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Head-Up Transition Behavior of Pilots During Simulated Low-Visibility Approaches

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Richard F. Haines

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Head-Up Transition Behavior of Pilots During Simulated Low-Visibility Approaches

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HEAD-UP TRANSITION BEHAVIOR OF PILOTS DURING SIMULATED LOW-VISIBILITY APPROACHES

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SUMMARY

Each of 13 commercial pilots from four airlines flew a total of 108 manual flight director approaches in a moving base simulation of a medium-sized turbojet (95,000-lb gross weight) which had a day and night Redifon external scene. Three levels of RVR (1,600; 2,400; and 8,000 ft), three wind-shear profiles, nine ceiling heights, and continuous and intermittent visibility after initial breakout were tested. The time required for the captain to evaluate the runway visual environment after looking up from the instrument panel following a descent below clouds, the number of head-up transitions from instrument reference, and various subjective ratings of the controllability and precision of control were obtained on every approach. The results indicated that: (1) mean decision time ranged from 2 to 4.6 sec for ceilings under 380 ft across the three RVR conditions ($p \leqslant 0.001$); (2) mean vertical distance traveled during the visual-cue assessment period was a relatively constant proportion below the existing ceiling; (3) a significant three-way interaction in mean decision time between wind shear, day-night, and ceiling-RVR variables occurred ($p \leqslant 0.05$); (4) mean number of head-up transitions to VFR conditions after breakout ranged from 4.6 to 13.4 and increased as a function of ceiling ($p \leqslant 0.001$) and severity of wind shear ($p \leqslant 0.01$) (the lower visibility conditions after breakout produced a less consistent relationship); the typical duration of fixation out the window was 1.5 sec; and (5) subjective pilot ratings of controllability and precision of control as well as amount of skill, attention, or effort required to make the landing were influenced significantly by the wind shear, night conditions, and low breakout ceiling conditions.

INTRODUCTION

The Head-up Transition

A pilot's transition from instrument reference to visual reference during a landing approach involves two separate but interrelated behaviors: (1) physical movement of the head and eyes (including refocus of the lenses of the eyes) and (2) cognitive processes involved in switching one's perceptual frame of reference from one set of cues to another. (The interested reader is referred to a laboratory study by Fischer (ref. 1) and to the many references cited therein for further information about cognitive switching between two superimposed information sets.) Although some work has been done to quantify the first type of behavior (refs. 2, 3), few have tried to quantify the time required for the perceptual switch. As will be discussed, both practical and conceptual difficulties seem to have inhibited previous investigators from pursuing research on this matter.

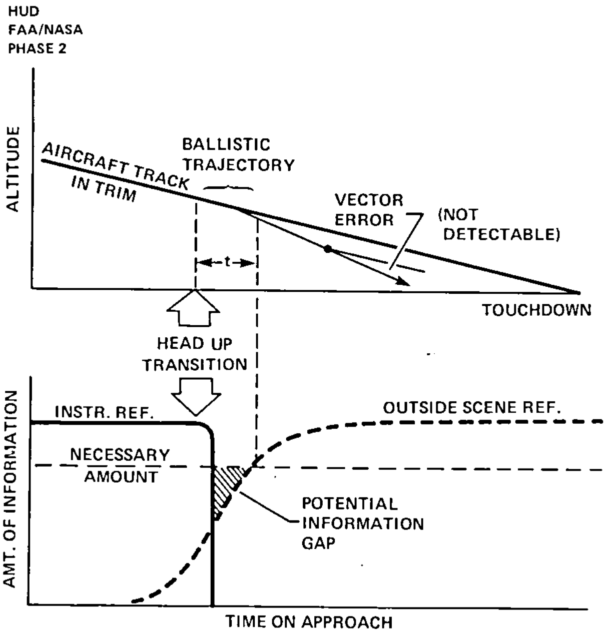


Figure 1.– Theoretical diagram of guidance information during the head-up transition.

It would seem to be important to commence a discussion on the head-up transition by pilots with an understanding of the concepts and terminology that are involved. Figure 1 illustrates the IFR to VFR transition in terms of the amount of information theoretically available to the pilot flying. Although it is acknowledged that there is a qualitative dimension to this guidance and control information that the pilot interprets in many ways (refs. 4–6), that dimension will not be discussed here. For the purpose of the present discussion suffice it to say that the "amount of information" axis in figure 1 includes this complex dimension. Considering the top diagram first, it is reasonable to assume that in the absence of changes in the wind and to the controls of the aircraft, an aircraft that is in trim and on the proper ILS glide-slope-localizer reference will continue to the runway touchdown point. Considering the bottom diagram, the pilot flying is presented with somewhat more than the necessary and sufficient amount of instrument reference information up to the moment when he looks up and out the windshield. At that point, the amount of instrument-derived information falls off rapidly. Frequently, the reason that the pilot flying on instruments looks up is because the second pilot, who has been looking outside for another set of necessary and sufficient external ground cues, eventually reaches the point where he calls out "runway in sight" or some other appropriate phrase.

This cockpit procedure is used by numerous commercial air carriers; by implication, it is assumed that when the pilot flying looks up he also should be able to see (within a short period of time) what the second pilot sees. The approximate manner by which this outside scene reference information increases is shown by the dashed line in figure 1. The homogeneity or nonhomogeneity of the particles (e.g., fog, rain) along the line of sight of the pilot to the ground and the nature of the runway environment's conspicuity combine to influence the exact form of this dashed line. (The term conspicuity is used to refer to all aspects of the runway environment that combine to yield an initial visual detection of its presence and subsequent perceptual integration of those cues that provide runway alignment, roll, range, vertical rate, and other landing information. As is discussed in detail elsewhere (ref. 7), the conspicuity of luminous sources, such as runway lights and reflective runway markings, differs over a wide range depending on numerous factors, not least of which is the pilot's own state of light adaptation.) The dashed line shown in figure 1 is based on the assumption of a homogeneous light-extinction coefficient (refs. 8–10).

Of course, extremely dense patches of fog can produce very rapid changes in the amount of outside scene reference information; as a result, by the time the second pilot detects and identifies some feature of the runway environment and then calls it out to the pilot flying head-down it may disappear again by the time the latter pilot looks up. In such circumstances, the question must be asked what the pilot flying does then. Does he stay head-up, expecting the required ground cues to reappear imminently, or does he look back to the instrument panel?

For the type of visual-range reduction portrayed in figure 1, there exists a "potential information gap" (shaded region); it results from the fact that although the pilot flying may be looking outside, he has not yet had enough time to assimilate the available cues into a consistent, or at least perceptually useful, pattern. Thus, a part of this delay is probably a result of optical factors external to the pilot; another part is a result of perceptual factors that introduce a delay in detecting or interpreting the available visual information. At the point the dashed line crosses the horizontal line (fig. 1) labeled "necessary amount" of information, the pilot has successfully organized his perception of the runway scene into a functionally useful array of information that permits him to decide to complete the landing approach or to execute a missed approach. It is the determination of the time duration *t* and the number of head-up transitions made that is of primary concern in the present investigation.

Of course, the duration of *t* could become a contributory factor in an incident or accident under some flight conditions. One such condition is illustrated in the top diagram of figure 1. The pilot may assume that the aircraft is both on the correct flightpath and in trim so that it will follow a ballistic trajectory during time period *t*. (Actually, aircraft trim holds airspeed constant (more accurately angle of attack) rather than a given trajectory in no-wind conditions.) In addition, track errors will normally stay within acceptable limits only for a few seconds, because of usual atmospheric disturbances. Finally, a vector error can arise during the transition period that may go unnoticed by the pilot who is (at this time) attempting to integrate a highly dynamic set of visual cues (ref. 5). This is particularly true in conditions in which the ground is obscured beyond the pilot's aim point. Thus, slight-pitch-attitude changes caused by atmospheric disturbances may not be perceived at all or not in time to effect corrective input. The result could be an undesirable change in flightpath that could result in an accident or an incident.

