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HEAD-UP TRANSITION BEHAVIOR OF PILOTS WITH AND WITHOUT HEAD-UP DISPLAY IN SIMULATED LOW-VISIBILITY APPROACHES

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To quantify head-up transition behavior with and without a flightpath type head-up display, eight rated B-727 pilots each flew 31 manual and coupled approaches in a simulator with B-727 dynamics and collimated model board external scene. Data were also obtained on the roll played by the head-up display in the coupled-to-manual transition. Various wind shears, low visibilities, and ceilings were tested along with unexpected misalignment between the runway and head-up display symbology. The symbolic format used was a conformal flightpath type optically superimposed over the external scene. The following results are reported. (1) Every pilot except one stayed head-up, flying with the display after descending below the ceiling. Without the display and as altitude decreased, the number of lookups from the instrument panel decreased and the duration of each one increased. (2) No large differences in mean number or duration of transitions up or down were found during the head-up display runs comparing the no-misalignment with the lateral instrument landing system offset misalignment runs. (3) The head-up display led to fewer transitions after the pilot made a decision to land or execute a missed approach. (4) Without the display, pilots generally waited until they had descended below the ceiling to look outside the first time, but with it several pilots looked down at their panel at relatively high altitudes (if they looked down at all). (5) Manual takeover of control was rapid and smooth both with and without the display. The display permitted smoother engine power changes, that is, fewer changes of usually smaller magnitude after autopilot disconnect. Vertical rate and control column displacement data before and after disconnect showed no significant differences. (6) A posttest debriefing indicated overall acceptance of the format used and overall test realism.

The head-up display (HUD) is a radical departure from the traditional philosophy of cockpit design for flight instruments. Its chief characteristic is the entirely different position chosen for presenting flight guidance and control information – superimposed over the pilot's forward line of sight through the aircraft's windshield. This is achieved by locating above the glare shield a semitransparent reflecting glass upon which various symbols are reflected toward the pilot's eyes. The HUD optical imaging system also presents the symbology at optical infinity so that it appears at the same distance as the runway. Because of these two HUD characteristics the number of transitions from head-down to head-up and vice versa and shifts in visual accommodation (theoretically) should be minimized.

Another important characteristic of HUD is its capacity for displaying a wide range of information through the use of microprocessor-controlled electronic display techniques. This may make it possible to more fully match the displayed information to the pilot's perceptual and cognitive capabilities. Nevertheless, with or without HUD, a transition from instruments to outside visual cues must be made during every approach to landing; however, it has been claimed that a HUD will ease this transition (ref. 1).

Both in-flight and simulator research on the issue of pilot head-up transition time has been reviewed in a previous paper (ref. 2). If a HUD is used during the approach and landing the pilot already will be head-up and looking out of the window at breakout. Of course this will depend, among other things, on the particular cockpit procedures used. The HUD might tend to ease the transition to external visual cues because the pilot is facilitated in attending to both the HUD information (which is predominately aircraft related) and the external scene information at the same time (refs. 3-5). That is, a well-designed HUD might allow the pilot to attend continuously to fields of information that can only be viewed disjointedly in the conventional cockpit (ref. 6). If this is true, the HUD should be useful in situations in which both the external world and the instrument information are needed at the same time; for example, in a missed approach, when the decision to go around has been left to the last moment at which the external world can still safely be scanned. Time is of the essence in reverting to instrument guidance (ref. 7). Therefore, for a pilot flying with a HUD, transition probably becomes a matter of continuously processing information along the flightpath from the two superimposed sets of information.

In aircraft without HUD the physical movement of the pilot's head and eyes, the refocus of his lens from near to far distance, and the cognitive processes involved in switching from one "frame of reference" to another take a finite amount of time as the pilot looks up from the instrument panel to the outside scene. In aircraft with HUD the pilot need not look back at the instrument panel if the display and external scene together present him with necessary and sufficient flight information. Relatively little work has been done to quantify these basic pilot behaviors; this is the primary objective of the present study, which was one of three coincident studies. The others were concerned with cognitive switching between the HUD and external scene when a mismatch between the two existed (ref. 8) and eye-scan behavior during the approach and landing.[1]

The head-up transition involves two separate components: (1) a *physical* one, involving movement of the head (and shifted line of sight) and a change in the accommodative state of the eye's focus distance, and (2) a *cognitive* or attentional component. Few investigators have attempted to separate these two basic types of behavior, perhaps because of the practical and theoretical difficulties in doing so.

In the following brief review previous research is described in terms of using a HUD during the transition from instrument meteorological condition (IMC) to visual meteorological condition (VMC) flight.

Transition Time with HUD

Several laboratory, simulator, and in-flight investigations have addressed the subject of transition time with HUD. Early simulator studies showed that pilots responded more rapidly to stimuli in the external world while performing a tracking task in the head-up mode than when tracking head-down (ref. 9). In addition, flight tests with HUD in which pilots known to be using HUD were given incorrect (fly-down) guidance when flying close to the ground during terrain-following showed that they survived the experience (presumably) because they were able to reject the incorrect commands. Apparently, the pilots were able to divide their attention successfully between the two separate sources of information. The pilots also perceived other air traffic and birds more effectively when flying with HUD.

A laboratory study found that the critical assessment of the presence of certain flight-related information in either or both information fields took a negligible amount of time (of the order of 25 msec for the external scene and 100 msec for HUD using a series of HUD symbol formats superimposed over external scenes (ref. 10)). The procedure used was that of presenting (briefly) the HUD symbology alone, the background scene alone, or the two superimposed and asking the pilot to answer questions that could only be answered correctly if the requested information was present and perceived. When the pilot was already "head-up," search and recognition time took place within a very brief period of time compared with typical visual fixation durations of from 0.4 to 1.9 sec (refs. 11-13).

No previous research could be found for the head-up transition time (from the instrument panel) or visual cue assessment and decisionmaking time of pilots using a HUD and external visual cues. Reference 10 does provide information on previous research with HUD related to cognitive switching between HUD and an external scene. Suffice it to say that the transition time one is dealing with when a HUD is used after breakout is primarily that of an ongoing perceptual processing of both sets of information.

Transition Time Without HUD

Transition time without HUD has been reviewed elsewhere (ref. 2); the following comments are limited to those previous findings that are related to the

[1]Pilot Eye Movements During Simulated Low Visibility Approaches, Proposed NASA Technical Paper by T. A. Price, R. F. Haines, and E. Fischer.

present study. The mean decision time required to assess the outside scene and then decide to execute a missed approach or continue to a landing was 2 to 4.6 sec for ceilings under 380 ft during manual instrument landing system (ILS) approaches. The approaches were flown in a simulator at approximately 126 knots; a variety of low-visibility and wind conditions were present (ref. 2). The required decision time is in agreement with findings of previous research (ref. 14). It was also found that the mean vertical distance traveled during this visual cue assessment period was a relatively constant proportion of the existing ceiling height. The mean number of head-up transitions after breakout ranged from 4.6 to 13.4 and increased in frequency as a function of ceiling height. The practical significance of this lies in the fact that each head-up transition requires a finite amount of time which, when summed, can account for an appreciable proportion of the total available viewing time. For example, for an aircraft flying at 135 knots on a 3° flightpath the transit time between each 100 ft of altitude is only 8.4 sec. If the aircraft is at 100 ft altitude and the pilot makes as few as four separate head-up/head-down transitions, each of which takes 1.5 sec, a total of 6 sec will have elapsed; moreover, some part of the total of 6 sec provides little useful guidance and control information, due to such factors as the blurred retinal images produced by the eye scans and changes in accommodation.

The large number of physical and cognitive response factors and their inherent complexity makes separation and quantification difficult. In the present investigation the methods used were those of (1) monitoring the head-up and head-down behavior of the pilot continuously in a variety of flight conditions where the quantity and quality of external cues was varied, and (2) determining the point on the approach where the pilot indicated that he had sufficient visual information to continue the approach to a landing or to execute a missed approach. Each of these methods was done with and without the aid of HUD. Flight performance data also were collected during the transition from coupled to manual flight with and without HUD during a limited number of approaches by each pilot.

This study was conducted as part of the joint FAA/NASA Head-Up Display Concept Evaluation Project, Task Order DOT-FAA77WAI-725 to Interagency Agreement NASA-NMI 1052.151, dated March 9, 1977. The present investigation constituted a subtask of Phase 2 work on perceptual and human factors related to the HUD concept.

We wish to thank Capt. C. F. (Dick) Pocius, Alan Simpson, Edward Leitner, and Donna Miller for their able assistance in the conduct of this study and to personnel of the Ames Simulation Sciences Division, Electronic Instrument Services Branch, and Flight Systems Research Division for their part in hardware and software development.

METHOD

Test Subject Pilots

Eight rated B-727 pilots were tested. A number of descriptive characteristics for each pilot are given in table 1. All pilots were obtained through a NASA

TABLE 1.– SUBJECT PILOT INFORMATION

Pilot	Age[a]	Seat	Aircraft type	Hours in type[b]	Cat. II rated/aircraft	Estimated number of manual day landings	
						Cat. I	Cat. II
A	47	FO	B-727	1,000	Yes	100	0
B	43	Capt.		1,500	No	16	
C	45	Capt.		300	Yes	12	
D	40	FO		1,667	Yes	24	
E	43	FO		200	No	4	
F	50	Capt.		6,000	Yes	20	
G	42	Capt.		1,550	Yes	10	
H	43	Capt.		2,400	No	[c]	

[a]Mean = 44.1.
[b]Mean = 1,827 hr.
[c]Pilot unable to provide an estimate, but responded "Lots."

contractor and all were paid for their services. Two pilots (B and E) had previous HUD simulator experience.

Experimental Design and Test Variables

This experiment was designed to permit valid comparisons to be made between the HUD and no-HUD runs across all other variables. These test variables included the following: the seven environmental conditions listed in table 2; five cognitive parameters described below and elsewhere in detail (ref. 8); and three control modes described below.

Since it was not possible to test all permutations of the above variables, a subset of 31 was tested. Each combination of three variables is listed in appendix A; they are defined in the following text.

