Landing Task and Pilot Acceptance of Displays

R. A. BEHAN* AND F. A. SICILIANI†
Serendipity Associates, Chatsworth, Calif.

The results of an analytical study of the landing task and an empirical study of pilot preferences of displays for landing in reduced weather minima suggest the following criteria for display evaluation. The information content of the display should allow one to initiate the final approach; to achieve departure and to know of departure from the glide angle; to maintain angle of attack, sink rate, roll attitude, and course; to determine crab angle, when to initiate flare, and heading during rollout. The presentation should be a compensatory display, a simple pictorial indication of the landing situation, and should be on the wind-screen. The display should provide redundant but independent information, require a minimum of user-supplied information, utilize a maximum of gain, provide for removal of a malfunctioning element, and be useful in other phases of landing. Alignment and other adjustments prior to use should be simple to accomplish and should be followed by a simple, foolproof checkout procedure.

The Landing Task

THE problem was to develop criteria for the evaluation of displays for landing in reduced weather minima. For visual flight rule (VFR) conditions, this task includes selection of the point at which to begin the final approach; flying the final-approach leg toward a selected aiming point, avoiding over- or undershooting; initiation of flare; and guiding the aircraft through touchdown and rollout. For instrument flight rule (IFR) conditions, exactly the same things must be accomplished. However, the cues for initiating the various phases of the landing and the procedures for conducting each phase are based on other information inputs.

The problem was attacked in two phases. The first was an analysis of the task which the pilot must perform under VFR conditions to determine the nature of the task and information required for performing the task. The second was to make a study of pilot preferences for displays for information presentation.

VFR Landing Operation

The landing operation can be described in two ways: what the aircraft does and how the pilot accomplishes this task. We will start with the former. For purposes of the present discussion, we will assume VFR conditions in the daytime, a straight-in approach with no adverse winds.

A typical landing profile consists of the following four phases:

1) Letdown: The pilot initiates letdown after reaching some predetermined point on cruise. The purpose of the letdown is to descend from cruise altitude to an appropriate approach altitude.

2) Initial approach: After the approach altitude is achieved, the aircraft is in the initial approach. During initial approach the aircraft is slowed and the pilot will make such banking turns as are necessary to line up with the runway centerline. The initial approach ends when the aircraft reaches the point at which the final approach must begin.

3) Final approach: The final approach brings the aircraft down toward the intended touchdown point of the runway at an angle dictated by the flight dynamics of the aircraft and by ground-based landing aids. The final approach ends with the aircraft approaching runway threshold, lined up with the centerline at an appropriate altitude to initiate flare.

4) Flare, touchdown, and roll-out: The purpose of the flare maneuver is to slow the rate of descent of the aircraft, to reduce the forward speed of the aircraft, and to change the attitude of the aircraft so that it can be landed. Impact on the runway is called touchdown. Theoretically, the airplane ceases to fly at the moment of touchdown. However, after touchdown comes roll-out, during which the aircraft is slowed to a speed suitable for ground maneuvers.

For discussion of the piloting task, we will devote our attention to the final approach and subsequent phases of the landing maneuver.

There are four prerequisites for the final approach: 1) appropriate angle of attack and throttle setting, 2) appropriate altitude, 3) straight and level flight, and 4) line-up with runway centerline. Given these four conditions, the initial task of the pilot is to select the point at which to begin the descent toward the runway aiming point. Once he has begun this descent, the pilot must adjust the rate of descent until it is appropriate for the given situation. Finally, he must maintain the rate of descent until he reaches the point at which to initiate flare.

The foregoing description suggests that there are three kinds of distance judgments which the pilot faces. The first of these is the distance from runway threshold at which to initiate the final approach. The second is the basis for the question, "Am I going to make it to the runway?" The third distance judgment is determining the distance above the runway for initiation of the flare maneuver. Given the preceding, we may ask what cues the pilot has to aid him in making these distance judgments.

There are three cues which the pilot may use to decide when to initiate the final approach. The first cue is the angular distance from the horizon to the intended touchdown point on the runway.[1,2] This distance will remain constant as long as the glide slope remains constant. There are two problems: one is to determine the impact point of the aircraft and to bring this into coincidence with the runway threshold; the second is to maintain the coincidence of these two points.