Another situation that can lead to a deliberate control input by the pilot during this critical head-up transition arises as a result of certain ambiguous, illusory conditions. As Jenny, Malone, and Schweickert (ref. 11) have stated, "One visual illusion usually associated with fog conditions is the pitch-up illusion where the pilot suddenly loses his visual field of view due to the rapid onset of fog. The pilot's past experience leads him to conclude that such a rapid loss of the visual segment means that he has inadvertently pitched the aircraft up. To correct this he then pitches down." Other examples of inappropriate control responses could be given to emphasize the often critical nature of period *t*.

Previous Research Findings on Head-up Transition Time

As mentioned above, the head-up transition involves two separate components, one physical, the other cognitive. Few investigators have attempted to separate the two types of behavior. In the brief review that follows, an attempt is made to group the available studies into these two categories based on details given in the original reports.

Physical transition time– According to work reported by Quilley (ref. 2), the period required for a pilot to make the transition from visual to instrument reference on takeoff is typically about 1 sec. Quilley suggests that this short period of time is probably due to the fact that: (1) the aircraft is progressing into a phase of flight where there is greater tolerance for minor perceptual errors that do occur because of a continuing build-up of takeoff energy over a minimum level, (2) the aircraft is gaining altitude and there is an increasing margin of needed separation distance with the ground, and (3) the crew members are likely to be less fatigued than during a landing.

The transition from instrument to visual reference during an approach may take substantially longer than 1 sec. Quoting the findings of the U.S. Air Force Flight Dynamics Laboratory, Wright-Patterson AFB and other groups, DeCelles (ref. 12) cites transition durations as long as 5 sec. Unfortunately, the exact basis on which these values are presented is not given; the present investigation was intended to address this issue.

Some insight may be gained on this matter from a study of pilot eye scan during simulated night approaches conducted by Langley Research Center using Piedmont Airline's FAA certified 727 simulator at Winston-Salem, North Carolina (ref. 13). Two of the responses monitored were the number of head-up transitions (from the instrument panel) to the computer-generated external scene and the dwell time during these looks outside. Unfortunately, no attempt was made to have the pilot signify, after having looked up, when he felt he had sufficient visual cues with which to make his decision to continue the approach or to execute a missed approach. Nevertheless, it is instructive to briefly review some of the data collected. Considering only nighttime conditions and manual approaches under VFR conditions without wind shear, the eight commercial pilots looked up (out the window) from the instrument panel (transitioned) an average of 4.8 times (with a mean dwell time of 0.8 sec) for the 1,000- to 500-ft altitude segment of the approach. For the 500- to 200-ft altitude segment they transitioned an average of 4.6 times with a mean dwell time of 0.8 sec. For the 200- to 20-ft altitude segment they transitioned an average of 3 times with a mean dwell time of 1.4 sec. The use of such long data-analysis flight segments makes it impossible to deduce the time required to transition up or down. It may be pointed out, however, that if one assumes that these pilots flew along a 3° glide slope at 135 knots, the 1,000-ft to 500-ft altitude segment would require 41.8-sec transit time. These mean data showed that the pilot was head-up a total of 3.8 sec (10.1%) of this duration. The theoretical transit time for the 500- to 200-ft altitude segment would be 25.1 sec with the pilot remaining head-up a total of 2.7 sec (17.2%) of this duration. The theoretical transit time for the 200- to 20-ft altitude segment would be 15.1 sec with the pilot remaining head-up a total of 4.2 sec (38.6%) of this duration. Presumably, the pilot stayed head-up during the remainder of the 1.6 sec to (theoretical) touchdown.

The above head-up mean durations provide a clue to the adequacy, as judged by the pilots tested, of the visual information seen outside the cockpit. The progressively longer periods of time the pilot stays head-up during a typical VFR approach strongly suggest that he is in the process of progressively emphasizing the judged usefulness of the available *external* guidance and control cues and progressively deemphasizing the judged usefulness of *on-board* information.

Cognitive transition time– The amount of time required to acquire the necessary guidance and control information from the external scene is integrally related to the length of the transition time under discussion. Brown (ref. 3) reported that for night Category II conditions in a simulator, his subject pilots required about 2 sec to assess the landing conditions and to make a decision to land *if the pilot in control was doing nothing else.* He found that a decision time of 3 sec was a more general (representative) duration from the 500 approaches conducted in his study. Also, he reported that pilots took almost twice as long to assess the visual situation at an altitude of 200 ft than at an altitude of 150 ft or 100 ft, under normal circumstances; however, visual contact time before reaching decision height was found to have little influence on the pilot's decision to land or to execute a missed approach.

Helmore and Shaw (ref. 14) conducted a landing study under Category III conditions in a simulator and also reported evidence that exposure time was not a critical factor in the pilot's decision to land or go around. They also stated that an expansion of the visual segment could lead to a decision to land in less than 1 sec, whereas if no expansion of the visual segment was perceived within a 2-sec period, a missed approach was far more likely to be executed. Interestingly, these investigators found no clear-cut relationship between the size of the visual segment at decision height (DH) and the decision to land or go around. On the other hand, they found that their pilots required at least 1 sec of an expanding visual segment in order to lead them to decide to land.

Helmore and Shaw used a "monitored approach" cockpit procedure in which the First Officer flew the aircraft down to the decision height while the Captain monitored the approach. If, in the opinion of the Captain, sufficient visual cues were present from the external scene at DH he would take command and land the aircraft. These investigators also used a triplex autopilot. Use of either the monitored-approach procedure, the autopilot, or both may have reduced the quantity or quality of external visual cues deemed necessary by the pilot flying to decide to continue the approach as compared with a fully manual landing.

The Present Study

The present study is concerned with the physical and the cognitive aspects of the head-up transition of pilots during conventional instrument flight. Included here are both the duration of the entire decisionmaking process after looking outside as well as the frequency of these head-up transitions under various environmental conditions.

This investigation was conducted as part of the joint FAA/NASA Head-up Display Concept Evaluation Project, Task Order DOT-FA77WAI-725 to Interagency Agreement NASA-NMI 1052.151, dated March 9, 1977. A detailed program plan is presented elsewhere (ref. 15). The present investigation constituted a subtask of Phase 2 work on perceptual and human factors related to the HUD concept and was conducted before a HUD was available for testing.

I wish to thank Barry Scott, Donna Miller, Dick Pocius, Kathleen Bird, and Rick Linares for valuable assistance provided during the conduct of this study and to the staff of the Simulation Sciences Division for their cooperative support.

METHOD

Pilot Subjects

The subjects of this study were 13 commercial airline pilots. Table 1 presents information about the test subjects.

TABLE 1.– SUBJECT PILOT INFORMATION

Pilot	Age	Airline	Seat flown	Aircraft type	Hours	Cat. II rated/ aircraft	Est. landings	
							Cat. I	Cat. II
A	45	A	Capt.	B707	3800	Yes/707	33	0
B	47	A	F/O	B707	1200	Yes/707	9	0
C	59	A	Capt.	B747	3780	Yes/707	9	6
D	42	A	Capt.	B707	1500	Yes/707	17	3
E	41	B	F/O	L1011	45	No	3	0
F	37	B	F/O	B707	600	Yes/707	?[a]	?[a]
G	49	B	Capt.	B707	6894	Yes/707	9	2
H	33	B	F/O	L1011	63	No	0	0
I	36	B	F/O	L1011	180	No	12	0
J	42	C	2nd/O	B727	2700	No	0	0
K	41	C	2nd/O	B727	1860	No	4	0
L	42	C	F/O	B727	6000	Yes/727	0	0
M	41	C	F/O	DC-8	5230	Yes/DC-8	0	2

[a] Pilot was unsure of the answer.

All subjects were paid for their services. A battery of vision examinations and an attitude and information survey were administered to each subject prior to testing. A copy of the attitude and information questionnaire is provided in appendix A. All subjects possessed 20:20 or better distance acuity, full and normal peripheral visual sensitivity, normal ocular motility, and no color deficiencies.

Experimental Design

A diagram of the experimental design is presented in appendix B. The investigation may be characterized as two separate randomized blocks studies. For one of these studies the pilot was presented with a continuous view of the runway environment after descending below a cloud ceiling (labeled "visibility continuous" and shown at the top half of appendix B). In the second study visual slant range was reduced to zero rapidly at an unexpected time, once the pilot flying had looked up from the instrument panel after descending below a given cloud ceiling (labeled "visibility intermittent" and shown at the bottom-half of appendix B). A randomly selected delay, programmed by the computer, ranging from 1.5 to 4 sec, caused the reduction in slant range.