Referring to table 2, it may be noted that the combination of breakout ceilings and runway visual ranges (RVR's) coupled with the decision height (DH) required the pilot to make a rapid assessment of the external scene before reaching decision height. For environmental condition (1), for instance, there was a 20-ft height difference between the ceiling and DH. At a 3° glide slope (GS) and nominal 135-knot approach speed the aircraft would travel this segment in only 1.8 sec. Comparable travel times for environmental conditions (4), (5), and (6) would be 3.8 sec, 1.6 sec, and 6.8 sec, respectively. For purposes of comparison, environments (2) through (5) were the same as those used in a previous head-up transition study (ref. 2). Finally, the variable runway visual range (RVR) condition of environment (6) was such that the runway environment became visible at an altitude between 700 and 550 ft. Thereafter a simulated scud layer totally and realistically obscured the ground between 550 and 275 ft, which then "opened up" to permit sight of the approach lights (RVR equivalent to about 2,400 ft) down to an altitude of 80 ft, followed by a final RVR of 1,000 ft. This changing visibility of the ground permitted the pilot flying with HUD to transition from HUD information only in IMC flight to HUD plus ground scene in (clear) VMC flight.

Referring to the wind shear column in table 2, no. 9 consisted of a 15-knot tower-reported headwind. From the 1,500-ft initial altitude to 150 ft there was a 30-knot headwind which sheared to 18 knots at 50-ft altitude followed by an exponential decay to 15 knots at the runway. Shear no. 25 consisted of calm wind reported at the tower. From the 1,500-ft initial altitude to the ground, the initial 25-knot headwind decreased exponentially to zero at the ground.

Five cognitive parameters were included in the study; they are described in table 3 and elsewhere (ref. 8). These parameters were included to meet the objectives of another phase of the study (ref. 8); nevertheless, head-up transition data was collected in cognitive parameters 2-4 described below.

Three control mode variables were also investigated in addition to the above described variables.

TABLE 2.– ENVIRONMENTAL CONDITIONS

Environmental conditions						Test runs[a]			
No.	RVR,[b] ft	Ceiling, ft	Shear	Turbulence	DH,[c] ft	Number		%	
						HUD	No HUD	HUD	No HUD
1	1,600	120	None	Light	100	4	2	13	6
2	8,000	380	No. 9	Moderate	200	4	2	13	6
3	8,000	615	No. 25	Moderate	200	3	2	10	6
4	2,400	245	No. 9	Moderate	200	2	2	6	6
5	1,600	170	No. 25	Light	150	2	2	6	6
6	Variable	700	None	Light	150	2	2	6	6
7	2,000	180	None	Light	100	1	1	3	3

[a]31 test runs per pilot – 18 with HUD, 13 without.
[b]Runway visual range.
[c]Decision height.

TABLE 3.– COGNITIVE PARAMETERS

Cognitive parameter	Description[a]
1	Runway incursion – Go around mandatory. Model of jet aircraft to same scale as the Redifon runway environment was placed on approach end of runway at 45° angle to centerline and halfway onto runway from taxiway [2; 6%].
2	Vertical misalignment of HUD – A simulated boresight misalignment of 2° produced by elevating entire HUD symbology relative to real runway [3; 10%].
3	Lateral misalignment of HUD – A simulated 3° boresight misalignment of the HUD to both the left- and right-hand sides relative to real runway [2; 6%].
4	Lateral simulated ILS HUD misalignment – Entire set of aircraft coordinates shifted 90 (scale) ft to left and right of real runway to simulate ILS lateral error [6; 20%].
5	No-mismatch – All of the conformal HUD symbols correctly overlay the proper points (and areas) on the background scene [18; 60%].

[a]The first number within each bracket is the number of approaches made by each pilot for the given cognitive parameter; the second is that number expressed as a percentage of the total number of approaches (31).

They were: (1) *manual flight,* in which the approach and landing (or missed approach) were made without autopilot or autothrottle; (2) *coupled flight,* in which the approach was controlled by an autopilot (without autothrottle) to flare altitude, after which the pilot uncoupled and executed the flare (or missed approach) manually; and (3) *unexpected autopilot disconnect,* in which the approach was controlled by the autopilot (without autothrottle) to an altitude about 10 ft above DH, at which time a red flashing glare-shield-mounted "disconnect" light came on. The pilot was instructed to continue the approach manually in this situation. The computer produced this disconnect at randomly determined heights from 5 to 12 ft above DH. For these trials the pilot was told (before starting the trial) only that it was to be a coupled approach. During training the pilots were told that if there should be an unexpected disconnect they should be prepared to take over manually. Twenty-five (81%) of the total 31 approaches made by each pilot were manual, 4 (13%) were unexpected autopilot disconnects, and 2 (6%) were coupled and flown to flare height, after which the pilot disconnected the autopilot and landed.

The final variable was whether or not a HUD was used. Eighteen (58%) of the 31 total approaches were flown with HUD and 13 (42%) without HUD in a random presentation order.

Head-Up Display

The head-up display was produced by a PDP 11/40 computer driving an Evans and Sutherland Picture System; it was displayed on a monitor in front of the simulator's left seat. The pilot viewed this symbology by reflection off a partially reflective mirror; the external (Redifon) scene also was viewed through this mirror such that both were correctly superimposed. Both sets of information (HUD and external scene) were collimated to apparent optical infinity by means of two acrylic, 61-cm (24-in.) focal length, 63.5-cm (25-in.) diameter lenses producing a 46° wide virtual image at the reference eye position (ref. 15).

The HUD symbology (described in detail in ref 16), consisted of an integrated array of flight guidance and control symbols (see fig. 1) presented within a field of view 24° wide by 21° high. Briefly, the horizon (labeled with heading numerals and ticks) was pitch and roll stabilized and moved in a 1:1 fashion with the horizon of the external scene. An unlabeled 5° pitch-up and a labeled 10° pitch-down and pitch-up line (all parallel to the horizon) were present. Only the 5° pitch-up line can be seen in figure 1. An aircraft reference (extension of the longitudinal body axis) was represented by the small "v" with horizontal wings; it is seen just above the 090 heading numeral in figure 2. This symbol, a flashing letter indicating transit over a marker beacon, and a distance measuring equipment (DME) readout (directly above this symbol), were the only symbols that did not move within the HUD's field of view. The small circle with bent wings represented the instantaneous flightpath. Digital airspeed in knots was located just to the left of the wingtip of this symbol

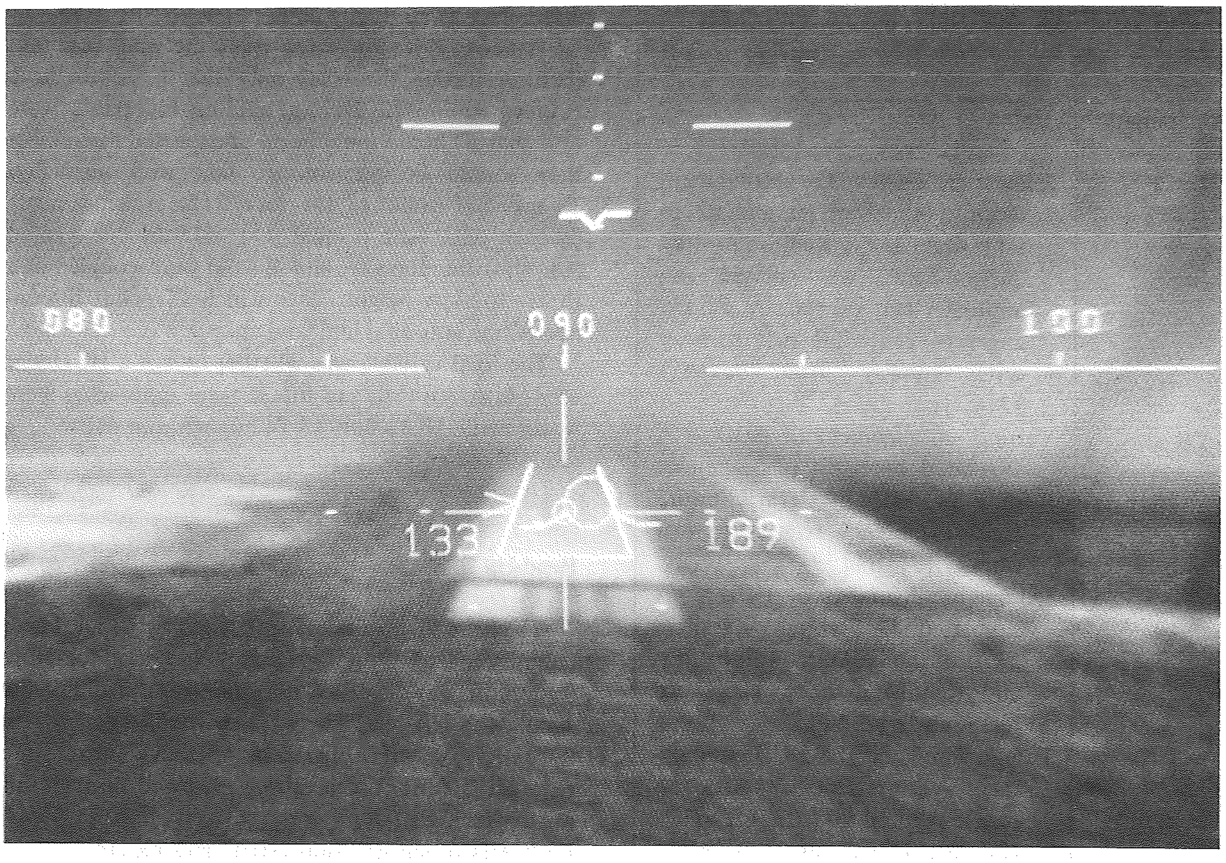

Figure 1.– Head-up display symbology.

and digital altitude in feet just to the right. These two digits stayed in the same position relative to the flightpath symbol to assist the pilot in quickly locating them. Speed error was indicated by a vertical tape rising out of the top of the flightpath symbol's left wing for positive speed error and descending from the bottom of the wing for negative speed error (relative to V_{REF} which the pilot manually set). A horizontal pointer, which traveled normal to the flightpath symbol's wings, indicated the acceleration along the flightpath at any instant. Known as the potential flightpath, this symbol provided a means for adjusting the power so as to maintain a desired acceleration for any given flightpath. A three-sided artificial runway outline symbol appeared inside the outer marker remaining conformal with the external runway (for the no-mismatch conditions). In addition, ILS localizer and glide-slope symbols were present. The glide-slope symbol consisted of a small circle with segmented horizontal lines at the same vertical position in the field of view as the circle; the circle was free to move vertically. The localizer symbol was a segmented vertical line with lateral freedom of motion. If the flightpath symbol was flown such that the glide-slope circle was inside it and the localizer lines bisected both circles, the aircraft would be in the correct location for continuing the approach to land.

