4	-1	-2	-10	-11	-14	-11	---	---
SD	6	10	12	7	8	5	7	6	9	13	18	10		
Localizer deviation														
Mean	0	-6	5	2	1	4	-5	-9	-11	-7	-7	-3	4	-1
SD	12	16	16	17	13	17	9	16	26	28	22	16	14	19
Environment 3														
Glide-slope deviation														
Mean	-4	-4	-5	-3	6	4	-1	8	6	4	0	-3	---	---
SD	1	16	12	8	9	7	6	12	7	7	10	13		
Localizer deviation														
Mean	-1	-2	-4	0	-3	-3	7	-6	-12	-12	-12	-11	-10	-9
SD	18	20	14	9	7	13	10	12	11	9	10	10	9	10

Other pertinent flight information

Condition	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
E1	0	855 (231)	0	1
E2	0	1107 (551)	0	0
E3	1	737 (402)	0	3

TABLE 10.– FLIGHT PERFORMANCE WITH NO HUD, NO OFFSET

Condition	800	700	600	500	400	300	200	150	100	75	50	25	FG	NG
	Altitude, ft													
Environment 1														
Glide-slope deviation														
Mean	56	36	12	5	10	2	0	-4	14	7	5	0	---	---
SD	81	65	53	40	45	45	38	36	28	24	24	23		
Localizer deviation														
Mean	49	30	20	19	32	44	18	3	3	5	5	2	1	15
SD	106	89	71	107	129	100	44	55	58	53	44	30	16	13
Environment 2														
Glide-slope deviation														
Mean	-5	-25	-17	-3	13	21	12	8	-5	-13	-22	-30	---	---
SD	26	43	34	38	26	23	13	10	9	10	10	10		
Localizer deviation														
Mean	69	52	15	27	34	20	19	18	14	11	9	7	6	4
SD	103	98	89	106	70	34	46	34	22	15	9	8	11	12
Environment 3														
Glide-slope deviation														
Mean	17	16	-10	-13	-23	-19	-4	17	19	14	7	2	---	---
SD	18	53	65	22	43	37	41	14	11	10	9	10		
Localizer deviation														
Mean	84	-12	-26	8	16	36	6	-5	-10	-11	-10	-8	-4	1
SD	218	90	111	161	71	92	38	31	20	14	12	13	10	7

Other pertinent flight information

Condition	Number of missed approaches	Landing distance from threshold (SD), ft	Number of short landings	Number of hard landings
E1	2	979 (872)	0	2
E2	1	106 (226)	2	3
E3	0	1216 (701)	0	0

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15. Supplementary Notes

This Head-Up Display (HUD) report is number 7 in a series.

16. Abstract

The ability of pilots to recognize and act upon unexpected information, presented in either the outside world or in a head-up display (HUD), was evaluated. Eight commercial airline pilots flew 18 approaches with a flightpath-type HUD and 13 approaches with conventional instruments in a fixed-base 727 simulator. The approaches were flown under conditions of low visibility, turbulence, and wind shear. Vertical and lateral flight performance was measured for five cognitive variables: an unexpected obstacle on runway; vertical and lateral boresight-type offset of the HUD; lateral ILS beam bend-type offset; and no anomaly. Mean response time to the runway obstacle was longer with HUD than without it (4.13 vs 1.75 sec), and two of the pilots did not see the obstacle at all with the HUD. None of the offsets caused any deterioration in lateral flight performance, but all caused some change in vertical tracking; all offsets seemed to magnify the environmental effects. In all conditions, both vertical and lateral tracking was better with the HUD than with the conventional instruments.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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