Each subject underwent the combination of conditions indicated by black dots in appendix B for a total of 46 visibility-continuous runs and 24 visibility-intermittent runs. The 35-day and 35-night conditions were presented in random order. As mentioned in the test instructions (appendix C), the pilots were provided information about tower-reported wind and RVR conditions before each run. A 200-ft decision height applied to the RVR 2,400 condition and a 150-ft decision height to the RVR 1,600 condition. These two weather conditions were referred to as Categories I and IIA, respectively.

Apparatus

Testing was conducted in a three degree-of-freedom simulator (fig. 2) at Ames Research Center with the motion characteristics given in appendix D. A medium-sized turbojet transport was simulated by a Sigma 7 digital computer driving an 8400 computer. The external scene was generated by a Redifon model board (900:1 scale), collimating lens, and other equipment described in detail elsewhere (ref. 16). The runway environment consisted of approach strobes, runway centerline, edge lights and markings representative of a Category II runway. A model without runway centerline, edge or approach lights was used in daytime runs; a different model, with runway, edge, and approach lights was used in the nighttime runs. The reduced visibility conditions were produced by electronic means, namely, video mixing a white line raster with the color scene to adjust the visual contrast of the display to a distance equivalent to the required RVR.

Figure 2.– Photograph of motion-base simulator used.

An instrument panel typical of a medium-sized turbojet aircraft was used only on the left side of the panel. The usual engine gauges were operational in the center console. A Sperry "Horizon Flight Director Indicator" model HZ-6B was used. Normal reference airspeed was 124 knots with 40° flaps and engine set to 72% power.

Figure 3 shows the interior of the cockpit. An experimenter sat behind the left seat, viewing the pilot's facial region and eye movements through an infrared viewer (by means of a mirror) under all ambient illumination conditions. A reference eye-position device was installed in order to precisely locate the pilot's head prior to testing. This device can be seen in figure 3 on each side of the forward window directly in front of the pilot; it consisted of a single light source located within a light-tight box (directly above the window) with a right-hand and left-hand fiber bundle extending downward on each side of the window to an aperture. The shape and aiming direction of the exit

Figure 3.– Photograph of simulator interior.

end of each optic bundle were such that both lights could be seen only when the pilot's eyes were in the correct position in space (±1 cm laterally and vertically; ±2 cm longitudinally).

Several wind shears were included in order to increase the pilot's workload during these manual ILS approaches. A no-wind control condition was included under all of the other testing conditions as was a 25-knot headwind at starting altitude (1,040 ft) decreasing exponentially to 0 knots at the runway (shear no. 25). Shear nos. 7 and 9 both had a 15-knot tower-reported headwind. Shear no. 7 had a 30-knot headwind at starting altitude down to 400 ft; this headwind dropped to 18 knots at 300 ft, followed by an exponential decay to 15 knots at the runway. Shear no. 9 had a 30-knot headwind from starting altitude down to 150 ft, which changed to 18 knots at 50 ft, followed by an exponential decay to 15 knots at the runway. Shear no. 22 had an 8-knot tower-reported tailwind; this shear had a 25-knot tailwind at 500 ft, which dropped to 10 knots at 350 ft, and was followed by an exponential decay to an 8-knot tailwind at the runway.

Procedures

The activites of the subject pilots may be described in three stages: pretesting, familiarization runs, and data runs. The pretesting consisted of vision tests and the completion of a questionnaire (see appendix A). From 10 to 15 familiarization runs were given to each subject pilot to help him become accustomed to the handling qualities of the simulator (aircraft model), the required cockpit procedures, and the general nature of the cockpit layout and external scene and its variations. From one to four warm-up runs were given on each testing day. Each subject had to return to Ames Research Center for several days to complete the data collection.

The pilot was instructed to request information over the intercom concerning prevailing weather conditions at the start of each run. An experimenter recited a standard weather briefing that corresponded to the test conditions for that run. This briefing included wind direction and velocity, ceiling, RVR, and the possibility of encountering wind shear. In no case was any specific information given regarding the shear profile; rather, the pilot was told "the aircraft that just landed reported a wind shear on final." This procedure not only added to the realism of the test environment but also helped ensure that the subject pilots knew approximately what to expect concerning the environmental variables on each run.

Since the Captain (pilot flying) and First Officer were always selected from the same airline, they were instructed to use their company procedures concerning minimum altitude (and other cockpit) call-outs, and operating procedures.

For each run the Captain was instructed to remain head-down, using the ILS glide slope and localizer bars and flight director for his primary guidance (and employing his normal eye scan behavior). The First Officer was instructed to remain head-up as much of the time as possible. He was also supposed to look at the instrument panel for all required instrument cross-check information and at the external scene for the required ground environmental cues. The pilot flying was also told to look up from his instruments as soon as practical after the First Officer said he had seen the previously agreed upon ground environmental cues (e.g., runway, approach lights). The First Officer pressed a response button as he said this. The pilot flying did not have to continue looking outside but could return to instrument reference as soon and as often as he liked. He was also instructed to say "decision" or "decision made" at that point in the approach (while he was looking outside) when he felt he had acquired sufficient visual information to decide whether to continue the approach or to execute a missed approach.

Some clarification of cockpit procedures was needed for the present study because not all airlines use the same procedures and because different cockpit equipment was used by different pilots. These clarifications included, but were not necessarily limited to, the following:

1. Definition of what constituted necessary and sufficient runway environmental cues at decision height.

2. Discussion of the procedures required to execute a missed approach.

3. Clarification of the correct interpretation of the flight director bars (when different from those already familiar with).

4. Clarification of required scan behavior of the pilots relative to the instruments.

5. Demonstration of the seat adjustment procedures to attain the correct reference eye position.

6. Discussion of the approach and landing checklist reading procedures.

At no time were the subject pilots told that their eye movements were being monitored. However, they were told that all speech was being recorded.

In order to help increase realism and workload, an abbreviated approach and landing checklist was used on every approach (appendix E). The pilot flying was supposed to ask the First Officer to read the checklist. This checklist took about 25 sec to complete.

Immediately after each run had finished, the experimenter (who sat in a jump seat behind the Captain) asked each crew member to rate the run on a numeric scale from 1 to 10 (see appendix F) with regard to: (1) the controllability and precision of control of the approach, and (2) the demands on the skill, attention, and effort of the pilot. The five "verbal anchor points" shown on each scale were adapted from Jex (ref. 17) who based the scale on earlier work by McDonnell (ref. 18). These interval scales permit averaging as well as other standard parametric statistical analyses. As Jex points out, "Use of two trait categories, task controllability-and-precision and display attentional workload, should permit separation of these often-confounded effects."

RESULTS AND DISCUSSION

Several head-up transition performance measures, subject pilot ratings of the controllability and precision of control of the approach, and pilot demands in terms of the degree of skill, attention, or effort required were quantified.

Mean Decision Time Results

Table 2 presents the mean decision time t for each experimental variable investigated. Each value represents the time between the First Officer's response indicating that he had seen the specified ground environment and the moment the Captain said "decision." These data were subjected to analysis of variance (ref. 19). Only data for the continuous visibility test condition are presented because the analysis of variance required a complete data matrix, i.e., no missing data cells, and the intermittent visibility condition lead to a relatively large number of missing data cells. A comparison between continuous and intermittent visibility test conditions is made below where the conditions permit such comparisons.

TABLE 2.– CAPTAINS' MEAN DECISION TIMES[a]

Variable	Decision height DH, ft	Decision time t, sec	Vertical distance from DH, ft
1. Ambient illumination			
Day	---	2.9	---
Night	---	3.9	---
2. Winds			
None	---	3.1	
Shear 25	---	3.8	---
3. RVR			---
8,000 ft	None		
Ceiling: 615 ft		7.3	---
Ceiling: 380 ft		4.6	---
2,400 ft	200		
Ceiling: 300 ft		3.5	+61.5
Ceiling: 245 ft		3.5	+6.5
Ceiling: 180 ft		2.3	-45.1
1,600 ft	150		
Ceiling: 230 ft		2.6	+51.3
Ceiling: 200 ft		2.7	+20.9
Ceiling: 170 ft		2.0	-2.2
Ceiling: 130 ft		2.2	-44.1

[a] Only data for the continuous visibility test condition are shown.