Procedures

The procedures used may be described in three sections: pretest, data collection, and post test. A written description with diagrams of the HUD symbology was mailed to each pilot several weeks prior to his arrival at Ames Research Center. On the first test day, the pilots were given a battery of vision tests and a HUD questionnaire to complete. Then they were shown a video tape, which presented the HUD as it

Figure 2.– Cockpit interior.

would appear to them against cloud and ground backgrounds in a variety of approach and landing maneuvers. This 24-min-long tape began by discussing each symbol as an individual information element and then in combination with other symbols, progressively including demonstrations of some effects on symbol motion of turbulence and shear and the appearance of runway environment details under varying visibilities. Reduced visibilities were produced electronically, using the technique of white raster line overlay to reduce contrast. The pilots were encouraged to ask questions about the HUD at any time they felt something was unclear.

The following pilot training regimen was used. Each pilot was taken to the simulator and shown all of the controls, HUD symbology controls, eye-reference positioning device, seat adjustments, autopilot disconnect and other response buttons, and intercom controls. Figure 2 shows a view of the cockpit with these controls. At least six no-HUD familiarization trials were then given; turbulence, crosswinds, moderate wind shear, and lower visibilities were introduced only in the later runs. When the pilot said he was familiar with the simulator environment and with the aircraft's flying qualities, the HUD symbology was introduced. Following are the basic HUD training and familiarization trial conditions given to every pilot. In several instances pilots asked to repeat a condition or two, presumably in an effort to improve his performance. All trials began at an altitude of 1,500 ft and at a distance of 9.5 miles from the runway, with the aircraft trimmed either for level flight (LF) or for a 3° glide slope (GS).

The training conditions with HUD were as follows:

1. RVR 50,000 ft; ceiling 700 ft; no turbulence, (LF).

2. Same as above. (The first two trials were primarily for symbol identification and demonstration of their motions.)

3. RVR 10,000 ft; ceiling 700 ft; no turbulence, (LF).

4. Same as above. (Trials 3 and 4 were to result in a landing. The flare symbol, DME, and marker beacon annunciation were pointed out and further familiarization with the flightpath and potential flightpath symbol was achieved.)

5. RVR 2,400 ft; ceiling 500 ft; light turbulence, (GS). (In this and the two preceding trails the glide-slope intercept procedures were demonstrated. This trial resulted in a landing.)

6. RVR 2,400 ft; ceiling 250 ft; moderate turbulence, 10-knot crosswind from the right, (GS). (The checklist used in the study was introduced and a landing was made.)

7. RVR 1,600 ft; ceiling 300 ft; moderate turbulence, (GS). (A deliberate missed approach was executed at about 50 ft. The runway clearance-weather briefing was given along with the use of the checklist.)

8. RVR 1,600 ft; ceiling 175 ft; no turbulence, moderate head-wind shear of 25 knots decaying to 0 knots at the runway, (GS). (All of the required cockpit procedures, call-outs, etc. were used.)

9. RVR 1,600 ft; ceiling 175 ft; moderate turbulence, (GS). (This trial provided further opportunity to clarify all of the testing requirements and call-outs desired by the pilot flying of the first officer who was an experimenter; RFH).

Use of the autopilot disconnect yoke button was demonstrated during at least two of these nine training runs. If a pilot requested to repeat one or more of these conditions it was done immediately after the trial. Training in control of the flightpath symbol was done using both the glide-slope and localizer reference symbols as the null or aiming point as well as having the pilot attempt to place the flightpath symbol directly on the runway touchdown zone. Training in control of the potential flightpath symbol consisted of asking the pilot to try to maintain a given airspeed at each of several different flightpath angles, to try to establish a specific flightpath angle for a fixed throttle setting, and to control both flightpath and throttle in the presence of a head-wind shear. By the end of training these pilots were proficient with these operations and indicated that they understood the meaning and use of each symbol.

Procedures used during the data collection portion of the study included a "radio" call by the first officer to an experimenter for the weather (RVR, ceiling, winds) for that approach and a clearance to land. In most instances, this information was completed before the outer marker was reached. The captain called for the checklist, which was read by the first officer (who also operated the gear and flap controls).

An experimenter stood behind the pilot ready to press a button (B) (see fig. 2) when the pilot said the word "decision." He was instructed to say "decision" when he was head-up and had enough visual information to decide whether he would continue the approach to a landing or would execute a missed approach. No special prompting was given concerning whether the decision was to be made as early or as late as possible. The pilot was supposed to scan the available external information – including HUD information for the HUD runs – in a manner typical of that which he would use during an actual approach. The experimenter also informed the pilot whether the approach was to be manual or coupled. For the manual-approach runs the pilot was simply to disconnect the autopilot and continue the approach manually. He was never told whether there would be an unexpected disconnect.

For the no-HUD runs the *decision time* was measured from the moment the pilot first looked up from the instrument panel (IP) to the moment he said "decision." For the HUD runs the decision time was measured from the moment the first officer indicated the runway was in sight to the moment the pilot said "decision." The two decision times cannot be compared directly; still, they are useful in setting approximate transition time limits on this response.

Figure 2 shows a HUD control panel (CP) located on the left end of the glare shield. Two press-and-turn-to-set control knobs were used by the pilot, after he started the trial, to set in the DH altitude and the V_{REF} for landing. Pressing in on each knob caused the current digital value to disappear; rotating each knob caused the desired number to appear on the HUD; letting go of each knob locked the desired number in and caused the current value to reappear. The DH value set in was made to flash at 3 Hz from 100 ft above its preset value to touchdown. As the V_{REF} knob was depressed and turned to the desired value the airspeed error "vertical tape" rose out of the top of the left "wing" of the flightpath symbol by a (scaled) amount proportional to the current difference between airspeed and V_{REF} (see fig. 1). To increase workload by requiring the pilot to set V_{REF} on every approach, the first officer called out a predetermined value that was to be set into the HUD. This was done during the checklist reading or, more often, just after the trial started.

The pilot's eye movements were monitored unobtrusively by means of an infrared oculometer (ref. 17), the projection and photocell reception head of which are shown at (O) in figure 2. The results of this part of the study are being prepared for a later report. A video tape, made on every approach, included the same color external view as was seen by the pilots, the superimposed HUD, eye movement "dot," and a black-and-white view of the pilot's head and eyes, which was inset into one corner of the screen. The TV lens used to obtain this view is labeled (L) in figure 2.

RESULTS AND DISCUSSION

The results are presented in four sections: (1) mean duration and number of separate transitions made with and without HUD; (2) mean altitude at which the first transition was made with and without HUD; (3) responses made to unexpected autopilot disconnect with and without HUD; and (4) subjective opinion results.

Mean Duration and Number of Transitions

A transition is defined as a change in the pilot's line of sight between the instrument panel and forward view. The fundamental distinction was which source of information was used rather than the direction of the pilot's line of sight at any instant. These mean transition data were analyzed separately for each of four flight segments for the no-mismatch and the mismatch runs. The *first* segment was from the glide-slope intercept to the ceiling and involved IMC flight in all cases. Because of the test instructions, the pilot should have stayed head-down during all of the no-HUD runs (since there was nothing visible outside for the first officer to see or call out). It can be mentioned that, in fact, all eight pilots stayed head-down during this segment except one: he looked outside several times during a run with a reported RVR of greater than 8,000 ft and a ceiling of 650 ft and looked out once during a run with a reported RVR of greater than 8,000 ft and a ceiling of 380 ft. The *second* flight segment was from the ceiling to decision height (DH), the *third* from decision height to 50 ft, and the *fourth* from 50 ft to the ground.

No-mismatch mean results– Mean data for runs in which there was no mismatch between the HUD and external scene are presented in appendixes B through H and in figures 3 through 5. The (typical) altitude range traversed and the theoretical transit time assuming a 3° glide slope and 135-knot approach speed are also given in brackets for each flight segment to allow comparisons to be made with the mean transition duration and other data. For the no-HUD data, these pilots made increasingly longer looks (up) outside the cockpit as altitude decreased and also made increasingly shorter looks (down) to the IP as altitude decreased, which is expected during normal information cross-check procedures. It can also be noted that fewer transitions tended to be made as altitude decreased, a finding in agreement with previous research (refs. 2, 17). Because of the small sample size and missing data it was not possible to carry out an analysis of variance on the data of appendixes B through H. Product-moment correlations were run on these mean data with the following results. The midrange altitude for each flight segment in each section of appendixes B through H was determined and then rank ordered; this became

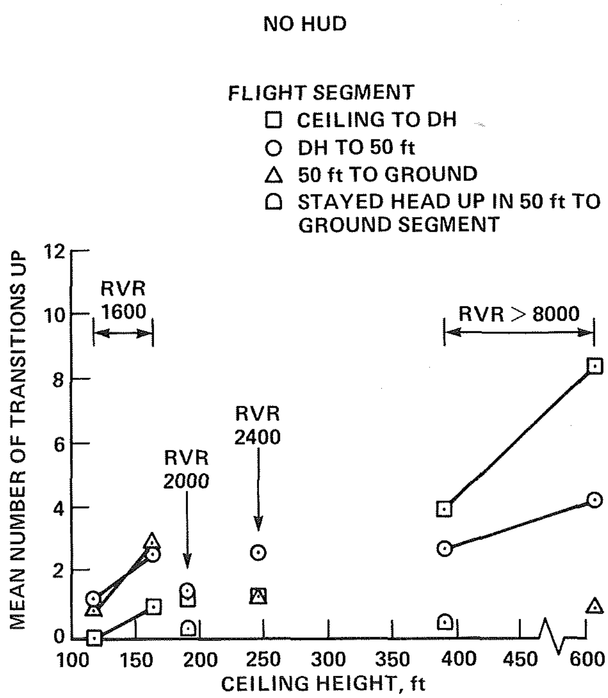

Figure 3.– Mean number of transitions up from instrument panel as a function of ceiling height: flying without HUD.