The second cue is relative size: the more distant a known object, the smaller it seems.[3] Since the size of the runway is known approximately, the reduced apparent size is interpreted as distance. The problem is to learn the appropriate apparent size which signals the point at which to initiate the final approach. The third cue is aerial perspective, which involves the change in color of distant objects coupled with the loss of sharp outline and detail.[3]

Presented as Preprint 65-722 at the AIAA/RAeS/JSASS Aircraft Design and Technology Meeting, Los Angeles, Calif., November 15–18, 1965; submitted December 13, 1965; revision received December 2, 1966. This project was sponsored and financed by NASA Ames Research Center, Moffett Field, Calif., under Contract NAS2-1346. [8.09, 8.15, 12.11]

* Senior Scientist. Member AIAA.
† Project Associate.

In judging whether he can make it to the runway, the pilot has four cues.

Angular distance between the horizon and the intended touchdown point: The horizon, because of its apparent placement at infinity, seems to be always the same distance away.[1,2] The perceived angular distance between the intended point and the horizon will remain constant as long as the glide angle remains constant. If this angular distance between the intended point and the horizon appears to increase, the aircraft will overshoot. Conversely, if this angular distance between the intended point and the horizon appears to decrease, the aircraft will undershoot. As the aircraft comes closer to the runway, this judgment is enhanced by the behavior of objects in the visual field.[2] As an example, if one were landing over trees and the trees seemed to move up toward the runway threshold, the aircraft would not clear the trees.

Motion perspective: The relative apparent motion of objects as the observer moves, e.g., the apparent movement of hangers and other buildings toward the observer as the aircraft approaches the runway.[3]

Runway perspective: This cue depends on the apparent shape or perspective of the runway.[1,2] The pilot must learn the shape of the runway, which indicates an appropriate approach path. Then on a given approach, if the runway shape appeared long and narrow, the pilot would know that the aircraft would overshoot the runway.

Stationary aiming point: The point at which the aircraft is actually aiming is said to be perceived as stationary. Points above the aiming point will appear to move away from the aircraft. Points below the aiming point will appear to move toward and under the aircraft.

The pilot uses these cues, in conjunction with the perceived rate of sink, to project the impact point of the aircraft with respect to the intended touchdown point. The difference between the intended point and the projected impact point is an indication of the error in the aircraft approach path. The pilot attempts to fly in the approach path so that the intended point and the impact point coincide; he attempts to null the approach error. It is thus seen that the information available to the pilot during the final approach is used very much as the information in a compensatory display,[4] which presents an indication of the error in the tracking output. This analysis suggests that it might be helpful to construe the VFR landing display as compensatory. The basic compensatory characteristic will be abstracted in order to be used as a heuristic device.

To determine the point at which to initiate the flare movement, the pilot must consider the aircraft's height above the runway. This is a problem in visual judgment of distance which is aided by three cues.

Head movement parallax or motion parallax: This cue is based on the different views of the runway which one obtains when one scans back and forth ahead of the speed blur.[3] The scanning helps provide more and different data for the judgment through the cue of head-movement parallax (motion parallax).

Motion-perspective: the gradient in motion in a direction as the aircraft approaches the runway.[3] As the aircraft approaches the runway, objects seem to pass beneath it at greater and greater speeds but begin to blur if the aircraft lands very fast. This cue may be most useful for pilots operating slower landing aircraft.

Density gradient in the texture of the runway and its surroundings[3]: As the aircraft comes closer to the ground, the gradient becomes much steeper. The increase in density generally runs upward in the visual field. Additional cues which assist the pilot in judging the appropriate distance from the runway for flare are the sizes of familiar objects and the clarity of their detail.

The preceding discussion has assumed that the aircraft is landing in a calm wind. Although this may be the case early in the morning, most aircraft landings are made in some degree of crosswind. The aircraft in flight is a part of the air mass and does not fly *through* the air but *in* the air. The pilot of an aircraft crabs into the wind to maintain a desired course. Thus the heading of the aircraft may not be identical with the course the aircraft flies.