It may be noted that the pilots took 1 sec longer (not significant) on the average to make their decisions during nighttime approaches than during daytime approaches. The main effect of RVR ceiling was statistically significant ($p \leqslant 0.001$) (see appendix 6) as was the three-way interaction between the three main variables ($p \leqslant 0.05$). The 1,600 ft RVR data of table 2 show that mean decision times ranged from 2 to 2.6 sec, depending on the ceiling. For a 2,400-ft RVR, the range was from 2.3 to 3.5 sec, and for an 8,000-ft RVR, the range was from 4.6 to 7.3 sec. These data suggest that these pilots required a minimum of about 2 sec to make the transition from instrument reference to external scene reference, a value close to that cited earlier by Brown (ref. 3). In addition, an analysis of the data upon which appendix G is based showed that while the wind-shear-RVR-ceiling interaction was not significant, it was the primary contributor to the significant three-way interaction. Thus, the contribution of the day-night illumination condition to this interaction

Subject pilot[a]	Mean t, sec (across the three variables)	Subject pilot[a]	Mean t, sec (across the three variables)
A	2.2	I	7.2
C	2.9	J	.6
E	5.3	K	1.9
F	4.2	M	1.9
H	4.4		

[a]See table 1 for further identification of pilots.

is negligible. Large individual differences also were found in the duration of t, which ranged from 0.6 to 7.2 sec across these variables as shown on chart at left.

The mean decision times given in table 2 were converted into vertical distance traveled, assuming that the aircraft remained on a 3° glide slope and maintained 124 knots; the times were then related to the decision heights that were applicable for the 2,400-ft and 1,600 ft RVR conditions. The positive values in the right-hand column of table 2 indicate the average number of of feet above decision height that the Captain's decisions were made; the negative values indicate the average number of feet below decision height that the decisions were made.

It can be seen that the aircraft descended below decision height in three conditions, all of which were the lower ceiling conditions. It is perhaps significant that the mean vertical distance traveled during this period of visual-cue assessment across all nine of the present RVR-ceiling conditions was a relatively constant proportion of the existing ceiling height. Put another way, these pilots descended about 14% below the existing ceiling altitude (SD = 1.9%) at the time they made their decision response. Although the meaning of this high degree of consistency is unclear, it may suggest that the pilots were integrating relative and not absolute quantitative and qualitative external visual-cue changes. For example, the perceived expansion pattern of ground-plane details from the pilot's aim point must last for at least 2 to 4 sec, no matter what the initial altitude is when the aim point first becomes visible. This finding is in agreement with earlier work by Helmore and Shaw (ref. 14). Whether this finding may be an artifact of the resolution limits that are inherent in the present external scene generator remains to be determined.

TABLE 3.– MEAN NUMBER OF TIMES CAPTAINS LOOKED UP DURING FINAL APPROACH[a]

Variable	Mean number of looks
1. Ambient illumination	
Day	7.4
Night	7.8
2. Winds	
None	6.7
Shear 25	8.4
3. RVR	
8,000 ft	
Ceiling: 615 ft	13.4
Ceiling: 380 ft	10.8
2,400 ft	
Ceiling: 300 ft	7.7
Ceiling: 245 ft	7.3
Ceiling: 180 ft	6.4
1,600 ft	
Ceiling: 230 ft	6.3
Ceiling: 200 ft	6.1
Ceiling: 170 ft	5.5
Ceiling: 130 ft	4.6

[a]Only data for the continuous visibility test condition are shown.

Mean Number of Head-up Transitions Results

The number of times each pilot looked up from the instrument panel after breakout was quantified (table 3). These mean data were evaluated by an analysis of variance; the summary table for the analysis is presented in appendix H. Only data for the continuous visibility test conditions are presented here (for the same reason as given previously). A comparison between continuous and intermittent visibility test conditions is made below, where conditions permit.

Although the day-night condition was not statistically significant (7.4 vs 7.8 head-up transitions, respectively), the presence of a wind shear produced significantly more head-up transitions ($p \leqslant 0.01$) than did the no-wind condition (8.4 vs 6.7, respectively). The RVR-ceiling effect also was significant ($p \leqslant 0.001$) with the mean number of transitions ranging from 4.6 for the lowest RVR and ceiling to 13.4 for the highest RVR and ceiling. As shown on the chart at left, these data also exhibit relatively large differences from pilot to pilot.

Subject pilot[a]	Mean lookups	Subject pilot[a]	Mean lookups
A	5.8	I	7.4
C	4.5	J	7.2
E	11.2	K	8.9
F	9.0	M	6.0
H	8.2		

[a] See table 1 for further identification of pilots.

Figures 4 and 5 present these mean data plotted as functions of ceiling height in order to emphasize the regular relationship that exists between the no-wind-wind-shear data for the day and nighttime conditions, respectively. In general, the greater the ceiling the greater the number of head-up–head-down transitions by the pilot flying, which is not particularly surprising if one assumes that the flying pilot feels he needs to maintain a continuing cross-check between his instruments and external visual cues.

Comparison of these data with combined data for the two lowest segments (i.e., 500 to 20 ft) of the Piedmont study referred to above (ref. 13) appears reasonable; one of the breakout altitudes in the present study was 615 ft. For this condition, the present pilots made an average of 10 transitions below an altitude of 615 ft; the pilots in the Piedmont study made 7.6 transitions and the mean dwell time was 1.1 sec for each transition. When one considers the differences in the external visual scene used in these two studies, the higher breakout altitude in the present study, and the other experimental differences, the agreement in these two values is quite good. Similar response data were also obtained during the Piedmont study for nighttime, Category I, manual approach conditions where the mean number of head-up transitions for the 1,000–500-ft altitude segment was 0.1 and the mean dwell time was 0.3 sec; for the 500–200-ft altitude segment where the mean

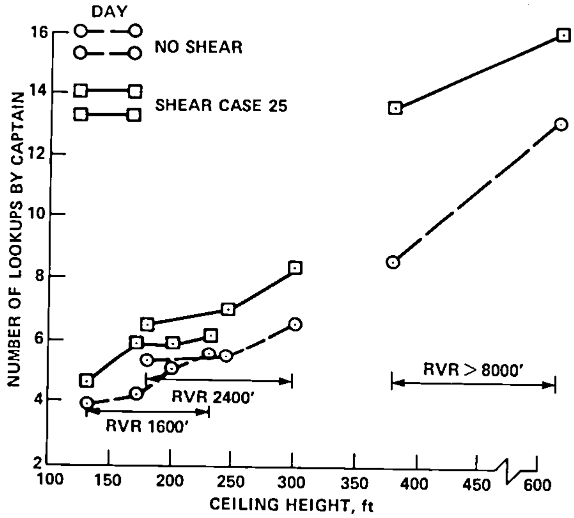


Figure 4.– Mean number of times Captain looked up during daytime final approach.

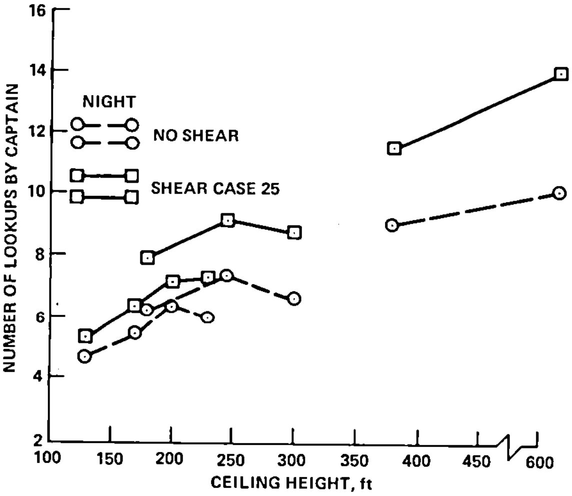


Figure 5.– Mean number of times Captain looked up during nighttime final approach.

number of transitions was 0.4 and the dwell time 0.6 sec; and for the 200–20-ft altitude segment where the mean number of transitions was 2.5 and the dwell time 1.6 sec. Thus, for these two lowest flight segments, the total number of head-up transitions was 2.9 and the total dwell time was 2.2 sec (per outside look). This compares with a mean of 6.6 head-up transitions for the comparable conditions in the present study. It is suggested that the greater number of separate looks outside during the present study occurred because the pilots were presented an external scene with a great deal more ground-plane detail than was contained in the CGI display used in the Piedmont study. It should also be mentioned that the 200-ft ceiling used in the Piedmont study would effectively preclude any view of the ground plane above that altitude, thereby discouraging the pilot from looking outside when at altitudes above 200 ft.