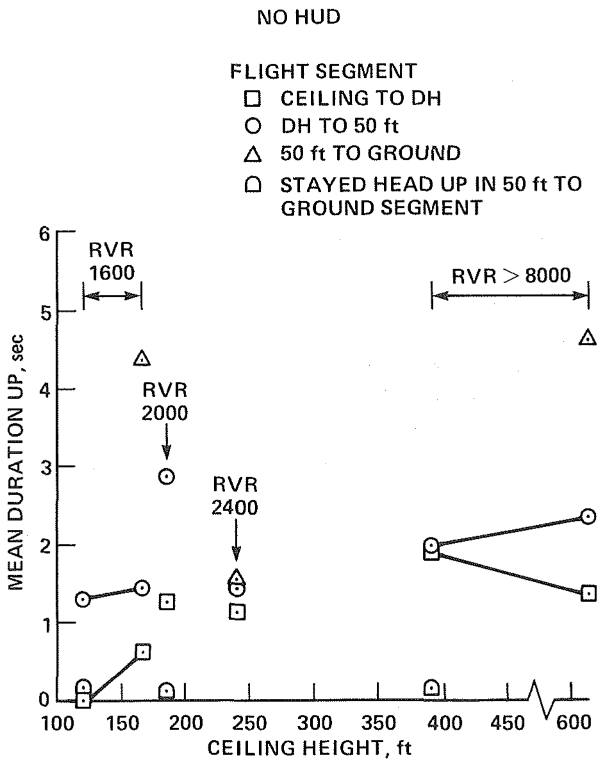

Figure 4.– Mean duration of transitions up from instrument panel as a function of ceiling height: flying without HUD.

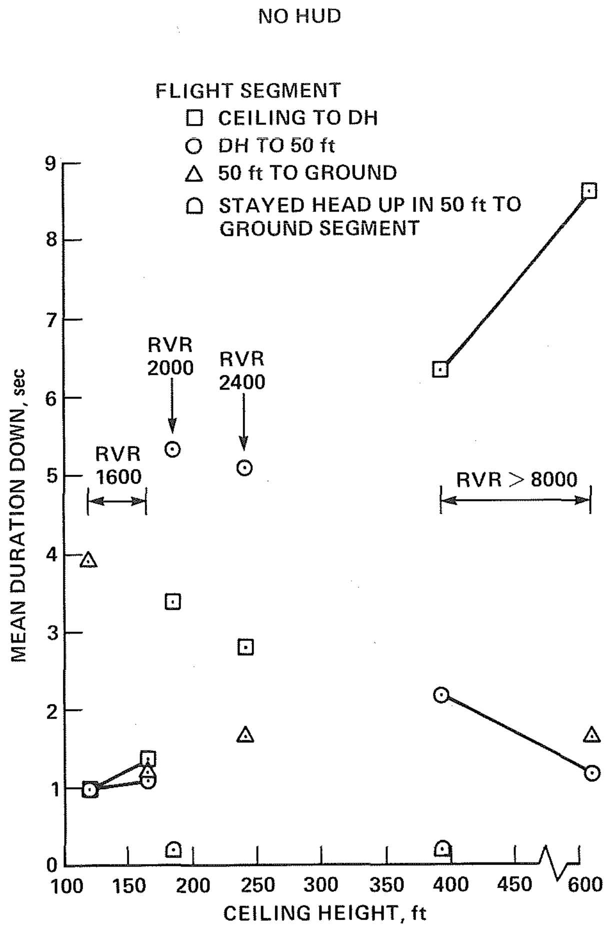

Figure 5.– Mean duration of transitions down from the external scene after first having looked up from instrument panel as a function of ceiling height: flying without HUD.

variable X in the correlation calculation. The mean number of looks (up) from the IP during the no-HUD runs corresponding to each ranked altitude was variable Y. A significant ($p \leqslant 0.005$) positive correlation of $r = 0.73$ was found, i.e., the lower the altitude the smaller the number of looks (up) after the pilots had once looked up from the IP. The second correlation tested was between the rank-ordered mean altitudes (as above) and mean duration of each transition up from the IP during the no-HUD runs. This correlation of $r = -0.4$ was not significant. The third correlation was between mean head-up transition duration and the mean number of looks (up) from the IP. The $r = 0.1$ value was not significant, a result that is probably due to the confounding effect of combining these mean data from six environments, each of which possessed different visibilities.

What is also of interest is the transition behavior of these pilots when they were using HUD. These mean data are also presented in appendixes B through H. For these no-mismatch conditions, every pilot stayed head-up, after descending below the ceiling for five of the six environmental conditions tested which involved homogeneous fog (i.e., environments (1)-(4) and (7)). Thus, these pilots never once looked at the IP after the ground had come into sight. Only one exception to this occurred involving one pilot (see appendix F for the 170-ft ceiling to 150-ft decision height segment). These findings are variously interpreted.

It may be that these pilots judged that HUD provided fully adequate flight guidance and control information for these test conditions. In other words, these pilots may have placed a high degree of reliance on the HUD even though they had never flown this type of display before. Perhaps such a finding is, at least partially, due to the fact that the pilots knew they were in a simulator; as a result, that could have led them to disregard the usual consequences of a crash or otherwise poorly executed approach and landing. These pilots indicated (during the post test comment period) that they did not feel a need to request additional call-outs by the first officer over those they normally used (without HUD). Still another possibility is that these pilots did not seriously consider the possibility that they would be allowed to fly a HUD that was somehow in error. Evidence to support this possibility is presented in a companion paper (ref. 8). This last interpretation raises the question of transition behavior during runs in which a deliberate mismatch was introduced in the HUD information, a subject considered in a later section of this paper.

Comparison of no-mismatch mean decision time and transition results with those from a previous study– In order to allow direct comparison of these results to be made with a previous head-up transition study (without HUD) (ref. 2), five of the present environmental conditions were the same as those used previously. The same basic instructions and method were also used in both studies. The mean number of transitions up from the IP averaged across all four flight segments for the present study and mean decision time (sec) from both studies are presented in table 4.

TABLE 4.– COMPARISON OF PRESENT NO-HUD MANUAL CONTROL RESULTS WITH PREVIOUS HEAD-UP TRANSITION STUDY

Environment and test conditions	Present study		Previous study (ref. 2)	
	$\bar{X}$ decision time, sec[a]	$\bar{X}$ no. of transitions	$\bar{X}$ decision time, sec[a]	$\bar{X}$ no. of transitions
3 RVR 8,000 ft Ceiling 615 ft	17.9	13.5	7.3	13.4
2 RVR 8,000 ft Ceiling 380 ft	5.2	7.7[b]	4.6	10.8
4 RVR 2,400 ft Ceiling 245 ft	4.3	5.4[c]	3.5	7.3
5 RVR 1,600 ft Ceiling as noted	6.6 Ceiling = 170 ft	4.8[c]	2.0 Ceiling = 180 ft	5.5
1 RVR 1,600 ft Ceiling as noted	2.3 Ceiling = 120 ft	2.3	2.2 Ceiling = 130 ft	4.6

[a]Decision time was measured from the moment the pilot looked up from the IP to the moment he said the word "decision."
[b]All pilots stayed head-up during the 50-ft-to-touchdown segment.
[c]All pilots stayed head-up during the glide-slope-intercept-to-ceiling segment.

Relatively similar results were found between the two studies. Neither the mean decision times nor the mean number of transitions were statistically significantly different between the two studies, using the $p < 0.05$ level of confidence criterion and the randomization test for two independent samples (ref. 18).

Generally, the lower the RVR and ceiling the fewer the number of transitions and the shorter the decision times. Although the mean number of transitions up from the instrument panel tended to be greater for each environmental condition in the previous study, all of the mean decision times were shorter. This may be due to the fact that a motion-base simulator was used in the previous study which could have led the pilot to perceive more instability in the external scene (perhaps due to head motion) than was present in the same scene presented in this study; such perceived instability may have led the pilot to make more head-up transitions to obtain the required information within the available time.

In summary, the present no-mismatch mean data indicate that, without HUD, pilots tend to make fewer transitions but make increasingly longer fixations outside the cockpit as altitude decreases.

HUD mismatch mean results– The only mismatch condition in which a direct comparison can be made between the HUD and the no-HUD runs is the lateral ILS mismatch condition (cognitive parameter 4). Appendixes I through K present the mean number of transitions and mean duration of these data. Three environmental conditions (1, 2, and 3) were used to compare performance with this type of visual mismatch situation.

In interpreting these data it should be pointed out that the Sperry flight director (model HZ-6B "Horizon Flight Director Indicator") used during the no-HUD runs presented angular-pitch-change information in reduced scale, presumably making these displacements more difficult to detect visually, even if the pilot were checking the flight director after looking up. It also might be presumed that if the pilot had an indication of an ILS deviation during the no-HUD runs, he would make more head-up and head-down cross-checks after breakout to try to resolve the incongruity. No clear-cut trends of this nature were found. There was some evidence to indicate that few of these pilots detected this mismatch without HUD; every pilot detected the mismatch with HUD, however. These results are presented in reference 8.

Pilot transition data also were obtained during the two other mismatch conditions that involved vertical and lateral boresight misalignment. Since there was no instrument panel condition that was equivalent to the head-up display misalignment, they were only tested in the HUD runs. As was the case with the lateral ILS mismatch condition discussed above, both of these misalignment conditions became apparent to the pilot after the runway environment came into sight. It was anticipated that pilots would tend to make more or longer head-down transitions to the instrument panel. This did not occur, except in the case of one pilot during the ceiling-to-DH segment and the DH to 50-ft segment in environment (3). For environment (3) this pilot looked down from the HUD once for 0.6 sec during the higher flight segment and once for 1 sec during the lower flight segment. For environment (2) (i.e., RVR > 8,000 ft, 380-ft ceiling, more severe headwind shear, moderate turbulence, and 200-ft DH) one pilot looked down from the HUD once for less than 1 sec for the lateral boresight runs and stayed head-up for the vertical boresight runs during all flight segments. Finally, for environment (1) (i.e., RVR 1,600 ft, 120-ft ceiling, no wind shear, light turbulence, and 100-ft DH) one pilot looked down from the HUD once for less than 1 sec for the vertical boresight run during the decision height to 50-ft flight segment. Otherwise, he stayed head-up for all of the other runs.

In summary it appears reasonable to say that these two unexpected HUD mismatch conditions did not lead these pilots to transition down from the HUD for any cross-check information, except in the extremely small number of instances cited above. This finding might be explained in a way that is somewhat different from that in which the lateral ILS offset data were explained, namely, that these pilots may have detected the offset at some point in the approach, but relied on the appearance of the background scene to bring about an adequate resolution, that is, an acceptable landing maneuver.

