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TECHNICAL REPORT

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THE ISOLATION OF MINIMUM SETS OF VISUAL IMAGE CUES SUFFICIENT FOR SPATIAL ORIENTATION DURING AIRCRAFT LANDING APPROACHES

Janice E. Eisele, Robert C. Williges, Stanley N. Roscoe

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental investigation of synthetic imaging displays was directed toward the isolation of minimum sets of visual cues sufficient for spatial orientation in ground-referenced aircraft landing approaches. Thirty-two flight instructors viewed static computer-generated airport scenes TV-projected onto a large screen viewed from the cockpit of a twin-engine general aviation trainer. Judgments of lateral and vertical deviations from a four-degree approach to landing aim point in the display were made to 32 combinations of

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20. four contact analog cues: runway outline, runway touchdown zone, runway centerline, and ground plane texture; and one guidance cue: glidepath-localizer symbol. Each resulting display was responded to once or more from each of 27 different flight position and attitude viewpoints by each of eight subjects in different serial orders. Dependent measures were response choice and response latency. The most accurate glidepath and course deviation judgments were made when the guidance cue glidepath was in the set. When only contact analog cues were present the best judgments of spatial orientation consistently were made when the runway outline was present at far and medium ranges from touchdown and when the runway centerline was present at near range.

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ACKNOWLEDGMENT

This paper describes research performed at the University of Illinois at Urbana-Champaign under contract with Engineering Psychology Programs, Office of Naval Research, with Gerald S. Malecki as scientific monitor.

CONTEXT

The Aviation Research Laboratory of the University of Illinois has investigated integrated synthetic-imaging displays and computer-augmented flight control for the Office of Naval Research. Mr. Gerald Malecki, Assistant Director, Engineering Psychology Programs, was the technical monitor of the research. Professor Stanley N. Roscoe was the principal investigator during the initial phase of study and experimental apparatus development; Professor Robert C. Williges served as principal investigator while Professor Roscoe was on academic leave during 1975-76.

The research was directed toward (1) the isolation of minimum sets of visual image cues sufficient for spatial and geographic orientation in the various ground-referenced phases of representative flight missions, (2) the generation and spatially integrated presentation of computed guidance commands and fast-time flight path predictors, and (3) the matching of the dynamic temporal relationships among these display indications for compatibility with computer-augmented flight performance control dynamics, both within each ground-referenced mission phase and during transitions between phases. The investigative program drew selectively upon past work done principally under ONR sponsorship or partial sponsorship, including the ANIP and JANAIR programs.

To study experimentally the effectiveness of alternate sets of visual cues the Aviation Research Laboratory developed a highly versatile computer-generated display system to present dynamic pictorial images either on a head-down, panel-mounted CRT or on a head-up television projection to a large screen mounted in front of the pilot's windshield on the Link GAT-2 simulator. Due to the great flexibility of the pictorial display, visual cues and flight status information could be manipulated experimentally. The experiment reported herein was conducted to isolate the visual cues sufficient for approach and landing by measuring subjects' orientation responses to TV-projections of static computer-generated images containing various combinations of skeletal symbology from various positions and attitudes on final approaches to landings.

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BACKGROUND

Aircraft technology has advanced rapidly since its beginning at the turn of the century, yet only recently has there been widespread recognition by the aviation community of the constantly changing role of the pilot in aircraft operations. Innovations in display technology, made possible by the advent of advanced airborne digital computers, can improve the pilot's performance by processing information to minimize transformations, including integrations and differentiations as well as simple arithmetic computations, required in the decision making and flight control process. In this way, computers can help pilots perform their new duties better.

In making and carrying out flight decisions, a pilot must convert long-term mission objectives to subgoals for each flight instrument, relate instrument subgoals to each other and control inputs to aircraft responses and instrument indications. For each of these functions, computers can improve pilot performance by storing, transforming, and integrating sensed information. With the ever increasing air traffic densities, expanding requirements for all-weather, night, and nap-of-the-earth operations, and the burgeoning complexity of navigation and weapon delivery profiles, the application of airborne computers to control augmentation and display integration is no longer generally discounted as a radical, irresponsible, dangerously unreliable folly.

Pictorial Vertical Situation Displays

To apply computers effectively to the transformation of sensed information and the generation of synthetic displays, information that is closely related functionally should be presented in a common frame of reference. More specifically, information concerning an airplane's attitude and flight path relative to surface objects, such as ground targets, airport runways, or carrier decks, should be presented in a pictorial, forward-looking, vertical situation display (VSD) context. All pictorial displays, by Carel's (1965) definition, have two common characteristics: first, the elements in the display are geometrically similar to those in the contact world; and second, the motion of displayed elements is analagous to that of their real-world correlates.

Literal VSDs. The most literal VSDs for approach and landing are flight periscopes and forward-looking IR and TV displays. Roscoe, Hasler, and Doughtery (1966) conducted several studies using a projection periscope mounted in a Cessna T-50. The pilot saw the forward view on an 8-inch screen mounted above the instrument panel with the periscope projecting through an aluminum windshield. Although safe takeoffs and landings were made by reference to this projected forward view, the accuracy of landings in terms of constant and variable errors was reliably influenced by image magnification, the optimum value being about 1.25. Campbell, McEachern, and Marg (1955) used a binocular periscope to investigate approach and landing performance and reached similar conclusions as to image magnification.