The present study and the Piedmont study have something else in common related to the VFR conditions. Both studies found that the mean number of head-up transitions decreases with decreasing altitude. For IFR conditions, on the other hand, the mean number of head-up transitions tends to increase with decreasing altitude. Of course, as altitude and visual slant range continue to decrease, so does the total available time to assess the external visual scene, so that under IFR viewing conditions pilots may feel that they require a more frequent information update.

Comparison of Continuous and Intermittent Visibility Mean Results

Twelve day and twelve night test conditions were compared for the continuous and the intermittent visibility conditions. The Captain's mean decision times between the continuous and intermittent visibility condition did not differ significantly for any of the day or night conditions of RVR ceiling or wind shear. This finding is not unexpected since the decision-time response is determined by the latest possible point on the approach before the actual control input is made (e.g., to execute a missed approach) so that the occurrence of the unexpected reduction in visibility should not affect this response measure. The mean number of head-up transitions was strongly influenced by whether visibility was continuous or intermittent, however. These results are presented in table 4.

From table 4 it may be noted that there is a large reduction in the number of head-up looks by the Captain for every intermittent visibility condition compared to the continuous visibility condition. Since the intermittent visibility condition prevented the pilot from seeing the ground cues after he looked up the first time, it is understandable that the number of head-up transitions would drop drastically relative to the continuous-visibility case. Considered from another point of view, the data suggest that these pilots made a nontrivial number of transitions at relatively low altitudes, that is, below altitudes represented by the present intermittent conditions.

Relationship Between Mean Decision Time and Landing Performance

An analysis was made of the degree of correlation between the individual pilot data for mean decision time (table 2) and mean touchdown distance from the runway threshold and vertical rate at touchdown for each pilot averaged across all runs. No statistically significant correlations were found, indicating that there was nothing particularly predictive about the mean decision time in terms of whether the subsequent landing was considered a good one. Another set of similar correlations was made between the individual pilot data for the number of head-up looks (table 3) and mean touchdown distance and vertical rate at touchdown for each pilot averaged across all runs.

TABLE 4.– MEAN NUMBER OF HEAD-UP LOOKS BY CAPTAINS

Variable	Visibility condition			
	Daytime, $\bar{X}$; SD; N		Nighttime, $\bar{X}$; SD; N	
	Continuous	Intermittent	Continuous	Intermittent
Wind: none				
RVR 2,400 ft				
Ceiling: 245 ft	6.0; 3.4; 13	2.9; 0.9; 12	8.2; 3.6; 12	3.5; 2.5; 11
Ceiling: 180 ft	5.5; 2.3; 13	2.3; 0.6; 13	6.1; 3.0; 8	3.1, 1.1; 10
RVR 1,600 ft				
Ceiling: 230 ft	5.4; 1.8; 13	2.5; 0.8; 13	6.8; 2.5; 12	2.2; 1.0; 9
Ceiling: 170 ft	5.1; 2.0; 12	1.9; 0.5; 12	4.6; 2.2; 10	2.8; 1.3; 12
Ceiling: 130 ft	4.8; 2.2; 10	2.1; 0.9; 11	5.2; 2.5; 9	2.3; 1.2; 8
Wind: shear 25				
RVR 2,400 ft				
Ceiling: 245 ft	8.0; 2.9; 12	2.0; 1.1; 12	9.9; 4.0; 10	2.0; 0.9; 9
Ceiling: 180 ft	6.2; 2.7; 13	2.5; 1.1; 13	7.1; 2.9; 9	2.6; 1.2; 12
RVR 1,600 ft				
Ceiling: 230 ft	5.8; 2.2; 12	1.7; 0.8; 13	6.8; 2.4; 9	2.3; 1.4; 11
Ceiling: 170 ft	6.0; 2.0; 12	2.3; 0.7; 11	6.0; 2.4; 8	2.6; 0.9; 8
Ceiling: 130 ft	4.4; 2.2; 11	2.2; 1.1; 13	3.9; 2.6; 9	2.1; 0.7; 11
Wind: shear 9				
RVR 2,400 ft				
Ceiling: 245 ft	7.3; 3.2; 13	1.8; 0.8; 13	6.3; 3.2; 9	3.1; 1.7; 12
RVR 1,600 ft				
Ceiling: 230 ft	6.0; 2.1; 11	2.3; 1.9; 12	6.3; 3.0; 12	2.6; 0.5; 9

Again, no significant correlations were found. To determine whether the use of mean data across all of the testing variables may have masked an existing correlation, further correlations were made for selected RVR-ceiling conditions for the daytime and nighttime runs and for the no-shear and shear-25 runs. As before, no significant correlations were found. Thus, it appears that landing performance under these testing conditions is not related in any clearly obvious way to the pilot's mean decision time nor to the number of head-up transitions he makes.

Head-up Transitions in Zero Visibility

The present data were also analyzed for the number of times each pilot looked up from the instrument panel after he knew that visibility had decreased to zero. It should be noted that the visibility was caused to reduce rapidly to zero and to remain at zero purposely and that this took place at or near the decision height, since it was of interest to know what pilots would do under such circumstances. Would they revert immediately to the instrument panel and initiate a missed approach? Would they continue to look outside expecting to see the runway environment eventually? For the present analysis the data were converted to percentages of the total possible runs (for each combination of test conditions shown by a black dot in the bottom part of appendix A) for which one or more head-up transitions were made after the external scene had disappeared. Table 5 presents these results. To illustrate how these data are to be interpreted, it can be seen that for the no-shear, daytime, 2,400-ft RVR, 245-ft ceiling condition, 36% of the approaches made by the 11 pilots who were tested under that condition looked up one or more times after the external scene had disappeared. Although the great majority of pilots tested looked up only once, pilots A and K accounted for the remaining instances of two separate head-up transitions. The typical duration of each look outside was about 1.5 sec. The relatively small sample size precludes a meaningful statistical analysis of these data. In general, the lower the RVR the larger was the percentage of pilots who looked up. It is also important to point out that a 200-ft decision height was used for the RVR 2400 and a 150-ft decision height for the RVR 1600 conditions. Thus, the 180-ft breakout ceiling condition in RVR 2400 runs and the 130-ft ceiling condition in RVR 1600 runs represent instances in which these pilots continued the approach below the designated minimums. These results might be interpreted in several ways. They may suggest (1) that these pilots were confident of their ability to control the simulator to a landing without external visual reference, (2) that they felt that the ground would come into sight momentarily if they continued to look outside, or (3) some combination of the two.

TABLE 5.– HEAD-UP LOOKS AFTER VISIBILITY WAS REDUCED TO ZERO

Variable	Pilots who looked up one or more times, %		
	No wind shear	Shear 9	Shear 25
Daylight			
RVR 2,400 ft			
Ceiling: 245 ft	36 (11)	17 (12)	30 (10)
Ceiling: 180 ft	50 (10)	---	33 (9)
RVR 1,600 ft			
Ceiling: 230 ft	50 (10)	0 (6)	33 (6)
Ceiling: 170 ft	33 (9)	---	45 (11)
Ceiling: 130 ft	57 (7)	---	14 (7)
Nighttime			
RVR 2,400 ft			
Ceiling: 245 ft	20 (10)	14 (7)	14 (7)
Ceiling: 180 ft	29 (7)	---	44 (9)
RVR 1,600 ft			
Ceiling: 230 ft	29 (7)	33 (9)	71 (7)
Ceiling: 170 ft	25 (8)	---	43 (7)
Ceiling: 130 ft	40 (5)	---	30 (10)

NOTE: Percentages shown are based on the number of pilot subjects shown in parentheses.