Information Requirements for Landing

From the foregoing discussion it may be inferred that the pilot needs information to assist his initiation of the final approach, to achieve and maintain the appropriate glide angle, to warn him of over- or undershooting the aiming point, to maintain the appropriate angle of attack, to maintain the appropriate sink rate, to maintain the appropriate roll attitude, to maintain an appropriate course, to indicate to him the crab angle required to maintain course, to assist his initiation of the flare maneuver, and to maintain aircraft heading during roll-out.

Nature of the Landing Task

From the preceding analysis, flying the final approach may be construed as a task in which the pilot is tracking a ramp input with the aid of a compensatory-type display. The approach path which the pilot wishes to fly is the ramp. The tracking task is complicated by the fact that the pilot must control the aircraft in three dimensions, and he must infer the error in the present position from a projection of the future position of the aircraft. The latter consideration has implications for understanding the period of transition from instrument to contact flying.

Laboratory studies of compensatory tracking tasks provide the following generalizations: 1) Performance of a compensatory tracking task is aided by including the first and second derivatives of the error (rate and acceleration of error, respectively) in the input to the display.[5] 2) When the control is unaided in relation to the display, compensatory tracking is superior to pursuit tracking with a simple input.[6] 3) With a shallow ramp input, as in the present case, there is a tendency for the operator to lead the input,[4] i.e., in the present case, to overshoot. 4) A compensatory indicator can give a more precise picture of the situation through the utilization of high display gain.[7] 5) When the desired output is time-invarient, as is the present case, the compensatory tracking task is equally as efficient as the pursuit tracking task.[4,6]

In view of the present analysis of flying the final approach as a tracking task utilizing a compensatory display, considerations of the possibility of negative transfer of training lead to the conclusion that whatever instrumentation is developed should present a compensatory-type display. Transfer of training refers to the effects of the performance of one task on the performance of another and may be negative or positive. If the performance of one task inhibits the performance of another, the transfer is negative. If the performance of one task facilitates the performance of another, the transfer is positive. In the given situation, it is desirable that the transfer of training from the VFR to the IFR landings be positive. Thus, it is desirable to make the landing task under IFR conditions as much like the landing task under VFR conditions as is possible.

IFR Landing Operation

The preceding discussion assumed VFR flight conditions. The same maneuvers must be accomplished for an IFR landing, which differs from the VFR in the information available to the pilot to accomplish the maneuvers. The letdown and the initial approach are the same as for VFR, with the exception that the initial approach may be accomplished with the assistance of radar guidance. However, under IFR conditions the pilot may rely on other sources of information for: initiation of the final approach, accomplishment of

Table 1 Information presented on the situation displays[a]

	Spect.	Collins	Type A	G.E.
Airspeed	Y		Y	Y
Altitude	Y		Y	
Horizon	Y	Y	Y	Y
Range	Y			
Closure rate	Y		Y	Y
Flight director	Y	Y	Y	Y
Aircraft symbol	Y	Y	Y	Y
Runway			Y	Y
Basic indication	Y	Y	Y	
Localizer		Y	Y	Y
Glide slope		Y	Y	Y
Pitch attitude		Y	Y	Y

[a] "Y" denotes yes, the display does present the information. A blank space denotes that the display does not present the information.

the final approach, initiation of the flare maneuver, and completion of the touchdown and roll out. Thus it is seen that the task of the pilot does not change during the IFR landing, apart from the demands made on him by instrumentation and by the IFR approach pattern peculiar to the airport where he plans to land.

Acceptance Study

The purpose of the acceptance study was to determine pilot preference for the display of information for landing in reduced visibility. The two types of information display considered were situation displays which present an integrated complex of information and displays of individual items of information, e.g., sink rate.

Method

The method used was the technique of paired comparisons. Pictures of representative displays were arranged in pairs by display type. The subjects were presented with each pair of display pictures and asked to express a preference for one of the pair. After he stated his preference, the subject was asked the reason for his preference.