Kibort and Drinkwater (1964) tested the effectiveness of a TV display in a DC-3 aircraft for the final approach and landing. A steerable camera was mounted on the nose and a second camera was placed just forward of the tailwheel. The output of either could be fed to a 14-inch monitor that subtended 16-17 degrees at the pilot's eye. The task of the pilot was to fly landing approaches from three miles out through touchdown and rollout. Kibort and Drinkwater concluded that only quantitative airspeed, vertical speed, and altitude information was necessary when flying the TV display.

From the evidence available, an unaided literal TV display appears inadequate for use as the primary instrument for approach and landing. The addition of quantitative information on flight and navigation guidance parameters would improve the pilot's spatial and geographical orientation cues. Information presented by a literal pictorial display is believable due to the availability of all the real-world landmarks, and this allows the pilot to decide among alternative courses of action with high confidence. In this way, literal displays take advantage of the overlearned perceptual habits that pilots acquire from VFR flight.

Analog VSDs. In the late 1950s through early 1960s, the ANIP program (Army-Navy Instrumentation Program) followed by the JANAIR (Joint Army Navy Aircraft Instrumentation Research) program were conducted. These programs included investigations and development of advanced instrument systems for aircraft and standards for electronic and optically-generated aircraft displays.

Carel (1965), in his frequently cited JANAIR report, defined a contact analog display as "the point perspective projection of a three-dimensional model to a picture plane." Typical computer-generated models contain reference objects significant for flight performance, such as a surface representing the horizon and ground plane, a surface representing the command path for the pilot to follow, and other surfaces or objects useful during various phases of a mission. Most importantly, the displayed surface dynamics are similar to those of their analog surfaces in the natural visual environment. The displayed surfaces still follow the laws of motion perspective, thus providing information coded in a fashion analogous to the coding provided in visual contact flight.

Investigators at Bell Helicopter Company carried out simulator and flight tests using a contact analog display developed by Norden. Abbott and Dougherty (1964) studied the accuracy with which altitude and groundspeed could be interpreted using the Norden display. No control was required of the subject pilots in the open-loop task. It was concluded that the display offered the same problem areas as does VFR flight in the presentation of altitude and groundspeed information. The higher the altitude or speed, the poorer was the judgment, and an interaction existed between speed and altitude judgments, with increasing difficulty in interpreting either as the other increased.

Emery and Dougherty (1964) studied low-altitude, ground-referenced maneuvers in the Bell moving-base helicopter simulator. The content of the displays was varied in four test conditions: ground plane only, ground plane and landing pad; ground plane with flight path border; and ground plane, flight path border, and "tarstrips" perpendicular to the border edges. Pilot performance improved as command guidance information was added in the form of a desired flight path.

In a third investigation, Dougherty, Emery, and Curtin (1964) compared pilot performances when flying with standard instruments and with the contact analog display. Two groups were trained to a criterion of "performance equivalence" with the two types of display in the moving-base helicopter simulator. Subjects were required to control altitude, heading, course, and airspeed while concurrently performing a digit-reading side task at variable rates. Pilot performances with the two types of display did not differ reliably under the control condition (no digit-reading task) or under the slowest rate condition; however, as the side-task rate was increased progressively, performance on the contact analog display remained relatively stable, while performance on the standard instruments deteriorated.

The authors concluded that "the pictorial JANAIR display was by far the superior display as the visual workload increased," and attributed this to three factors:

1. The pilot may more quickly assimilate qualitative information from the pictorial display.
2. Using conventional information, the pilot samples one parameter of information per glance. With the pictorial display, he accumulates information on more than one parameter per glance.
3. Because of its relatively large angular field of view, the pictorial display permits use of peripheral vision.

Williams and Kronholm (1965) reported the results from simulation studies of an integrated electronic vertical situation display developed by Norden under JANAIR support. The object of the Universal Contact Analog Display (UCAD) research program was to formulate a methodology for determining VSD requirements and to generate design criteria for an integrated cockpit display applicable to both fixed-wing and rotary-wing aircraft. Significant among the conclusions and recommendations were: 1) the desirability of quantitative indications of altitude, airspeed, vertical velocity, turn rate; and 2) the desirability of incorporating computed control information into the display for critical tasks.

Ketchel and Jenny (1968) surveyed the literature, presented display design considerations, and delineated areas in which further research was needed. Their report included consideration of information requirements, symbology and format, and quantitative display characteristics, with the primary emphasis on CRT displays for fixed-wing aircraft. Following publication of the Ketchel and Jenny report, a new program of experimentation on contact analog displays was undertaken at the Naval Missile Center, Pt. Mugu.

Cross and Cavellero (1971) investigated pilot performance during simulated landing approaches to an aircraft carrier. Performances in the simulator were found to be "comparable" to performances on approaches to a CVA carrier in an actual F-4 aircraft. In addition, pilots expressed the opinion that the nature and level of task difficulty experienced in the simulator were similar to those encountered in the aircraft in the landing phase. From the evidence, synthetically generated contact analog displays appeared to facilitate spatial orientation and allow manual control not greatly different from literal imaging displays of comparable dimensions.

A projected flight path indication was added to the display used by Cross and Cavallero to allow investigation of a possible means of further improving performance during approach and landing. Wulfeck, Prosin, and Burger (1973) had pilots fly approaches in a fixed-base F-4 simulator with the baseline contact analog display, the predictor display, and a glideslope reference element of the predictor display. The predictor display proved reliably superior to the baseline display in all comparisons, including altitude and lateral error variability, oscillatory control patterns, landings within error criteria, and "acceptable" approaches at the ramp.