Comparison of mismatch and no-mismatch mean results without HUD– A comparison was also made between the mean decision time and number of transitions for the no-HUD runs in which there was lateral ILS mismatch on the flight director versus those in which there was not. No clear-cut differences were found, and, for all but 3 of the 36 comparisons, mean decision time was within 1.3 sec for the two conditions (typically of the order of 0.3 sec). The remaining three comparisons gave mean-decision-time differences of 2.4 sec (no-mismatch longer); 5.3 sec (mismatch longer); and 19.4 sec (mismatch longer). The 19.4-sec value was probably due to the fact that the pilot was attending to the external scene at a relatively high altitude (615 ft) during a greater proportion of the available viewing time compared with the lower ceiling and RVR conditions in which he would be expected to refer to the flight director on the instrument panel more of the time.

Number of transitions following the pilot's decision– A third response measure, which is of interest from the point of view of informational adequacy during the final stages of an approach with and without HUD, is the number of transitions made after the pilot indicated (verbally) that he had sufficient visual information to continue the approach to a landing or to execute a missed approach. If when flying head-up without the HUD he looks down at his IP after his decision it implies that he feels the need to update the information that (previously) led to his decision; if when flying head-up with the HUD he looks down at his IP after his decision is made it may imply the same thing, it may imply that he perceives a mismatch or other information discrepancy that can be resolved by looking down at the IP, or it could mean that he still does not fully understand the HUD information. Such transitions following a pilot's decision while flying HUD might provide a measure of the adequacy of the HUD symbology for leading the pilot to make the correct decision. Table 5 presents these data for the no-mismatch runs. For example, the upper left-hand data cell shows that seven pilots made no transitions while one made two transitions using the HUD.

It can be seen that the HUD runs lead to a larger proportion of pilots making fewer transitions down to the instrument panel and that the no-HUD runs lead to their making a relatively large number of transitions down once they had looked up in order to make their decision. The data of table 5 have been arranged from the top down in terms of increasingly lower minima and visibility. Interestingly, even the relatively low ceilings lead to a number of head-down transitions without HUD after the pilot's decision has been made. It might be argued, of course, that the pilots made their decisions relatively early after assessing the ground cues, which would permit them to continue to make subsequent transitions to "update" the adequacy of their decision.

Mean Altitude at First Transition

Another basic response measure of interest is the altitude at which each pilot made his first transition down to the IP when flying with HUD or up to the external scene when flying without HUD. Individual pilot data are plotted in figure 6 in no particular order for each environmental condition and for the HUD and no-HUD runs. The dashed horizontal line indicates the ceiling.

Most of the pilots did not look up from the IP until after descending below the ceiling, as was required by the test instructions, while flying without HUD. The data are arranged without regard to which data point refers to which pilot so as to illustrate the manner in which these altitudes are distributed. For the two highest ceilings (615 and 380 ft), both with RVR $>$ 8,000 ft, the pilots flying without HUD looked up the first time over a wider range of altitudes (173 and 192 ft, respectively), having once descended below the ceiling, than they did for the lower ceilings and RVR conditions. Typically only three or four of the eight pilots ever looked down at all, depending on the environmental condition. Although all of the above data are for the manual runs, no substantial differences were noted in the altitude at which each pilot first transitioned up or down in the coupled runs.

In summary it may be said that only about one-half of the present pilots flying with HUD ever cross-checked against the instrument panel. When they did so it was in IMC flight. Although this finding may be interpreted as pointing to the adequacy of the HUD information, it might also be seen as a reason to take a careful look at the procedures that are implemented for use with future HUDs. It is still problematical whether the call-outs and other cross-checks made by the pilot not flying (without a HUD in a single HUD installation) will adequately fill the information gaps that may be left by this seeming dependency upon HUD information alone.

Control Responses Made to Unexpected Autopilot Disconnects

Pilot control performance with and without HUD following an unexpected autopilot disconnect was analyzed for each of the two environmental conditions in which this situation occurred (i.e., environments (5) and (6)). The instantaneous vertical rate before and at the moment of disconnect (DISC) and each 2.5 sec thereafter to a maximum of 10 sec was quantified to see whether the HUD information would influence the smoothness of the manual takeover. The results showed that there were no large

TABLE 5.– NUMBER OF TRANSITIONS DOWN TO THE IP. FOLLOWING THE PILOT'S DECISION – NO-MISMATCH RUNS ONLY

Environment and test conditions	HUD		No-HUD	
	Pilots	Transitions	Pilots	Transitions
3			1	n.d.[a]
RVR 8,000 ft	7	0	1	2
Ceiling 615 ft	1	2	2	6
Shear: 25			1	8
			2	9
			1	10
2			1	n.d.[a]
RVR 8,000 ft	6	0	1	3
Ceiling 380 ft	1	2	2	5
Shear: 9	1	3	1	8
			2	9
			1	10
4			1	n.d.[a]
RVR 2,400 ft	8	0	1	2
Ceiling 245 ft			2	3
Shear: 9			3	4
			1	5
7				
RVR 2,000 ft	1	n.d.[a]	1	n.d.[a]
Ceiling 180 ft	7	0	5	1
Shear: none			2	2
5			1	n.d.[a]
RVR 1,600 ft	7	0	3	2
Ceiling 170 ft	1	1	2	3
Shear: 25			1	5
			1	6
1			1	n.d.[a]
RVR 1,600 ft	7	0	1	0
Ceiling 120 ft	1	2	3	1
Shear: none			2	2
			1	3

[a]n.d. = no decision.

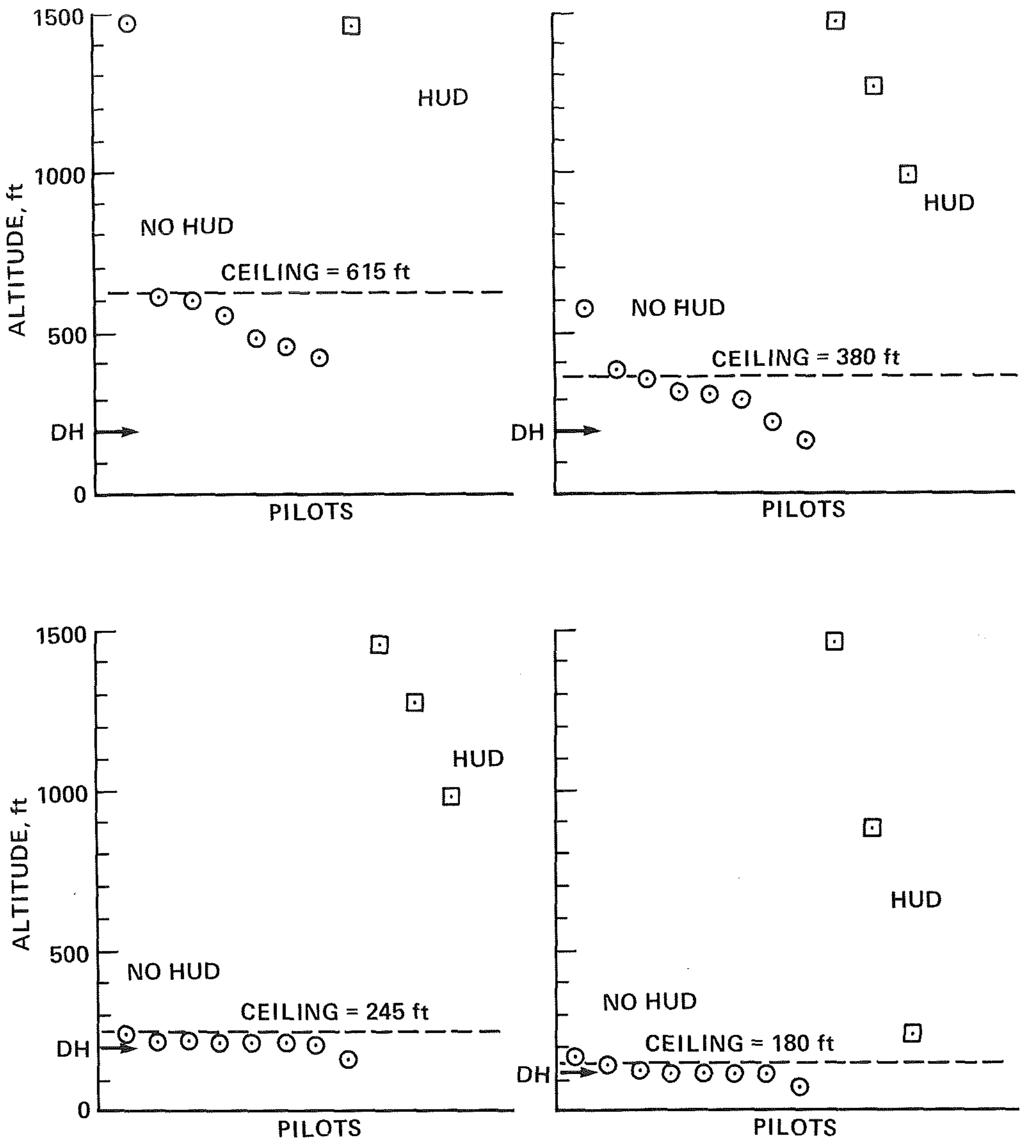

Figure 6.– Mean altitude at which each pilot made an initial transition with and without HUD for each environmental condition – continued.

or statistically significant differences in this performance measure. The same can be said of the control column displacement. A comparison of each pilot's control of engine rpm (%) generally showed fewer and lower magnitude power setting changes with HUD following disconnect, as illustrated in figure 7. A disconnect (DISC) line and touchdown (TD) arrow are also shown. Percent power is shown on the abscissa and 5-sec tick marks on the ordinate. This finding is probably the result of having the potential flightpath symbol available within the central eye-scan area on the HUD.

In summary, it may be said that these pilots took over manual control smoothly following an unexpected autopilot disconnect both with and without the HUD. Use of the HUD seemed to assist them in making desired engine power settings after the disconnect.