Subjects

The subjects were 30 American Airlines line pilots, each of whom were interviewed separately. The average age of the pilots was 46 years. They had been flying for an average of 26 years and had an average of 17,520 hours in the air. Twenty-nine were qualified in jet aircraft; the average number of hours in jets was 2490.

Displays

Four situation displays were chosen: the Collins 329B-7A flight director display, the Spectocom windscreen display, the type A windscreen display of Baxter and Workman,[8] and the General Electric CRT display. The Collins display was chosen to represent the conventional panel-mounted situation display[9] and is a standard "fly-to" director display which, as was estimated correctly, would be unfamiliar to the pilots in the study. The Spectocom windscreen display was chosen as one of two windscreen displays because it was rated so low by Baxter and Workman.[8] The type A windscreen display was chosen because it was a synthesis of the best characteristics of several displays.[8] The General Electric cathode ray tube display was chosen to represent the CRT type. The information shown on the situation displays is presented in Table 1.

The following individual information displays were selected. 1) Three altimers: a conventional dial with three pointers, one with the 10,000-foot pointer modified as a moving yellow line index, and third a vertical moving tape with a fixed index. 2) Three airspeed indicators: a conventional dial, a digital readout, and a vertical moving tape with a fixed index. 3) Three vertical-rate-of-climb indicators: a conventional indicator with fine graduations, a conventional indicator with minimum graduation, and a vertical tape with a moving index.

Table 2 Preferences for situation displays

Instrument type	First preference	Times chosen in preference to A	B	C	D
A. Spectocom	7	...	19	12	10
B. Collins	4	11	...	9	16
C. Type A	11	16	18	...	18
D. General Electric	7	12	18	10	...
No Preference	1	...	...	...	...

Table 3 Preferences for airspeed, altitude, and sink rate indicators

Information	Instrument preference: First	Second
Airspeed	Conventional (16)	Vertical tape (9)
Altitude	Yellow line (18)	Vertical tape (7)
Sink rate	Conventional Fine graduations (13)	Conventional Gross graduations (10)

Results

The display preference for each pilot was determined for each display type by the instrument he chose. In cases where the pilot had "no preference," the choices were analyzed for consistency and a preference was assigned logically. The appendix contains all charts on preferences as well as pilots' reasons for choices.

The preferences among the four situation displays are presented in Table 2. Although the type A display was preferred by most pilots, the proportion of pilots favoring it was not large enough for significance at the 0.05 level of confidence. However, comparing the two windshield displays, Spectocom and Type A, with the other two, we find that a windshield type was picked significantly more frequently than the other types. $X^2 = 11.16$, significant beyond the 1% level of confidence.

The Spectocom display was the only one that did not present the situation of the aircraft in relation to the glide slope. The other three displays were picked significantly more often than the Spectocom, which only has a command "fly-to" director. $X^2 = 7.76$, significant beyond the 1% level of confidence.

Another difference among these displays was the presentation of airspeed information. Displays presenting airspeed (Spectocom, Type A, General Electric) were picked signifi-

Table 4 Pilot preference for situation displays

Reason for preference	Frequency
1st choice: Type A	
Windshield	15
Better pictorially	11
Simpler; less interpolation	5
Runway	4
2nd Choice: Spectocom	
Simplicity making it easy to read	15
Windshield	11
3rd Choice: General Electric	
"Real" pictorial presentation	20
Simplicity/easy to grasp	5
4th Choice: Collins	
Familiar: less transition	13
Simpler: more understandable	6

Table 5 Pilot preference for airspeed presentations

Reason for preference	Frequency
1st Choice: Conventional clock-type	
Familiarity (experience)	12
Read angle of pointer	11
Can see trend	8
Easier and quicker to read	4
Relationship to other number: Range	4
2nd Choice: Vertical tape	
Can see trend	5
Easier and quicker reading	4
3rd Choice: Digital readout	
Simple, precise	4

cantly more than those which did not present airspeed (Collins). $X^2 = 15.21$, significant beyond the 1% level of confidence.

Comparison of the displays as regards altitude information, Spectocom and the type A vs the Collins and the G. E., resulted in a value of X^2 which was not significant at the 0.05 level of confidence. This result may reflect the fact that it is the task of the co-pilot to monitor altitude during the final approach, not the task of the person landing the aircraft.