Unanswered Questions

Although much has been learned from the experiments just reviewed, the overriding conclusion is that pilots can land airplanes by reference to an infinite number of sets of visual cues, each of which may be sufficient to support performance at a particular level, no one of which is uniquely necessary. Thus, when one speaks of the "essential" visual cues for landing, he is implicitly addressing the unanswered questions concerning the relative effectiveness of the various sets of cues that might be presented by a visual display within our present sensing, computing, and display technology.

The approach taken in the present experimental investigation was to select a clearly sufficient set of visual indications symbolic of geometric aspects of the contact visual scene and to conduct a parametric comparison of their various combinations in terms of the performances of qualified pilots in judging their flight positions and attitudes relative to the nominally correct landing approach path. Open-loop responses were made to successive static presentations of flight situations represented by computer-generated images of the various display configurations projected onto a large screen viewed from the cockpit of a flight simulator.

METHOD

Apparatus

A Raytheon 704 digital computer was used to generate the displays, control the experimental display presentations, collect the dependent measures, and record the data. The computer-generated displays were imaged on a CRT from which a TV camera relayed them to an Advent Video-beam projector. The Advent projector, mounted above the simulator cab, projected the TV image onto a 68.5 x 51.5-in spherical-section screen mounted in front of the simulator, a modified Singer-Link General Aviation Trainer (GAT-2). The left half of the windscreen was removed so that the subject, sitting in the pilot's seat, had an unobstructed view, straight ahead, of the Advent screen. The simulator's cab and Advent system as shown in Figure 1 were entirely enclosed in a black plastic curtain that shielded the projection screen from ambient light. The response device was a nine-button keyboard, installed on the end of the subject's right armrest and adjustable for various arm and finger lengths.

Experimental Design

The displays were developed by the full factorial combination of five symbolic elements, four representative of visible aspects of an airport scene and one synthetic element not present in the real world. The real-world or "contact analog" display elements included: (1) runway outline, (2) touchdown zone, (3) runway centerline, and (4) a grid of "section lines" that served to define a textured surface.

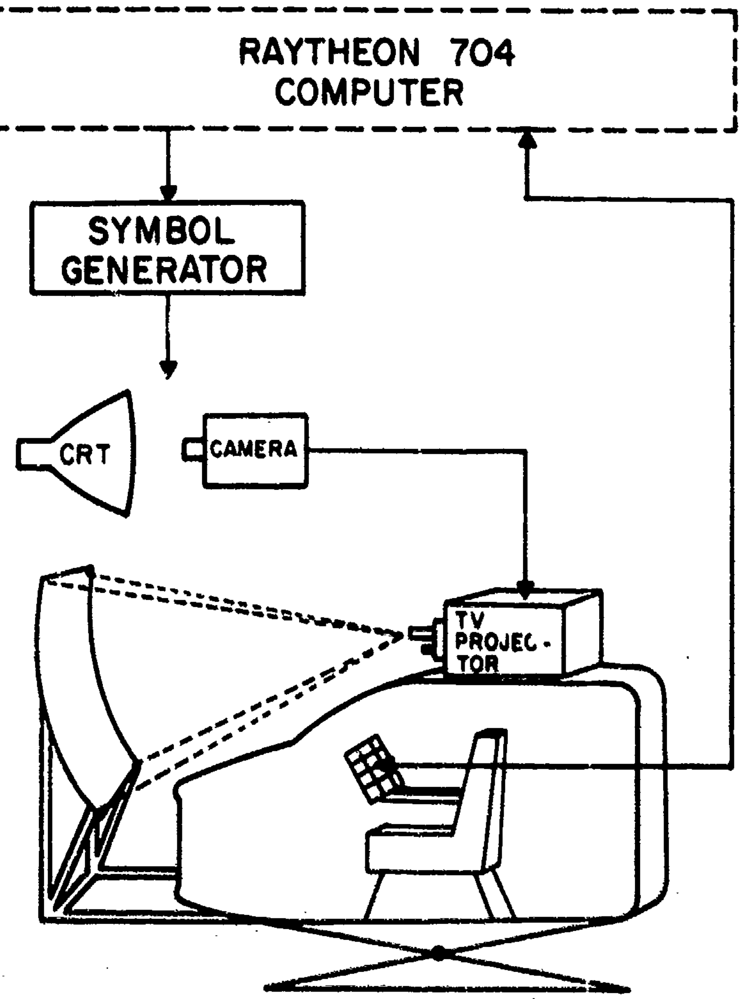

Figure 1. Pictorial landing display simulation equipment.

The synthetic element was a row of four "T-bars" of increasing height positioned along the approach centerline at 1/4, 1/2, 1, and 2 miles from the touchdown aimpoint to provide a visual representation of an imaginary glideslope and localizer path (analogous to a "highway in the sky").

Two additional elements from the contact scene, present in all 32 displays, were touchdown aimpoint and horizon. To approximate the viewing condition that would result in subjective equality of distance judgments relative to those obtained with a direct, contact view of a real airport, the computer-generated scenes were projected with a magnification factor of 1.2 as measured at the pilot's eye position (Roscoe, Hasler, and Dougherty, 1966). The 32 displays were divided into four groups of eight displays each by selecting two elements, runway outline and glideslope-localizer path, as between-subjects factors. The four groups of displays are given in Table 1 and in Figures 2-5.