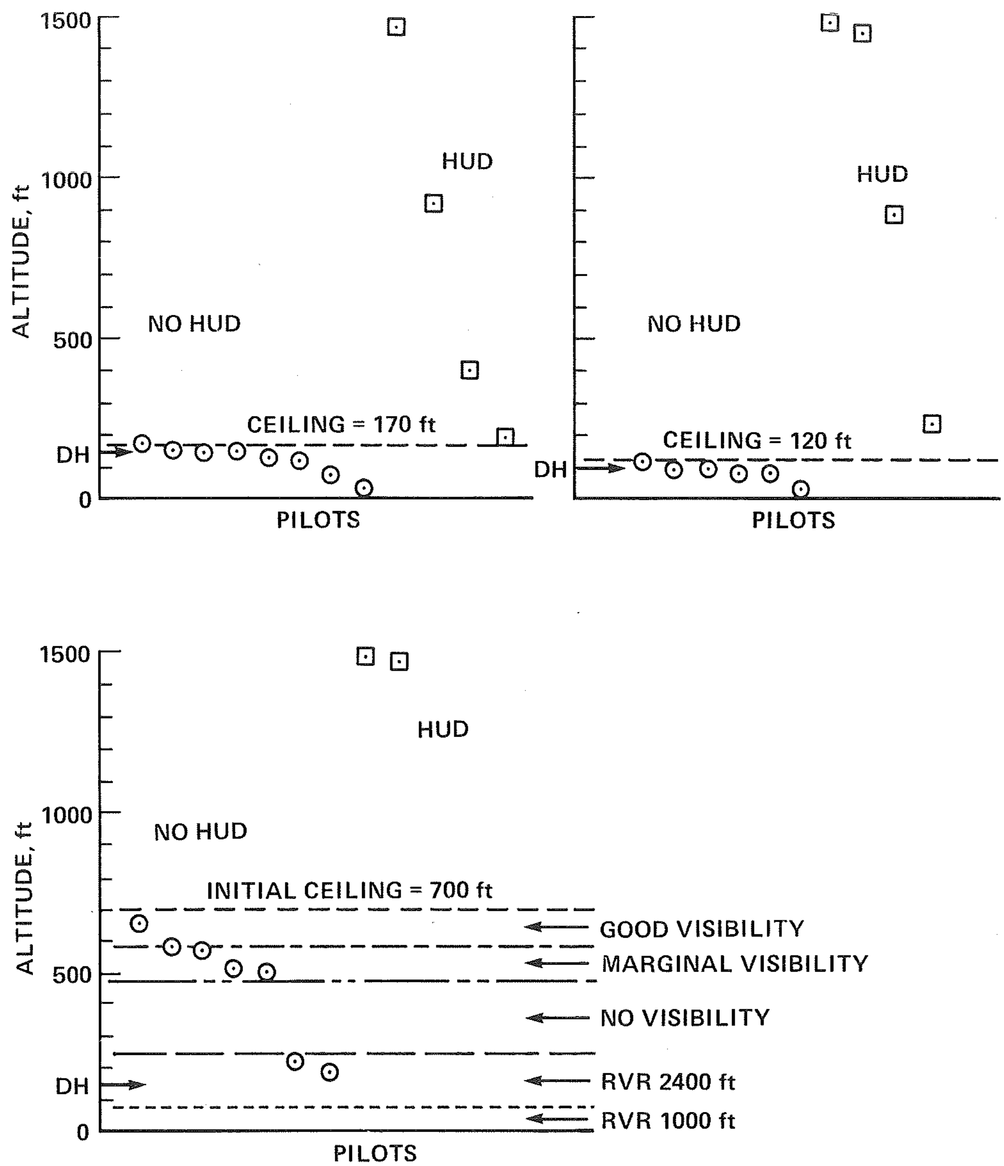

Figure 6.– Mean altitude at which each pilot made an initial transition with and without HUD for each environmental condition – concluded.

Subjective Opinion Results

Following each test run the pilots were asked to comment on a number of issues related to the adequacy of the experimental simulation, the information provided by the HUD and instrument panel, and other matters.

The following questions were asked:

1. Was there anything about the cockpit environment that served to distract you from obtaining all the information needed to land?
2. List here anything about this simulation which you feel was so unrealistic as to invalidate your data.
3. Was anything unclear to you during this study? If so what?
4. Once you were familiar with the HUD did it ever lead you to seriously consider descending below minimums?
5. Were you at any time transfixed or overly concentrating upon any particular HUD symbol? If "yes" specify which one.
6. Which of the following pairs of test conditions was most difficult for you?

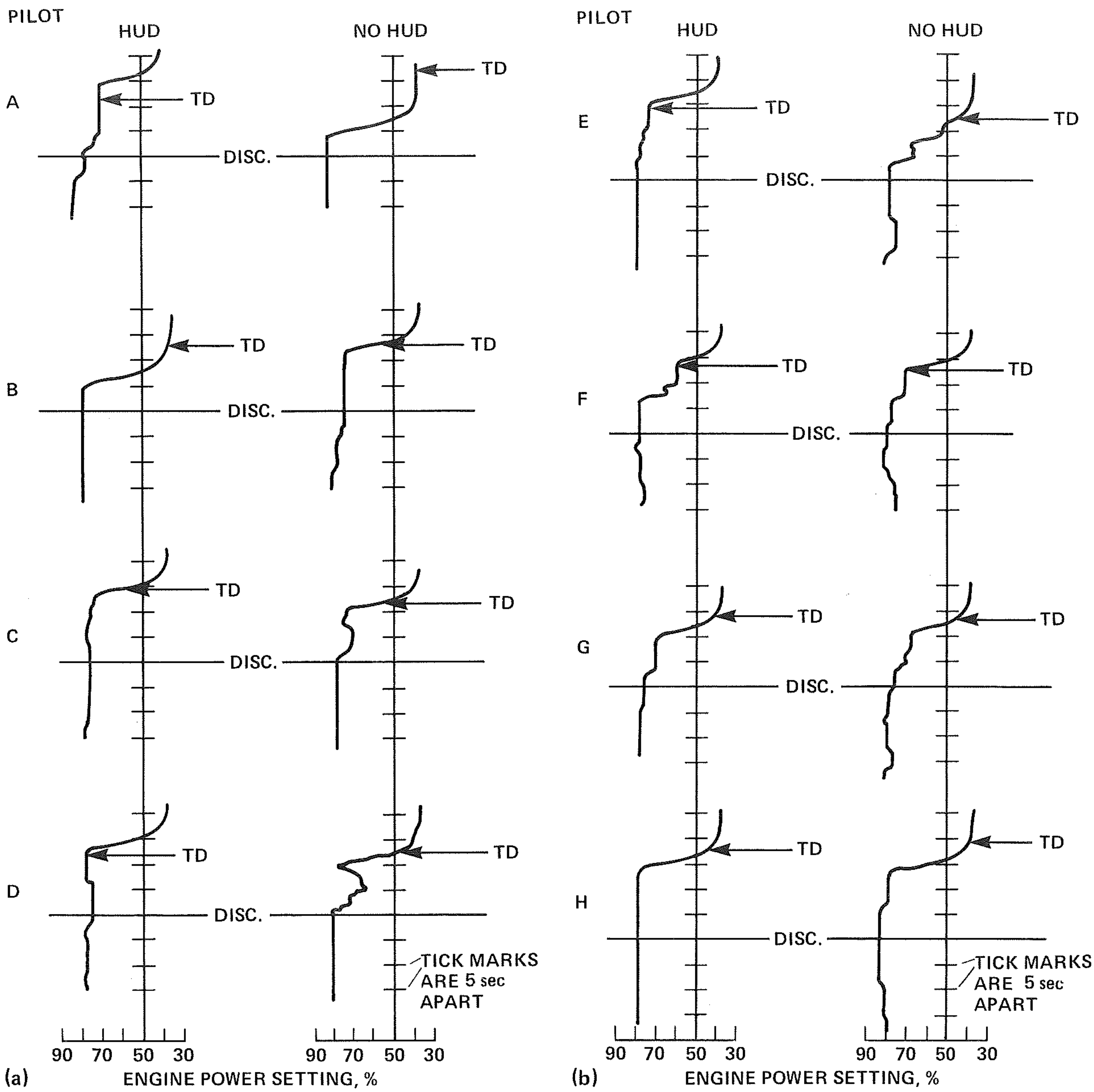

Figure 7.– Engine power setting before and after unexpected autopilot disconnect flying with and without HUD: environment (5).

7. Considering only the wind-shear conditions presented, which HUD symbols seemed to be most useful to you? (Rank order from most to least useful.)

8. Considering only the low RVR conditions presented, which HUD symbols seemed to be most useful to you? (Rank order from most to least useful.)

9. Comparing the HUD with the no-HUD runs, do you think you made (select answer from list) head-up transitions using the HUD?

10. Only considering those approaches on which there was a mismatch between the real runway and the HUD runway outline, how do you feel your flight control performance was affected?

11. How would a well-designed HUD affect flight safety in your opinion?

The responses of each pilot are presented in table 6. All responses are direct quotes.

TABLE 6.– SUBJECTIVE OPINION RESULTS

Abbreviated question	Pilot							
	A	B	C	D	E	F	G	H
1. Any cockpit distractions?	No	No	No	No	Yes, MM light too bright	No	Yes, OM light too bright	No
2. Any unrealistic simulation features?	No	No	No	On day 1 the column forces were a little high	No	No	Outside scene isn't as good as real world	No
3. Anything unclear about the study?	No	No	No	No	Setting V_{ref} initially	No	No	No
4. Did HUD lead you to consider descending below minimums?	Yes	No	Not sure	No	No	No	No	No
5. At any time were you overly concentrating upon any HUD symbol?	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
If "yes" which one?	Glide-slope circle		Setting V_{ref} and DH	Initially, "potential flightpath"	Glide-slope circle	Flare lines	Glide-slope circle and flightpath alignment	Flightpath
6. Most difficult test condition? (A) HUD + manual vs. (B) no-HUD + manual	No answer	B	B	B	B	B	B	A (due to more available information)
(A) HUD + coupled vs. (B) no-HUD + coupled	No difference	No difference	No difference	B	B	B	B	No difference