Table 3 presents the first and second preferences of the pilots for airspeed, altitude, and sink rate indicators. The first preference for each display is a dial instrument. Tables 4–10 present reasons for pilot's preferences and preference scores for airspeed, altitude, and vertical-speed presentations.

Reliability and Validity

The altimeters and the airspeed and sink rate indicators were chosen to assess the reliability and validity of the results of the study. The method of assessing validity was to compare the preferences for certain displays with recommendations for these types of displays in the human-engineering literature. If the preferences indicated by the pilots coincided with the human-engineering recommendations, and if the pilot's reasons for their preferences did not contradict the human-engineering literature, the results of the study would be assumed to have been validated.

Assessment of the reliability (internal consistency) of the results of the study is afforded by the use of the paired comparison technique. On the assumption that consistent preferences follow the transitive law, the preference choices could be used to assess consistency. The transitive law asserts: xPy and yPz, then xPz. The transitive law was applied also to test the results obtained with the four situation displays.

Consistency of the pilots' responses is attested by the fact that of 450 choices where inconsistency was possible, only two inconsistencies occurred. Thus the empirical probability of an inconsistency obtained in this study is 0.0044. Furthermore, both of the inconsistencies occurred with respect to the situation displays where there were six choices (four situation displays, six pairs). In no case where there were three choices were inconsistencies found. One may conclude from the low occurrence of inconsistencies in pilot judgments that the data collected are reliable. In other words, there is consistency within pilots.

The validity of the results may be judged by the agreement between pilot choice and human-engineering recommendations.[10] The test displays are those for altitude, indicated airspeed, and sink rate. The source of human-engineering recommendations suggests a moving pointer and a circular dial as superior to a moving scale or counter for: qualitative and check reading, setting in information, tracking, and general use. In every case, the majority preference of the pilots corresponded with the human-engineering recommendations.

In terms of the reasons given for selection of a particular instrument, the pilots' reasons do not conform exactly to those of the human-factors literature. However, there were no contradictions. The only sins were those of omission. In view of the preceding, we conclude that the data collected concerning altitude, airspeed, and sink rate displays are valid. Further, we infer from this that the data for situation displays are also valid.

Table 6 Pilot preference for altitude presentations

Reason for preference	Frequency
1st Choice: Modified conventional clock-type	
Easy to read	10
Less chance for error	4
An improvement	4
2nd Choice: Conventional three-pointer	
Familiarity (experience)	8
Easier to read	4
3rd Choice: Vertical tape	

Table 7 Pilot preference for vertical-speed presentations

Reason for preference	Frequency
1st Choice: Graduated standard clock-type	
Less interpretation/markings	13
Familiarity	9
2nd Choice: Conventional clock-type	
Simple-no clutter: no need for more markings	13
Familiarity	7
Easy to read	5

Summary of Results

The results as regards situation displays allow the generalizations that pilots prefer a display for landing in reduced visibility which is presented on the windscreen, contains information about the position of the aircraft with respect to the glide slope, presents a picture of the landing situation, and contains information about airspeed.

The results for the individual information displays allow the generalizations that pilots prefer displays of altitude, airspeed, and sink rate to be presented as circular scales with moving pointers in order to facilitate quick checks and so that they may note trends.

Criteria for Display Evaluation

The following criteria were derived from the analysis of the landing task, the pilot-opinion study, and the literature on compensatory displays.

1) Information content: a) to assist initiation of the final approach, b) to achieve and maintain the appropriate glide angle, c) to warn of over- or undershooting the aiming point,

Table 8 Preference scores for airspeed presentations

Instrument type	First preference	Times chosen in preference to A	B	C
A. Digital readout	4	...	7	8
B. Conventional clock-type	16[a]	23	...	18
C. Vertical(moving) tape	9	16	11	...
No preference	1	...	...	...

[a] Significant at the 0.05 level of confidence $X^2 = 7.52$.

Table 9 Preference scores for altitude presentations

Instrument type	First preference	Times chosen in preference to A	B	C
A. Vertical moving tape	7	...	8	10
B. Yellow-line altimeter	18[a]	20	...	25
C. Conventional three-pointer	5	20	5	...