A central-composite design (CCD) was used to derive 27 different viewpoints from which subjects would respond to the airport scenes projected onto the screen mounted in front of the simulator. This systematic strategy provided an economical sampling of ranges from touchdown aimpoint, vertical and lateral deviation from the glideslope/localizer T-bars, and aircraft pitch and bank attitudes. The coded factor levels and corresponding real-world values used to generate the 27 different perspective views of the landing approach scene (for each of the 32 displays) are shown in Table 2. A one-half replicate of a 2^5 factorial combination of variables (± 1 values), plus 2 x 5 extended axial "star" points ($\pm\alpha$ values), plus 10 replications of the centerpoint (0 values) yielded 36 presentations

TABLE 1

Visual Elements Present or Absent in Each of the Eight Displays in Each of the Four Display Groups Presented to Independent Groups of Eight Flight Instructors Each

Group I					Group II					Group III					Group IV				
Runway Outline	Touchdown Zone	Runway Centerline	Texture Grid	Glideslope/Localizer	Runway Outline	Touchdown Zone	Runway Centerline	Texture Grid	Glideslope/Localizer	Runway Outline	Touchdown Zone	Runway Centerline	Texture Grid	Glideslope/Localizer	Runway Outline	Touchdown Zone	Runway Centerline	Texture Grid	Glideslope/Localizer
0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1
0	1	0	0	0	1	1	0	0	0	0	1	0	0	1	1	1	0	0	1
0	0	1	0	0	1	0	1	0	0	0	0	1	0	1	1	0	1	0	1
0	0	0	1	0	1	0	0	1	0	0	0	0	1	1	1	0	0	1	1
0	1	1	0	0	1	1	1	0	0	0	1	1	0	1	1	1	1	0	1
0	1	0	1	0	1	1	0	1	0	0	1	0	1	1	1	1	0	1	1
0	0	1	1	0	1	0	1	1	0	0	0	1	1	1	1	0	1	1	1
0	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1

Legend:

0 = without element; 1 = with element

All displays with aimpoint and visible horizon.

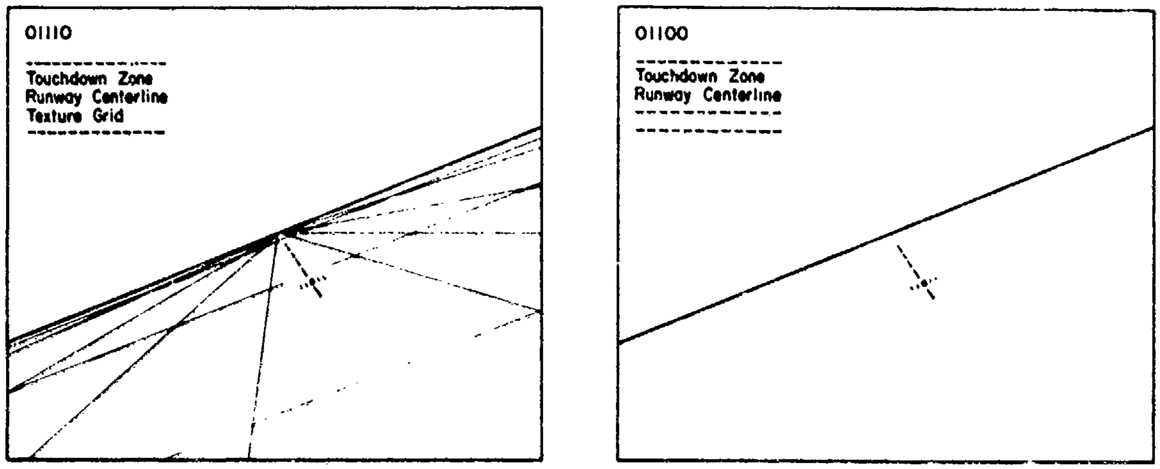

Figure 2. Group I display elements: composite of all Group I elements (left) and composite of Group I elements with Texture Grid omitted (right).

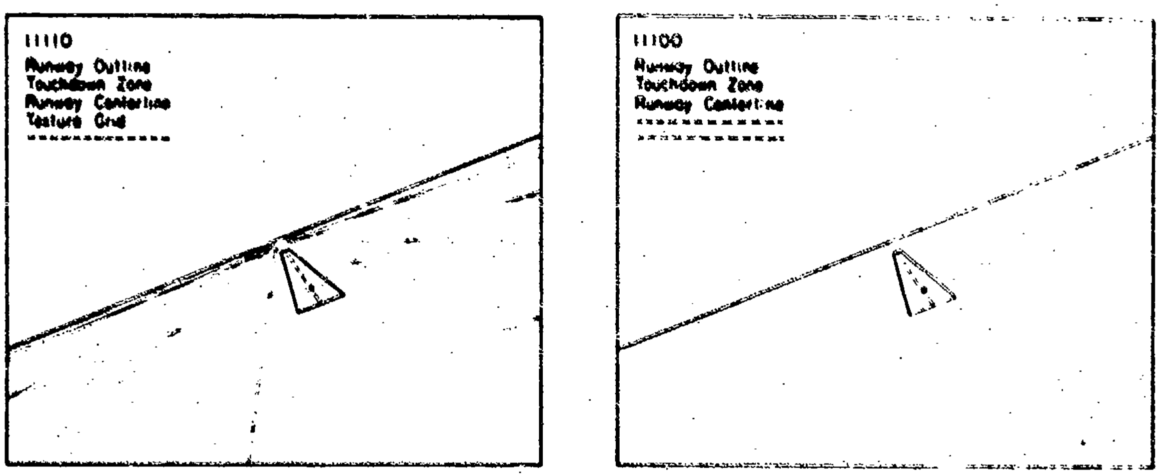

Figure 3. Group II display elements: composite of all Group II elements (left) and composite of Group II elements with Texture Grid omitted (right).