TABLE 6.– CONTINUED

Abbreviated question	Pilot							
	A	B	C	D	E	F	G	H
6. Concluded (A) HUD + unexpected autopilot DISC (B) no-HUD + unexpected autopilot DISC	No difference	B	B	B	B	B	B	No difference
7. Most useful HUD information for coping with wind shear? (ranked)	Airspeed, potential flightpath	Airspeed error, altitude digit	Flightpath, potential flightpath, airspeed error, altitude digit, DME	Potential flightpath, airspeed digit, flightpath	Potential flightpath, airspeed error, G.S. circle	Airspeed error, potential flightpath, airspeed digit	Potential flightpath, airspeed error, airspeed digit	Potential flightpath, airspeed error, airspeed digit
8. Most useful HUD information for coping with low RVR? (ranked)	Airspeed, potential flightpath	Flightpath (all others about equal)	Same as for question (7)	Same as for question (7)	G.S. circle, altitude digit, airspeed error	Same as for question (7)	Flightpath, potential flightpath, altitude digit (for flare), airspeed digit	Same as for question (7)
9. Head-up transitions made with and without HUD (A) Approximately same number (B) Somewhat more with (C) Great many more with (D) Somewhat less with (E) Great many less (F) Can't say (G) Other answer	G Never went head-down with HUD	D	E	E	E	E	E	E

TABLE 6.– CONCLUDED

Abbreviated question	Pilot							
	A	B	C	D	E	F	G	H
10. Flight control performance with HUD during mismatch runs only (A) Very negligibly affected (B) Somewhat negligibly affected (C) Not affected – annoying (D) Not affected in any way	D	B	C	D	B	C	B initially, but C after three runs	C
11. How would a well-designed HUD affect flight safety? (A) Significantly degrade (B) Possibly degrade (C) No particular influence (D) Possibly improve (E) Significantly improve	E	E	E	E	E	E	E	E

Each pilot was allowed to comment on anything pertaining to this debriefing questionnaire – several comments are noteworthy. Regarding question (5), most of the pilots said that their excessive concentration on HUD symbols occurred principally during the earlier runs before they had become familiar with particular symbols. One pilot commented that such over-concentration "could happen with a head-down flight director." Another said that he felt his visual "cross-check wasn't that good on the HUD because it is a new display." Several pilots commented on the seemingly long time needed to manually set in the HUD V_{REF} and DH values. Regarding question (10), pilot A said he was never aware of a mismatch when flying without HUD. Pilot C stated that he felt he could handle the offsets better with a HUD; however, he did not think that the mismatches he encountered in this study were deliberate. Pilots D and E also stated that they felt a misalignment between the aircraft and real world was coped with better with a HUD because, as one of the pilots put it, ". . . with a HUD, I can see what's happening earlier."

Following are comments given freely in regard to question (11).

Pilot A: "A beautiful system. Cross-check is easier, everything is there, (it) makes your eye-scan easier."

Pilot B: "I'm very impressed with it . . . this is a mechanical gadget which can fly better than the pilot can under many circumstances."

Pilot C: "It's like looking directly at the ground, a continuation of the outside world. All (the) information needed is right there."

Pilot D: "From what I know now about HUD and particularly flare . . . a well-designed HUD would significantly improve flight safety."

Pilot G: "After a few flights and flight (tests) proven by others and a few flights (in an aircraft) by myself . . . a well-designed HUD would significantly improve flight safety."

To summarize this section, the post test questions that dealt with the simulation and experiment itself seemed to point to the general acceptance by these pilots of the overall realism of the cockpit. No pilot felt his data should be eliminated from the analysis on the basis of nonrealistic testing conditions. The questions that dealt with HUD versus no-HUD performance showed that these pilots felt that manual approaches and unexpected autopilot disconnect situations were easier to cope with when HUD was used. There was less consistency of opinion concerning whether HUD helped the pilot monitor the coupled approach (to the point of flare). Regarding question (9), it should be noted that most of these pilots were very conservative in their answer that use of HUD led to a great many less head-up transitions. Comparison of the number of transitions with and without HUD (table 5) illustrates this fact; indeed, almost every pilot stayed head-up when flying the HUD below the breakout ceiling.

CONCLUSIONS

The primary objective of this study was to quantify the head-up transition behavior of pilots in simulated low-visibility conditions with and without HUD. It was found that when flying without HUD, pilots generally made increasingly longer looks outside the cockpit as altitude – thus distance to the touchdown point – decreased. This was true for both the no-mismatch and the mismatch conditions. The pilots also made fewer transitions outside as altitude decreased. With one exception, these pilots, when flying with HUD, did not look down at the instrument panel after the ground came into sight for either the no-mismatch or the mismatch condition. These findings are interpreted to mean that the pilots were satisfied with their control performance with HUD and did not feel they needed supplementary panel information. This interpretation is supported by the fact that these pilots did not request additional call-outs by the first officer other than those used for the no-HUD runs. For the ILS-offset runs, the pilots seldom noticed the offset displayed on the attitude director indicator (ADI) whereas they perceived it relatively quickly after breakout with the HUD.

A decision to land or to go around is very likely made on a continuous basis during the approach. This is suggested in the present study by the relatively large number of head-down transitions to the instrument panel made after the pilot made his decision. Since the no-HUD runs led to a larger proportion of pilots making a larger number of such transitions than on the HUD runs, it would appear that HUD does contribute to reducing the pilot's visual scanning tasks, an important component of his workload.

Although these simulator performance data may be representative of the transition behavior likely to be found in flight, there are reasons they should not be accepted uncritically. For example: (1) the possibility that these pilots were not as experienced in the task of evaluating two superimposed sets of visual information simultaneously as they might have been; (2) they were not as familiar with the simulator environment as they are with their own aircraft, and/or (3) some feature of the simulator's external visual scene (e.g., reduced resolution compared with the real world) may make these data different from those found in flight. The relatively good agreement between the mean transition data from this and a previous simulator study does lend confidence in the reliability of these data. Further simulator research is called for to quantify pilot eye-scan and fixation behavior along with transition behavior during low-visibility approaches with and without HUD. Such data would help us understand better the quantitative and qualitative dimensions of the visual cues pilots use to land their aircraft.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035, July 28, 1980

APPENDIX A

TEST VARIABLES ADMINISTERED

Run	Environment	Cognitive parameter	Control mode	HUD
a	1	2	1	On
b		3		On
c		4		On
d		4		Off
e		5		On
f		5		Off
g	2	2		On
h		3		On
i		4		On
j		4		Off
k		5		On
l		5		Off
m	3	2		On
n		4		On
o		4		Off
p		5		On
q				Off
r	4			On
s				Off
t			2	On
u			2	Off
v	5		1	On
w			1	Off
x			3	On
y			3	Off
z	6		1	On
aa			1	Off
bb			3	On
cc			3	Off
dd	7	1	1	On
ee	7	1	1	Off

APPENDIX B

TRANSITIONS: NO MISMATCH, ENVIRONMENT 3

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches only. Environment 3: RVR > 8,000 ft, shear 25, ceiling 615 ft, moderate turbulence.

TABLE B1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	8.9	9.5	4	2	*c*	*c*	1	1
615-ft ceiling to DH (415 ft = 35 sec)	*b*	1.4	*b*	8.4	*b*	0.6	8	7
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	2.4	*b*	4.1	*b*	2.0	8	7
50 ft to ground (50 ft = 4.2 sec)	*b*	4.6	*b*	1	*b*	0.6	8	2

TABLE B2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.7	2.8	4	2	*c*	*c*	1	1
615-ft ceiling to DH (415 ft = 35 sec)	*b*	8.6	*b*	8.8	*b*	6.2	8	7
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	1.2	*b*	4.3	*b*	0.8	8	7
50 ft to ground (50 ft = 4.2 sec)	*b*	1.7	*b*	1	*b*	*c*	8	1

[a]Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b]All pilots stayed head-up.
[c]N too small to calculate a valid SD.

APPENDIX C

TRANSITIONS: NO MISMATCH, ENVIRONMENT 2

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches only. Environment 2: RVR > 8,000 ft, shear 9, ceiling 380 ft, moderate turbulence.

TABLE C1.– TRANSITIONS UP FROM IP

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	36.2	0.3	3.3	1	30.9	*c*	3	1
380-ft ceiling to DH (180 ft = 15 sec)	*b*	1.9	*b*	4	*b*	2.1	8	7
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	2.0	*b*	2.8	*b*	1.7	8	8
50 ft to ground (50 ft = 4.2 sec)	*b*	*b*	*b*	*b*	*b*	*b*	8	8

TABLE C2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	2.5	200	3.3	1	0.83	*c*	3	1
380-ft ceiling to DH (180 ft = 15 sec)	*b*	6.4	*b*	4	*b*	37.1	8	7
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	2.2	*b*	3.4	*b*	2.3	8	8
50 ft to ground (50 ft = 4.2 sec)	*b*	*b*	*b*	*b*	*b*	*b*	8	8

[a] Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b] All pilots stayed head-up.
[c] N too small to calculate a valid SD.

APPENDIX D

TRANSITIONS: NO MISMATCH, ENVIRONMENT 4

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches only. Environment 4: RVR 2,400 ft, shear 9, ceiling 245 ft, moderate turbulence.

TABLE D1.– TRANSITIONS UP FROM IP

Flight segment [a]	$\bar{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	70.2	*b*	3	*b*	63	*b*	2	8
245-ft ceiling to DH (45 ft = 3.8 sec)	*c*	1.2	*c*	1.3	*c*	1.1	8	6
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*c*	1.5	*c*	2.8	*c*	0.9	8	8
50 ft to ground (50 ft = 4.2 sec)	*c*	1.6	*c*	1.3	*c*	1.3	8	8

TABLE D2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment [a]	$\bar{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.7	*b*	2.3	*b*	0.18	*b*	3	8
245-ft ceiling to DH (45 ft = 3.8 sec)	*c*	2.8	*c*	1.6	*c*	1.8	8	5
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*c*	5.1	*c*	3	*c*	7.9	8	8
50 ft to ground (50 ft = 4.2 sec)	*c*	1.7	*c*	1.3	*c*	1.4	8	3

[a]Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b]All pilots stayed head-down.
[c]All pilots stayed head-up.

APPENDIX E

TRANSITIONS: NO MISMATCH, ENVIRONMENT 7

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches only. Environment 7: RVR 2,000 ft, no shear, ceiling 180 ft, light turbulence.

TABLE E1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	39	*b*	1	*b*	*c*	*b*	2	8
180-ft ceiling to DH (80 ft = 6.7 sec)	*d*	1.3	*d*	1.3	*d*	*c*	8	3
100-ft decision height to 50 ft (50 ft = 4.2 sec)	*d*	2.9	*d*	1.5	*d*	*c*	8	2
50 ft to ground[e] (50 ft = 4.2 sec)	*d*	*d*	*d*	*d*	*d*	*d*	8	8

TABLE E2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	35.3	*b*	1	*b*	49.3	*b*	3	8
180-ft ceiling to DH (80 ft = 6.7 sec)	*d*	3.4	*d*	1	*d*	*c*	8	2
100-ft decision height to 50 ft (50 ft - 4.2 sec)	*d*	5.4	*d*	1.7	*d*	8.0	8	3
50 ft to ground[e] (50 ft = 4.2 sec)	*d*	*d*	*d*	*d*	*d*	*d*	8	8

[a]Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.