Pilot Rating Results

The pilots were asked to rate the "controllability and precision of control of the approach" after each run was over. Following this they rated the "amount of skill, attention, or effort required." Regarding the "controllability" mean ratings, a number of experimental conditions produced statistically significant differences, namely the shear–no-shear comparisons for all three RVR-ceiling conditions at the $p \leqslant 0.001$ level of confidence. (The relatively small number of significant comparisons out of the total possible led to the decision not to present the mean data for the subjective ratings. Interested readers may contact the author for these data.) Not surprising was the fact that the shear runs and the nighttime runs were judged as involving less controllability. Considering the fact that the mean decision time was about 1 sec longer for the night runs than for the day runs (table 2) and that the mean number of lookups out the forward window was approximately the same for the night and day runs (table 3), it is possible that the basis for this pilot judgment of less controllability during night runs arises from having fewer visual cues available from the external scene. No clear-cut differences in this subjective rating were found between the continuous and intermittent visibility conditions.

Regarding the mean subjective ratings of "demands on the pilot . . ." the shear–no-shear comparisons produced the most pronounced statistical results, with the shear runs yielding consistently higher ratings, that is, judged as being more demanding. Also, the night runs yielded higher ratings than the day runs, and lower ceiling and RVR conditions yielded higher ratings than did higher ceiling and larger RVR conditions.

CONCLUSIONS

Perhaps the most general conclusion that can be drawn from these data is that pilots require a relatively long period of time after looking up from the instrument panel to critically assess available runway environmental cues. Mean head-up transition-decision times were about 3.5 sec for ceilings of 300 ft or less and RVR of 2,400 ft and 1,600 ft. At an approach speed of 124 knots, this is equivalent to a distance of 733 ft along the approach path and 38 ft of vertical travel, assuming a 3° glide slope. Evidence was also found suggesting that this visual-cue-assessment process is not altitude dependent per se (for the present set of conditions) but rather breakout ceiling dependent, which might point to perceptual processing of relative changes of the ground detail more than absolute changes.

The present pilots made from 4 to 14 separate head-up transitions, depending on RVR and ceiling height. The smallest mean number of transitions was 4.6. If this number of transitions is made in an actual cockpit by pilots possessing relatively long eye-focus response times (from instrument panel to runway distances), the potential exists for significant visual cue evaluation problems. These problems, involving poorly focused retinal images, will be compounded by the reduced visual contrast of ground detail caused by low visibility (e.g., fog) conditions.

These data point to the need for additional studies that involve the use of means for providing the pilot with guidance and control information superimposed over the external scene, that is, the head-up display, since the claim has been made that such devices will avoid this critical transition at low altitudes. The present data can serve as useful comparative baseline data against which later head-up transition data obtained with head-up displays may be compared.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035, January 3, 1980

APPENDIX A

NASA-Ames Research Center

Head-up Display

Test Pilot Questionnaire

Note: This study is designed to assess the advantages and disadvantages of the headup display concept for possible use in commercial aviation. All information you give on this form will be kept confidential and will be summarized statistically.

Leave blank
Subj. assigned code: ____
Exp. No.: ____
BOT: ____
EOT: ____
Vis. Tests: ____
Form Compl. ____

[Please print all answers]

Name: ____

Address: ____ zip ____

Phone (office pref.) [ ] ____ Birthdate: ____

Do you wear spectacles while flying? yes no (circle)
If you have no military experience skip questions 1a. - 1d.

1a. Military Background: Branch ____

b. Did you receive military pilot training? yes no (circle)

c. List aircraft types in which you trained (if applicable - otherwise leave blank):

1st. ____ 2nd. ____

3rd. ____ 4th. ____

d. List all aviation-related (specialized) training: ____

____

(continue on opposite side if necessary)

---

2. List all pilot associations in which you are *now* a member: ____

____

3. List all airlines and military commands you have ever flown for beginning with the most recent:

(Insert in brackets the approximate starting date for each)

(continue on opposite side if necessary)

[ ] ____
[ ] ____
[ ] ____
[ ] ____
[ ] ____
[ ] ____

4a. Total hours flown (approx.) not including Flight Engr.: ____

4b. Years flying since solo: ____

5. Flight Experience Breakdown by Aircraft Type/Model:

Using your log book as necessary, try to be as complete as possible on this question. Include your Civil (non-commercial-private), Airline, and Military flight experience in this table following the sample given. Place a check in the small box for those aircraft for which you hold a 'type' rating.

SAMPLE

Aircraft Type/Model				Crew Position				
				Pilot	Copilot	Instr.	Flt. Engr.	Other
B 707	c		Hrs.	300	2850		1200	
	a	✓						
☑	m		Dates	2-73 / 5-77	4-68 / 3-73	/	2-65 / 4-63	/

Check here if 'type' rated

Check one for
c = civil
a = airline
m = military

From/To

Insert total hrs. at top of box

LM 26

Test Pilot Questionnaire

5. Flight Experience Breakdown by Aircraft Type/Model: (continued)

Aircraft Type/Model				Crew Position				
				Pilot	Copilot	Instr.	Flt. Engr.	Other
1. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
2. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
3. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
4. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
5. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
6. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
7. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
8. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
9. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
10. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
11. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/
12. ☐	c		Hrs.					
	a							
	m		Dates	/	/	/	/	/

6a. Are you Cat. II rated? yes no (circle)

b. If "yes" specify type(s) of aircraft: (1)____________________ (2)____________________
(3)____________________ (4)____________________

7a. Are you Cat. III qualified? yes no (circle)

b. If "yes" specify type(s) of aircraft: (1)____________________ (2)____________________
(3)____________________ (4)____________________

8. Summary of Reduced Visibility Landing Experience:

Insert in each appropriate box the *number of landings* you have made in the weather conditions noted in the table on following page.

8. Summary of Reduced Visibility Landing Experience: (continued)

	Cumulatively within the past	Weather Condition			
		Category I		Category II	
		Manual	Coupled	Manual	Coupled
DAY	6 months				
TIME	12 months				
ONLY	2 years				
NIGHT	6 months				
TIME	12 months				
ONLY	2 years				

9. Head-up Display Experience:

For purposes of this questionnaire, a head-up display is defined as a visual display of flight information located in the field of view when looking outside through the forward windshield. It may be electro-mechanical or cathode-ray driven.

9a. Have you ever flown an aircraft(s) that had a head-up display? yes no

b. If "yes" specify type of aircraft and approx. number of hours for each one in brackets:
(1)__________ [ ] (2)__________ [ ] (3)__________ [ ]

c. If "yes" place an asterisk (*) in all those spaces of question 9b. if the head-up display you used presented IFR information suitable for making a "*l*anding" as opposed to weapons delivery type of display.

d. Have you ever made instrument approaches using a head-up display? yes no

e. If "yes" specify approximate number of such approaches: __________

10. What is your professional opinion of head-up displays for commercial aviation? __________

____

____

____

11. What is your professional opinion of the autoland concept for commercial aviation? __________

____

____

____

12. Based upon what you now know about head-up displays, list below the benefits (advantages) and limitations (disadvantages) which you think apply to its use in commercial aviation operations?

a. Benefits (advantages)

Most important: __________
Next most important: __________
Next most important: __________
Next most important: __________
Next most important: __________
Next most important: __________

(continue on opposite side if necessary)

Test Pilot Questionnaire

12b. Limitations (disadvantages)

Most important: ____________________
Next most important: ____________________
Next most important: ____________________
Next most important: ____________________
Next most important: ____________________
Next most important: ____________________

(continue on opposite side if necessary)