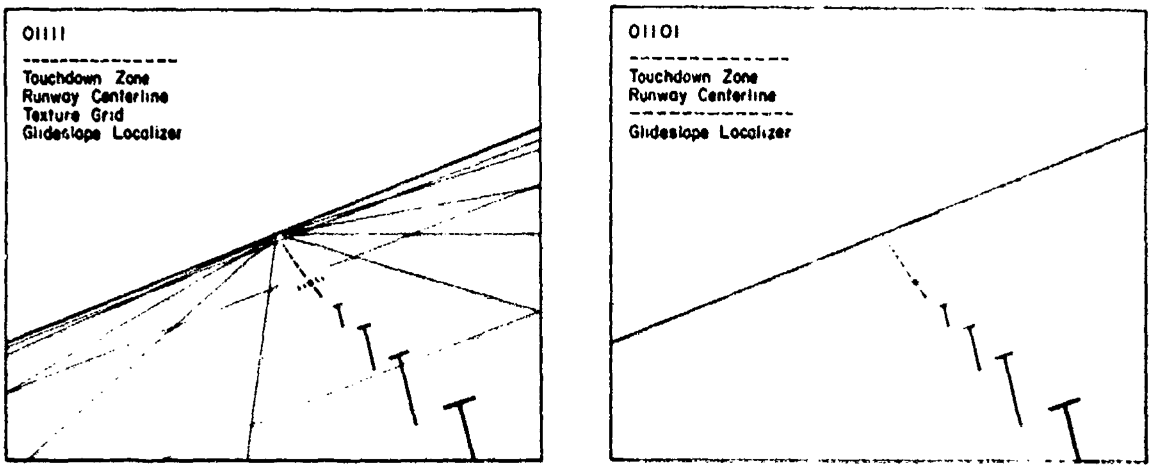

Figure 4. Group III display elements: composite of all Group III elements (left) and composite of Group III elements with Texture Grid omitted (right).

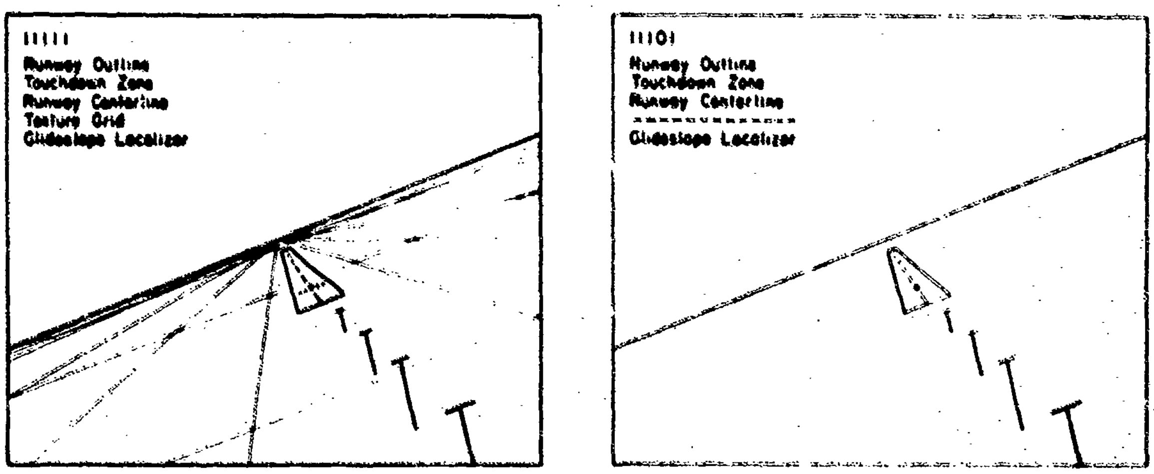

Figure 5. Group IV display elements: composite of all Group IV elements (left) and composite of Group IV elements with Texture Grid omitted (right).

TABLE 2

Coded and Real-World Values of the Flight Position and Attitude Variables in Accordance with the Central Composite Experimental Design

	Coded Values				
	$-\alpha$	-1	0	+1	$+\alpha$
Position Variables	Real-World Values				
RANGE (feet from aimpoint)	1000	2730	4460	6190	7920
VERTICAL DEVIATION (degrees from glideslope)	-1.0	-0.5	0	0.5	1.0
LATERAL DEVIATION (degrees from localizer)	-1.0	-0.5	0	0.5	1.0
Attitude Variables					
PITCH (degrees from horizontal)	0	-2	-4	-6	-8
BANK (degrees from horizontal)	-10	-5	0	5	10

of each display (Cochran and Cox, 1957). The value of α was set at 2 to make the design rotatable (Myers, 1971; Williges, 1976).

Subjects were randomly assigned to one of the four display groups, and within a group each of the eight subjects saw the eight displays in a different order in accordance with a counterbalanced design. The counterbalancing of the presentation orders caused each display to appear once in each serial position and to precede and follow every other display once across each group of eight subjects. The 36 viewpoints from which subjects responded to any one display were randomized, with the constraint that no display was presented to more than one subject in the same viewpoint order throughout the experiment.

Subjects

Thirty-two University of Illinois flight instructors volunteered to participate. Thirty males and two females between the ages of 20 and 45 each had at least 5 hours of flight time during the six months preceding their participation in the experiment.

Experimental Procedure

A subject began by reading a short introduction to the experiment and an explanation of his task. He was given a written explanation of the visual-world cues he would see according to his group assignment. All questions were answered before the next phase of the task began. The subject was then seated in the left seat of the simulator, and the arm-rest keyboard was adjusted if necessary. The keyboard and its use were explained to the subject, and any questions he had were answered.