[a] Significant at the 0.01 level of confidence, $X^2 = 10.69$.

Table 10 Preference scores for vertical-speed presentations

Instrument type	Preference	Times chosen in preference to A	B	C
A. Conventional clock-type	10	...	11	22
B. Modified conventional	13	18	...	23
C. Vertical fixed tape	5[a]	7	6	...

[a] Significant at the 0.01 level of confidence, $X^2 = 13.71$.

d) to maintain the appropriate angle of attack, e) to maintain the appropriate sink rate, f) to maintain appropriate roll attitude, g) to maintain an appropriate course, h) to indicate the crab angle required to maintain course, i) to assist initiation of the flare maneuver, and j) to maintain aircraft heading during roll-out. 2) Presentation of a compensatory display. 3) Presentation of a simple, pictorial indication of the landing situation. 4) Presentation on the windscreen. 5) Utilization of maximum display gain. 6) Provision for redundant but independent information. 7) Require a minimum of user-supplied information. 8) Usefulness in phases of the flight other than landing. 9) Provision for removal from the display of a malfunctioning element. 10) Alignment, and other adjustments prior to use, should be simple to accomplish and should be followed by a simple foolproof checkout procedure.

Inferential validity, as obtained in the present study, should always be checked in simulated or actual flight conditions. On the other hand, it should be noted that the paired comparison design cannot be used under such conditions. After the present study was completed, the FAA announced the results of tests which confirm those reported here.[11] In simulated IFR landings, performance with a conventional panel-mounted Sperry HZ-4 display was compared with performance using the Sperry R-4A windshield display, which is similar to the Type A.[2] At the completion of the tests the six pilot subjects unanimously favored the windshield display. In the present study, 25 of 30 pilots (83%) rejected conventional displays. ($t = 2.49$, $p \leq 0.05$). It should be recognized that the FAA-Sperry study was not designed primarily as a study of pilot preferences but, rather, to collect numerical data on specific flight performance for which purpose the design was adequate.

References

[1] Lane, J. C. and Cumming, R. W., *The Role of Visual Cues in the Final Approach to Landing* (Aeronautical Research Laboratories, Victoria, Australia, 1956), p. 15.

[2] Langewiesche, W., *Stick and Rudder* (McGraw-Hill Book Company Inc., New York, 1944), Chap. 15, p. 285.

[3] Gibson, J. J., *The Perception of the Visual World* (Houghton-Mifflin Company, Boston, 1950), Chap. 7.

[4] Briggs, G. E., "Pursuit and compendatory modes of information display," Army Medical Research Lab., Fort Knox, Ky., AMRL-TDR-62-93, 1962.

[5] Chernikoff, R., Birmingham, H. P., and Taylor, F. V., "A comparison of pursuit and compensatory tracking under conditions of aiding and no aiding," J. Exp. Psychol. **49**, 55–62 (1955).

[6] Chernikoff, R. and Taylor, F. V., "Effects of course frequency and aided time constant on pursuit and contemporary tracking," J. Exp. Psychol. **53**, 285–292 (1957).

[7] Birmingham, H. P. and Taylor, F. V., "A human engineering approach to the design of man operated continuous control systems," U. S. Naval Research Lab. Rept. 4333 (1954).

[8] Baxter, R. J. and Workman, J. D., *Review of Projected Displays of Flight Information and Recommendations for Further Development* (Aeronautical Research Laboratories, Victoria, Australia, 1962).

[9] Fritzie, E. H., *Flight Director, Comparator Monitor, and Automatic Flight Control Guidance Development for All-Weather Operations* (Collins Radio Co., Cedar Rapids, Iowa, 1963).

[10] Baker, C. A., "Visual presentation of information," *Human Engineering Guide to Equipment Design,* edited by C. T. Morgan, A. Chapanis, J. S. Cook, and M. W. Lund (McGraw-Hill Book Company Inc., New York, 1963), Chap. II, pp. 94–107.

[11] "Pilot reaction to Sperry display assessed," Aviation Week and Space Technology **83,** 115–117 (1965).