13. Narrative Description of the Most Extreme Landing Conditions you have ever Encountered.

Please describe, using as much detail as you desire, the most extreme landing conditions (environmental, procedural inside the cockpit, etc.) with regard to the following basic categories: (continue on opposite side as necessary)

a. Headwind: ____________________

b. Tailwind: ____________________

c. Wind Shear: ____________________

d. Other Unusual Weather (e.g., precipitation): ____________________

e. Nighttime Visual Illusions: ____________________

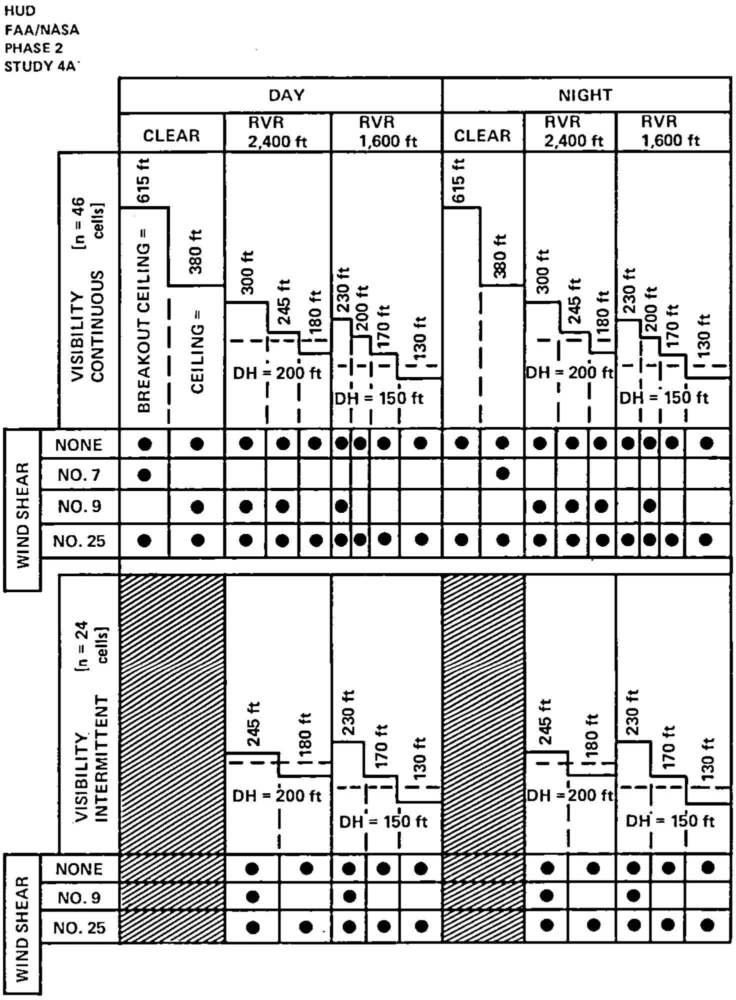
f. Daytime Visual Illusions: ____________________

g. Intermittent Visual Conditions (including unexpected visual range reductions): ____________________

h. Others: ____________________

Thank you for providing us with this useful information

EXPERIMENTAL DESIGN



Visibility continuous [n = 46 cells]

	Day Clear 615 ft	Day Clear 380 ft	Day RVR 2,400 ft 300 ft	245 ft	180 ft	Day RVR 1,600 ft 230 ft	200 ft	170 ft	130 ft	Night Clear 615 ft	Night Clear 380 ft	Night RVR 2,400 ft 300 ft	245 ft	180 ft	Night RVR 1,600 ft 230 ft	200 ft	170 ft	130 ft
Wind shear NONE	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
NO. 7	●										●							
NO. 9		●	●	●		●						●	●	●		●		
NO. 25	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Visibility intermittent [n = 24 cells]

	Day Clear	Day RVR 2,400 ft 245 ft	180 ft	Day RVR 1,600 ft 230 ft	170 ft	130 ft	Night Clear	Night RVR 2,400 ft 245 ft	180 ft	Night RVR 1,600 ft 230 ft	170 ft	130 ft
Wind shear NONE	▨	●	●	●	●	●	▨	●	●	●	●	●
NO. 9	▨	●		●			▨	●		●		
NO. 25	▨	●	●	●	●	●	▨	●	●	●	●	●

APPENDIX C

PILOT SUBJECT INSTRUCTIONS
(To be read by all pilots prior to testing)

The study you are about to participate in has been designed to measure various performances associated with the head-down to head-up transitions during an approach procedure in different weather conditions. The flight simulator you are going to fly is equivalent to a B-737 aircraft with gross weight of 95,000 lb. Just before you begin each approach you should request the wind information and runway visual range from the experimenter (acting as an air traffic controller). All approaches will be straight in and will begin at an altitude of about 1,000 ft.

Your primary task will be to land the "aircraft" safely under the test conditions presented. The following decision heights (DH) will apply: RVR = 2,400 ft, DH = 200 ft; RVR = 1,600 ft, DH = 150 ft. These two weather conditions may also be referred to as Categories I and IIA, respectively. Although we cannot tell you specifically what the wind conditions will be on every approach, we can say that you will encounter various shears and turbulence. The correct procedures to be followed by both test pilot subjects in this experiment are given next.

We have attempted to make this simulation fairly realistic in terms of the cockpit coordination procedures you are to use. At the start of each approach trial (both pilots will have already adjusted their seats to the correct position) the First Officer (F/O) will be looking out of the forward window in the anticipated direction of the runway (regardless of whether or not he can see it). His chief task is to visually acquire the necessary ground cues and then call out "runway in sight," "approach lights in sight," or other appropriate words. (The pilots could use whatever words are required by the airline they fly for.) At the instant the F/O sees these cues he is to depress the square button located to his immediate left (located on the center console). It should be held down for about 2 sec. The second task of the F/O is to read the checklist (one copy provided for each pilot). This checklist reading may be done at any time desired after descending below 900 ft. The captain may, at his own discretion, request altitude callouts in reduced visibility conditions.

All approaches will be manual for this experiment.

The Captain will remain head-down at all times until he hears the F/O say "runway in sight" (or other appropriate words), at which time he (Captain) will then immediately look up to visually acquire the required (visual) ground cues. When the point is reached where he has acquired enough cues *to decide* whether to continue toward landing or to execute a missed approach, he (Captain) will depress the button on the control yoke (pointed out by the experimenter). (This button pressing response should not be made at the initial call-out by the F/O but only after the Captain has perceived the necessary and sufficient external visual information required to make up his mind to land or to go-around.) At the moment he presses this response button simultaneously he should say that he has made his decision. He may merely repeat the words used by the F/O or may otherwise indicate that enough cues are now present to make his decision. He need not indicate which decision he has made at this time. He (Captain) should continue to control the "aircraft" in accordance with the decision he has just made.

Both pilots are responsible for performing cross-checks that are deemed appropriate. *Observed disagreement in any instrument will be made known immediately.* All voiced comments will be tape-recorded for later analysis.

After each approach (trial) the experimenter in the simulator jump-seat will ask both pilots to judge two things about that approach. These things are stated on the back side of the checklist sheet along with the numerical rating scale that must be used. *It is important that both pilots understand the meaning of the questions asked (for each judgment) in the same way.* More explicit information will be given by the experimenter concerning these definitions, if requested by either pilot. Each pilot will call out a whole number and a decimal for each of the two questions and the experimenter will record the answers.

The following events will occur just prior to each approach trial:

1. Experimenter 1 (in jump seat) will verbally authorize start of testing on every approach.

2. Captain will call approach control for clearance and weather.

3. Captain will then have the authority to begin the approach (by depressing the illuminated "operate" button on center console).