When a subject had no further questions, he was given a series of 16 practice trials identical to the subsequent test trials. A square appeared on the display screen, signalling that the computer was ready for the trial. When the subject was ready, he pressed and released the home-base key. Immediately, a display appeared on the screen. The subject would then make a response indicating his vertical and lateral deviation relative to a 4-degree glideslope and localizer path by pressing the appropriate key on the keyboard. During the practice trials, the cues in the display were pointed out, and the appropriate responses were discussed. Practice trials consisted of both "right on" approaches with no deviation from the desired approach path and ones with vertical and lateral deviations from the desired path, all viewed from various flight attitudes.

After appearing for 15 sec, the display disappeared whether or not the subject had responded. When the computer finished recording the data for the trial and generating the next display, the box reappeared on the screen indicating that the next trial could begin. The subject again pressed the home-base key when ready. In this manner the subject had control over the pacing of the session. After the practice trials, questions were answered, and the test trials began. The 16 practice and 288 test trials required about 80 minutes. After the session the subject was given a short questionnaire, any questions he had about the experiment were answered, and he was thanked for his participation.

RESULTS

Table 3 presents the Percent Correct Responses and Median Latencies of all responses, both correct and incorrect, for each of the 32 displays at Far, Medium, and Near ranges from the runway aimpoint. "Far" and "Near" ranges from aimpoint include, respectively, the +1 and $+\alpha$ ranges and the -1 and $-\alpha$ ranges called for by the central-composite design, whereas the Medium range is the 0, or centerpoint, range called for by the design. The analyses of variance of these data are summarized in Tables 4-9.

In addition to these overall response data, the latencies of correct responses only were tabulated and analyzed, as were the incorrect responses and their associated latencies in the lateral and vertical dimensions separately. Although these detailed breakdowns are not presented, the multiple regression equations based thereon are given in Table 10. All statistical analyses of response latencies were performed on the logarithmic transformations of the raw data, thereby more closely satisfying the assumptions of normality of distributions and homogeneity of variances implicit in the application of parametric statistical treatments (Muller, 1949; Edwards, 1950).

Both an analysis of variance and a multiple regression analysis were performed on each set of data. Because the experimental variables were all dichotomous (each of the five display elements was either present or absent), the regression equations and the analyses of variance are merely alternate ways of expressing the same basic information. Of primary interest was the effect of each of the 32 visual element combinations on performance, both singly and in combination with the various other elements. Tables 4-9 show the main effects of the five display elements and their statistically reliable first-order interactions.

TABLE 3

Percent Correct Responses and Median Latencies of All Responses to Each of the 32 Displays at Far, Medium, and Near Ranges from the Touchdown Zone

DISPLAY					RANGE TO TOUCHDOWN					
					Far		Medium		Near	
Outline	TD Zone	Centerline	Texture	Glideslope	Percent Correct	Median Latency	Percent Correct	Median Latency	Percent Correct	Median Latency
0	0	0	0	0	31.9	3.52	56.9	3.10	45.8	3.81
0	1	0	0	0	25.0	3.33	66.7	3.13	55.6	3.55
0	0	1	0	0	58.3	3.16	51.4	3.05	84.7	2.79
0	0	0	1	0	48.6	3.58	55.6	2.96	57.0	3.30
0	1	1	0	0	55.6	3.27	63.9	2.85	80.6	2.71
0	1	0	1	0	44.5	3.90	54.2	3.40	57.0	4.10
0	0	1	1	0	62.5	4.03	61.1	3.69	83.3	3.43
0	1	1	1	0	44.5	4.22	51.4	3.85	81.9	3.43
1	0	0	0	0	59.7	2.72	70.8	2.54	65.3	2.63
1	1	0	0	0	59.7	3.01	73.6	3.02	75.0	2.94
1	0	1	0	0	61.1	3.50	75.0	3.02	61.1	3.75
1	0	0	1	0	68.1	3.20	62.5	3.09	58.3	3.08
1	1	1	0	0	63.9	3.13	68.1	3.30	73.6	3.16
1	1	0	1	0	75.0	3.64	68.1	3.92	61.1	3.34
1	0	1	1	0	75.0	3.45	61.1	3.20	59.7	2.88
1	1	1	1	0	75.0	2.93	61.1	3.18	62.5	2.85
0	0	0	0	1	98.6	1.60	91.7	1.44	90.1	1.93
0	1	0	0	1	97.2	1.57	91.7	1.70	87.5	1.92
0	0	1	0	1	98.6	1.78	94.5	1.73	90.3	2.11
0	0	0	1	1	98.6	1.70	93.1	1.83	91.7	2.18
0	1	1	0	1	100.0	1.67	94.5	1.79	95.8	1.76
0	1	0	1	1	98.6	1.79	93.1	2.43	93.1	2.06
0	0	1	1	1	94.5	1.67	97.2	2.04	93.1	2.04
0	1	1	1	1	95.8	1.72	98.6	1.85	98.6	1.92
1	0	0	0	1	98.6	1.95	94.5	1.98	97.2	1.82
1	1	0	0	1	98.6	1.88	98.6	1.87	94.5	1.74
1	0	1	0	1	98.6	1.64	97.2	1.84	100.0	1.36
1	0	0	1	1	98.6	1.74	97.2	1.70	97.2	1.73
1	1	1	0	1	100.0	1.57	91.7	1.88	95.8	1.68
1	1	0	1	1	100.0	1.68	93.1	1.95	97.2	1.77
1	0	1	1	1	98.6	1.67	95.8	1.73	97.2	1.62
1	1	1	1	1	94.5	1.74	94.5	1.78	93.1	1.77