[b]All pilots stayed head-down.

[c]N too small to calculate a valid SD.

[d]All pilots stayed head-up.

[e]This environment was used for the runway incursion run. None of the pilots descended below 50 ft because they executed a missed approach prior to reaching this segment, as described elsewhere (ref. 8).

APPENDIX F

TRANSITIONS: NO MISMATCH, ENVIRONMENT 5

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches only. Environment 5: RVR 1,600 ft, shear 25, ceiling 170 ft, light turbulence.

TABLE F1.– TRANSITIONS UP FROM IP

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	71.8	*b*	4.3	*b*	55.8	*b*	3	8
170-ft ceiling to DH (20 ft = 1.7 sec)	184.4	0.7	1	1	*d*	*d*	1	2
150-ft decision height to 50 ft (100 ft = 8.4 sec)	*c*	1.5	*c*	2.8	*c*	0.7	8	5
50 ft to ground (50 ft = 4.2 sec)	*c*	4.4	*c*	2	*c*	*d*	8	1

TABLE F2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.6	*b*	3.5	*b*	0.2	*b*	4	8
170-ft ceiling to DH (20 ft = 1.7 sec)	0.7	1.4	1	1.1	*d*	42.7	1	3
150-ft decision height to 50 ft (100 ft = 8.4 sec)	*c*	1.1	*c*	2.6	*c*	0.8	8	5
50 ft to ground (50 ft = 4.2 sec)	*c*	1.2	*c*	1.3	*c*	1.1	8	3

[a] Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b] All pilots stayed head-down.
[c] All pilots stayed head-up.
[d] N too small to calculate valid SD.

APPENDIX G

TRANSITIONS: NO MISMATCH, ENVIRONMENT 1

Mean number N, SD, and duration of transitions (sec) for no-mismatch, manual approaches. Environment 1: RVR 1,600 ft, no shear, ceiling 120 ft, light turbulence.

TABLE G1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	13.1	*b*	4.5	*b*	12.6	*b*	4	8
120-ft ceiling to DH (20 ft = 1.7 sec)	*c*	0	*c*	0	*c*	*e*	8	0
100-ft decision height to 50 ft (50 ft = 4.2 sec)	*c*	1.3	*c*	1.3	*c*	0.5	8	3
50 ft to ground (50 ft = 4.2 sec)	*c*	*c*	*c*	*c*	*c*	*c*	8	6

TABLE G2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.9	*b*	5	*b*	0.5	*b*	4	8
120-ft ceiling to DH (20 ft - 1.7 sec)	*c*	1	*c*	1	*c*	*d*	8	2
100-ft decision height to 50 ft (50 ft = 4.2 sec)	*c*	1	*c*	1	*c*	*d*	8	2
50 ft to ground (50 ft = 4.2 sec)	*c*	3.9	*c*	1	*c*	*d*	8	2

[a]Altitude and duration values for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b]All pilots stayed head-down.
[c]All pilots stayed head-up.
[d]N too small to calculate a valid SD.
[e]Although each of two pilots made one transition down, neither transitioned back up in this flight segment.

APPENDIX H

TRANSITIONS: NO MISMATCH, ENVIRONMENT 6

Mean number N, SD, and duration of transitions (sec) for no mismatch, under manual control. Environment 6: RVR variable, no shear, ceiling variable, light turbulence.

TABLE H1.– TRANSITIONS UP FROM IP

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	8.1	2.1	4.5	1	3.3	---	2	2
Variable ceiling to DH	16.5	1.5	2	3.5	---	1.2	1	6
150-ft decision height to 50 ft (100 ft = 8.4 sec)	[b]	3.4	[b]	2.5	[b]	2.6	8	4
50 ft to ground (50 ft = 4.2 sec)	[b]	3.9	[b]	2	[b]	2.8	8	3

TABLE H2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment [a]	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.98	10	5	1	0.12	---	2	2
Variable ceiling to DH	0.55	5.7	2	4.3	---	17.5	1	6
150-ft decision height to 50 ft (100 ft = 8.4 sec)	[b]	0.9	[b]	2.4	[b]	0.4	8	5
50 ft to ground (50 ft = 4.2 sec)	[b]	0.5	[b]	1.3	[b]	0.3	8	3

[a] Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b] All pilots stayed head-up.

APPENDIX I

TRANSITIONS: LATERAL ILS MISMATCH, ENVIRONMENT 3

Mean number N, SD, and duration of transitions (sec) for lateral ILS mismatch under manual control. Environment 3: RVR > 8,000 ft, shear 25, ceiling 615 ft, moderate turbulence.

TABLE I1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	28.6	*b*	2	*b*	*d*	*b*	1	8
615-ft ceiling to DH (415 ft = 35 sec)	*c*	1.6	*c*	6.8	*c*	1.2	8	8
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*c*	1.8	*c*	3.1	*c*	1.1	8	8
50 ft to ground (50 ft = 4.2 sec)	*c*	0	*c*	0	*c*	---	8	8

TABLE I2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.3	*b*	1	*b*	*d*	*b*	2	8
615-ft ceiling to DH (415 ft = 35 sec)	*c*	3.8	*c*	7.4	*c*	25.6	8	8
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*c*	1.5	*c*	3.3	*c*	0.7	8	8
50 ft to ground (50 ft = 4.2 sec)	*c*	1.4	*c*	1	*c*	1.1	8	2

[a] Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b] All pilots stayed head-down.
[c] All pilots stayed head-up.
[d] N too small to calculate a valid SD.

APPENDIX J

TRANSITIONS: LATERAL ILS MISMATCH, ENVIRONMENT 2

Mean number N, SD, and duration of transitions (sec) for lateral ILS mismatch under manual control. Environment 2: RVR > 8,000 ft, shear 9, ceiling 380 ft, moderate turbulence.

TABLE J1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	*b*	0.5	*b*	1	*b*	*c*	8	2
380-ft ceiling to DH (180 ft = 15 sec)	0	1.8	0	5.4	---	0.9	8	8
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	1.8	*b*	2.8	*b*	1.3	8	6
50 ft to ground (50 ft = 4.2 sec)	*b*	0	*b*	0	*b*	---	8	8

TABLE J2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	*b*	21.0	*b*	2	*b*	17.7	8	2
380-ft ceiling to DH (180 ft = 15 sec)	0.8	2.1	1	5.5	*c*	14.4	1	8
200-ft decision height to 50 ft (150 ft = 12.6 sec)	*b*	2.0	*b*	2.4	*b*	1.3	8	7
50 ft to ground (50 ft = 4.2 sec)	*b*	1.6	*b*	1	*b*	0.6	8	3

[a] Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.

[b] All pilots stayed head-up.

[c] N too small to calculate a valid SD.

APPENDIX K

TRANSITIONS: LATERAL ILS MISMATCH, ENVIRONMENT 1

Mean number N, SD, and duration of transitions (sec) for lateral ILS mismatch under manual control. Environment 1: RVR 1,600 ft, no shear, ceiling 120 ft, light turbulence.

TABLE K1.– TRANSITIONS UP FROM IP

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	25.8	*b*	3	*b*	16.4	*b*	4	8
120-ft ceiling to DH (20 ft = 1.7 sec)	*c*	0.4	*c*	1	*c*	*d*	8	2
100-ft decision height to 50 ft (50 ft = 4.2 sec)	*c*	0.6	*c*	1.3	*c*	0.3	8	3
50 ft to ground (50 ft = 4.2 sec)	*c*	*c*	*c*	*c*	*c*	*c*	8	8

TABLE K2.– TRANSITIONS DOWN FROM EXTERNAL SCENE AFTER FIRST HEAD-UP TRANSITION

Flight segment *a*	$\overline{X}$, sec		N		SD		Number of pilots	
	HUD	No HUD	HUD	No HUD	HUD	No HUD	HUD	No HUD
GS intercept to ceiling	0.7	*b*	5.3	*b*	0.3	*b*	3	8
120-ft ceiling to DH (20 ft = 1.7 sec)	*c*	2.3	*c*	1	*c*	*d*	8	1
100-ft decision height to 50 ft (50 ft = 4.2 sec)	*c*	1.9	*c*	1.7	*c*	1.7	8	3
50 ft to ground (50 ft = 4.2 sec)	*c*	1.5	*c*	1	*c*	*d*	8	1

[a]Altitude and duration values given for each flight segment are based on an assumed airspeed of 135 knots and a 3° glide slope.
[b]All pilots stayed head-down.
[c]All pilots stayed head-up.
[d]N too small to calculate a valid SD.

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15. Supplementary Notes

This Head-Up Display (HUD) report is number 10 in a series.

16. Abstract

To quantify head-up transition behavior with and without a flightpath type head-up display, eight rated B-727 pilots each flew 31 manual and coupled approaches in a simulator with B-727 dynamics and collimated model board external scene. Data were also obtained on the roll played by the head-up display in the coupled-to-manual transition. Various wind shears, low visibilities, and ceilings were tested along with unexpected misalignment between the runway and head-up display symbology. The symbolic format used was a conformal flightpath type optically superimposed over the external scene. The following results are reported. (1) Every pilot except one stayed head-up, flying with the display after descending below the ceiling. Without the display and as altitude decreased, the number of lookups from the instrument panel decreased and the duration of each one increased. (2) No large differences in mean number or duration of transitions up or down were found during the head-up display runs comparing the no-misalignment with the lateral instrument landing system offset misalignment runs. (3) The head-up display led to fewer transitions after the pilot made a decision to land or execute a missed approach. (4) Without the display, pilots generally waited until they had descended below the ceiling to look outside the first time, but with it several pilots looked down at their panel at relatively high altitudes (if they looked down at all). (5) Manual takeover of control was rapid and smooth both with and without the display. The display permitted smoother engine power changes, that is, fewer changes of usually smaller magnitude after autopilot disconnect. Vertical rate and control column displacement data before and after disconnect showed no significant differences. (6) A posttest debriefing indicated overall acceptance of the format used and overall test realism.

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