APPENDIX D

SIMULATOR MOTION CHARACTERISTICS

Axis	Displacement	Acceleration	Velocity
Roll	±9°	4.7 rad/sec^2	0.22 rad/sec Frequency at 30° phase lag = 0.5 Hz
Pitch	+14° -6°	4.7 rad/sec^2	0.22 rad/sec Frequency at 30° phase lag = 0.5 Hz
Heave (vertical)	24 in.	±1 g (from ambient)	Frequency at 30° phase lag = 0.5 Hz

APPENDIX E

APPROACH AND LANDING CHECKLIST

APPROACH AND LANDING CHECKLIST

Altimeter and instruments	Set and X checked
Radio altimeter	MDA/DH
Speedbrake	Armed (no lights)
Landing gear	Down (2 green lights)
Flaps	Check (angle call out)
Confirm runway in sight	Roger

Optional for reduced visibility

Call out altitudes
(500 ft; 100 ft; at
minimum)

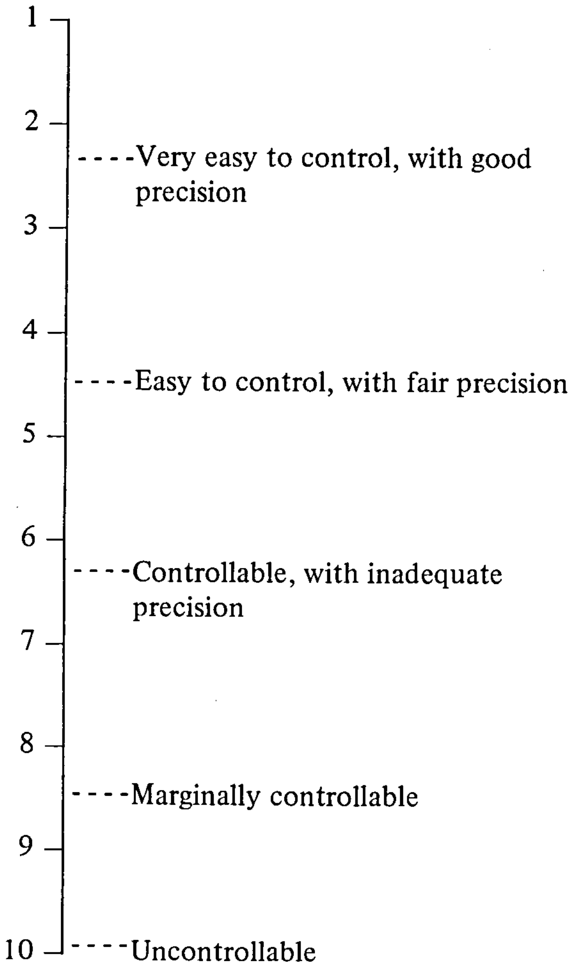
Modified from B737 operating manual.

APPENDIX F

PILOT SUBJECTIVE RATING SCALE
(From ref. 17)

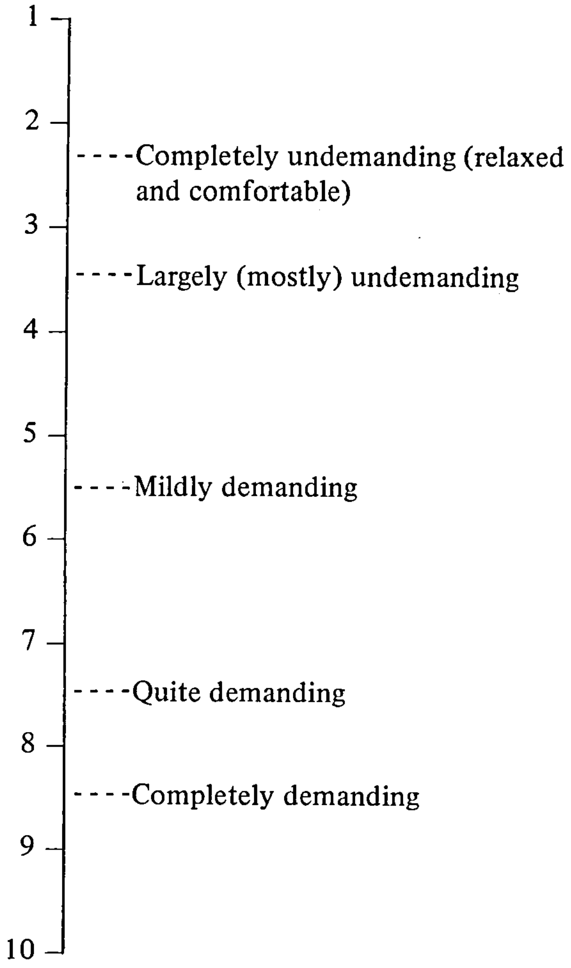
"Controllability and precision of control of this approach?"

SEMANTIC SCALE



"Demands on the Pilot in terms of amount of skill, attention, or effort required."

SEMANTIC SCALE



APPENDIX G

ANALYSIS OF VARIANCE SUMMARY FOR THE CAPTAINS' DECISION TIME

Source	df	SS	MS	F	p
Day-night (A)	1	77.14	77.14	1.81	ns
Wind shear (B)	1	37.68	37.68	1.69	ns
RVR ceiling (C)	8	809.22	101.15	4.15	<0.001
Subjects (D)	8	1231.7	153.96	*a*	
(A) X (B)	1	7.50	7.50	.17	ns
(A) X (C)	8	118.75	14.84	.50	ns
(A) X (D)	8	340.37	42.54	*a*	
(B) X (C)	8	288.66	36.08	1.05	ns
(B) X (D)	8	178.23	22.28	*a*	
(C) X (D)	64	1558.54	24.35	*a*	
(A) X (B) X (C)	8	469.32	58.67	2.24	<.05
(A) X (B) X (D)	8	353.72	44.21	*a*	
(A) X (C) X (D)	64	1899.53	29.68	*a*	
(B) X (C) X (D)	64	2192.10	34.25	*a*	
(A) X (B) X (C) X (D)	64	1672.83	26.14	*a*	
Mean	1	3772.00	3772.00	24.50	

[a] Cannot be tested because subject component is used as error term.

APPENDIX H

ANALYSIS OF VARIANCE SUMMARY FOR THE NUMBER OF TIMES THE CAPTAIN LOOKED UP FROM THE INSTRUMENT PANEL DURING FINAL APPROACH

Source	df	SS	MS	F	p
Day-night (A)	1	13.4	13.4	0.84	ns
Wind shear (B)	1	245.4	245.4	14.20	<0.01
RVR ceiling (C)	8	2233.8	279.2	29.86	<0.001
Subjects (D)	8	1189.4	148.7	*a*	
(A) X (B)	1	.11	.11	.01	ns
(A) X (C)	8	135.4	16.9	2.84	<0.01
(A) X (D)	8	127.4	15.9	*a*	
(B) X (C)	8	91.6	11.4	1.43	ns
(B) X (D)	8	138.4	17.3	*a*	
(C) X (D)	64	598.5	9.4	*a*	
(A) X (B) X (C)	8	20.3	2.5	.83	ns
(A) X (B) X (D)	8	64.4	8.0	*a*	
(A) X (C) X (D)	64	380.2	5.9	*a*	
(B) X (C) X (D)	64	513.0	8.0	*a*	
(A) X (B) X (C) X (D)	64	195.7	3.1	*a*	
Mean	1	18586.8	18586.8	125.0	

[a] Cannot be tested because subject component is used as error term.

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

16. Abstract

Each of 13 commercial pilots from four airlines flew a total of 108 manual flight director approaches in a moving base simulation of a medium-sized turbojet (95,000-lb gross weight) which had a day and night Redifon external scene. Three levels of RVR (1,600; 2,400; and >8,000 ft), three wind-shear profiles, nine ceiling heights, and continuous and intermittent visibility after initial breakout were tested. The time required for the captain to evaluate the runway visual environment after looking up from the instrument panel following a descent below clouds, the number of head-up transitions from instrument reference, and various subjective ratings of the controllability and precision of control were obtained on every approach. The results indicated that: (1) mean decision time ranged from 2 to 4.6 sec for ceilings under 380 ft across the three RVR conditions ($p \leqslant 0.001$); (2) mean vertical distance traveled during the visual-cue assessment period was a relatively constant proportion below the existing ceiling; (3) a significant three-way interaction in mean decision time between wind shear, day-night, and ceiling RVR variables occurred ($p \leqslant 0.05$); (4) mean number of head-up transitions to VFR conditions after breakout ranged from 4.6 to 13.4 and increased as a function of ceiling ($p \leqslant 0.001$) and severity of wind shear ($p \leqslant 0.01$) (the lower visibility conditions after breakout produced a less consistent relationship); the typical duration of fixation out the window was 1.5 sec; and (5) subjective pilot ratings of controllability and precision of control as well as amount of skill, attention, or effort required to make the landing were influenced significantly by the wind shear, night conditions, and low breakout ceiling conditions.

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