TABLE 4

Summary of Analysis of Variance and Results for Percent Correct Responses at Far Range

Source of Variance	F	df	p
Runway Outline	7.856	1,28	.009
Touchdown Zone	1.059	1,28	.312
Runway Centerline	4.998	1,28	.034
Texture Grid	1.300	1,28	.264
Glideslope/Localizer	115.759	1,28	.000
Reliable Interactions			
Outline x Glideslope	6.876	1,28	.014
Centerline x Glideslope	7.466	1,28	.011

Cell Means and Effects

Outline 0 = 72.1 1 = 82.8	Presence of Runway Outline (1) resulted in a reliably higher percentage of correct responses.
Touchdown Zone 0 = 78.1 1 = 76.7	Percentages for absence (0) and presence (1) of Touchdown Zone did not differ reliably.
Centerline 0 = 75.1 1 = 79.8	Presence of Runway Centerline (1) resulted in a reliably higher percentage of correct responses.
Texture 0 = 75.4 1 = 79.5	Percentages for absence (0) and presence (1) of Texture Grid did not differ reliably.
Glideslope 0 = 56.8 1 = 98.1	Presence of Glideslope/Localizer T-bars (1) resulted in a reliably higher percentage of correct responses.
Outline x Glideslope 0/0 = 46.4 0/1 = 97.7 1/0 = 68.0 1/1 = 98.4	Presence of the Runway Outline had no evident effect when the Glideslope/Localizer was present (0/1 and 1/1), but its presence yielded a higher percentage of correct responses when the Glideslope/Localizer was absent (1/0 versus 0/0).
Centerline x Glideslope 0/0 = 51.6 0/1 = 98.6 1/0 = 62.0 1/1 = 97.6	Presence of the Runway Centerline interacted with the absence of the Glideslope/Localizer in the same way that the Runway Outline did.

TABLE 5

Summary of Analysis of Variance and Results for Percent Correct Responses at Medium Range

Source of Variance	F	df	p
Runway Outline	1.658	1,28	.208
Touchdown Zone	0.157	1,28	.312
Runway Centerline	0.039	1,28	.845
Texture Grid	1.439	1,28	.240
Glideslope/Localizer	57.491	1,28	.000

(No first-order interaction was statistically reliable.)

Cell Means and Effects

Outline 0 = 76.0 1 = 81.4	Percentages for absence (0) and presence (1) of Runway Outline did not differ reliably.*
Touchdown Zone 0 = 78.5 1 = 78.9	Percentages for absence (0) and presence (1) of Touchdown Zone did not differ reliably.
Centerline 0 = 78.8 1 = 78.6	Percentages for absence (0) and presence (1) of Runway Centerline did not differ reliably.
Texture 0 = 80.0 1 = 77.3	Percentages for absence (0) and presence (1) of Texture Grid did not differ reliably.
Glideslope 0 = 62.6 1 = 94.8	Presence of Glideslope/Localizer T-bars (1) resulted in a reliably higher percentage of correct responses.

*The corresponding regression analysis (see Table 10), which took into account all of the individual response data for the ten replications of the centerpoint of the central composite experimental design, showed the presence of the Runway Outline to contribute reliably to correct responses at Medium Range ($p < .05$). The analysis of variance included only the first of the ten centerpoint responses by each subject.

TABLE 6

Summary of Analysis of Variance and Results for Percent Correct Responses at Near Range

Source of Variance	F	df	p
Runway Outline	0.002	1,28	.970
Touchdown Zone	1.258	1,28	.272
Runway Centerline	21.958	1,28	.000
Texture Grid	0.073	1,28	.790
Glideslope/Localizer	39.037	1,28	.000
Reliable Interactions			
Outline x Centerline	23.910	1,28	.000
Centerline x Glideslope	12.712	1,28	.001

Cell Means and Effects

Outline 0 = 80.4 1 = 80.6	Percentages for absence (0) and presence (1) of Runway Outline did not differ reliably.
Touchdown Zone 0 = 79.5 1 = 81.4	Percentages for absence (0) and presence (1) of Touchdown Zone did not differ reliably.
Centerline 0 = 76.5 1 = 84.5	Presence of Runway Centerline (1) resulted in a reliably higher percentage of correct responses.
Texture 0 = 80.8 1 = 80.1	Percentages for absence (0) and presence (1) of Texture Grid did not differ reliably.
Glideslope 0 = 66.4 1 = 94.5	Presence of Glideslope/Localizer T-bars (1) resulted in a reliably higher percentage of correct responses.
Outline x Centerline 0/0 = 72.2 0/1 = 88.5 1/0 = 80.7 1/1 = 80.4	Presence of Runway Centerline in the absence of a Runway Outline (0/1) resulted in a disproportionately high percentage of correct responses.
Centerline x Glideslope 0/0 = 59.4 0/1 = 93.6 1/0 = 73.4 1/1 = 95.5	Although the highest percentage of correct responses occurred when both Glideslope/Localizer and Runway Centerline were present (1/1), the percentage was disproportionately high when either was present in the absence of the other (1/0 or 0/1), and the percentage with Glideslope/Localizer present in the absence of Runway Centerline (0/1) was nearly equal to that with both present.

TABLE 7

Summary of Analysis of Variance and Results for Median Latencies of All Responses at Far Range

Source of Variance	F	df	p
Runway Outline	0.124	1,28	.728
Touchdown Zone	0.000	1,28	.988
Runway Centerline	0.007	1,28	.936
Texture Grid	3.232	1,28	.083
Glideslope/Localizer	23.496	1,28	.000

(No first-order interaction was statistically reliable.)

Cell Means and Effects

Outline	
0 = 2.47 sec	Latencies for absence (0) and presence (1) of
1 = 2.34	Runway Outline did not differ reliably.
Touchdown Zone	
0 = 2.40	Latencies for absence (0) and presence (1) of
1 = 2.40	Touchdown Zone did not differ reliably.
Centerline	
0 = 2.41	Latencies for absence (0) and presence (1) of
1 = 2.40	Runway Centerline did not differ reliably.
Texture	
0 = 2.33	Latencies for absence (0) and presence (1) of
1 = 2.48	Texture Grid did not differ reliably.
Glideslope	
0 = 3.39	Presence of Glideslope/Localizer T-bars (1) resulted
1 = 1.71	in reliably shorter response latencies.

TABLE 8

Summary of Analysis of Variance and Results for Median Latencies of All Responses at Medium Range

Sources of Variance	F	df	p
Runway Outline	0.001	1,28	.972
Touchdown Zone	3.118	1,28	.088
Runway Centerline	0.673	1,28	.419
Texture Grid	5.324	1,28	.029
Glideslope/Localizer	12.459	1,28	.001
Reliable Interaction			
Touchdown Zone x Centerline	4.791	1,28	.037

Cell Means and Effects

Outline 0 = 2.42 sec 1 = 2.40	Latencies for absence (0) and presence (1) of Runway Outline did not differ reliably.
Touchdown Zone 0 = 2.33 1 = 2.48	Latencies for absence (0) and presence (1) of Touchdown Zone did not differ reliably.
Centerline 0 = 2.38 1 = 2.44	Latencies for absence (0) and presence (1) of Runway Centerline did not differ reliably.
Texture 0 = 2.30 1 = 2.52	Presence of Texture Grid (1) resulted in reliably longer response latencies.
Glideslope 0 = 3.19 1 = 1.82	Presence of a Glideslope/Localizer T-bars (1) resulted in reliably shorter response latencies.
Touchdown Zone x Centerline 0/0 = 2.24 0/1 = 2.43 1/0 = 2.53 1/1 = 2.44	Presence of Touchdown Zone marker in the absence of a Runway Centerline (1/0) resulted in disproportionately long response latencies, whereas its presence made no reliable difference when the Runway Centerline was present (0/1 versus 1/1).

TABLE 9

Summary of Analysis of Variance and Results for Median Latencies of All Responses at Near Range

Source of Variance	F	df	p
Runway Outline	0.581	1,28	.452
Touchdown Zone	0.168	1,28	.685
Runway Centerline	1.542	1,28	.225
Texture Grid	1.306	1,28	.263
Glideslope/Localizer	14.087	1,28	.001
Reliable Interactions			
Outline x Texture	4.264	1,28	.048
Touchdown Zone x Texture	4.742	1,28	.038

Cell Means and Effects

Outline 0 = 2.58 sec 1 = 2.31	Latencies for absence (0) and presence (1) of Runway Outline did not differ reliably.
Touchdown Zone 0 = 2.46 1 = 2.43	Latencies for absence (0) and presence (1) of Touchdown Zone did not differ reliably.
Centerline 0 = 2.50 1 = 2.39	Latencies for absence (0) and presence (1) of Runway Centerline did not differ reliably.
Texture 0 = 2.41 1 = 2.48	Latencies for absence (0) and presence (1) of Texture Grid did not differ reliably.
Glideslope 0 = 3.21 1 = 1.86	Presence of Glideslope/Localizer T-bars (1) resulted in reliably shorter response latencies.
Outline x Texture 0/0 = 2.49 0/1 = 2.70 1/0 = 2.34 1/1 = 2.29	Presence of the Texture Grid in the absence of a Runway Outline (0/1) resulted in disproportionately long response latencies, whereas its presence in combination with a Runway Outline (1/1) resulted in the shortest latencies.
Touchdown Zone x Texture 0/0 = 2.48 0/1 = 2.44 1/0 = 2.33 1/1 = 2.53	Presence of the Touchdown Zone in the absence of a Texture Grid (1/0) resulted in disproportionately short response latencies, whereas its presence in combination with Texture Grid (1/1) resulted in slightly longer latencies than with Texture Grid alone (0/1).

TABLE 10

Regression Equations, with their Associated Multiple Correlation Coefficients, for the Presence (1) or Absence (0) of the Various Display Elements at Near (N), Medium (M), and Far (F) Ranges from the Runway Aimpoint (underlined regression coefficients are statistically reliable; $p < .05$).

DISPLAY ELEMENT

PREDICTED VALUE		Runway Outline x_1	Touchdown Zone x_2	Runway Centerline x_3	Texture Grid x_4	Glideslope Localizer x_5	MULTIPLE CORRELATION
Percent Correct Responses:							
y_N	=	$.000x_1$	$+.039x_2$	$+.\underline{165}x_3$	$-.014x_4$	$+.\underline{584}x_5$	$\underline{R} = .632$
y_M	=	$.\underline{117}x_1$	$+.009x_2$	$-.006x_3$	$-.058x_4$	$+.\underline{695}x_5$	$\underline{R} = .707$
y_F	=	$.\underline{185}x_1$	$-.024x_2$	$+.081x_3$	$+.072x_4$	$+.\underline{713}x_5$	$\underline{R} = .745$
Median Latency, Correct Responses:							
y_N	=	$-.092x_1$	$+.019x_2$	$-.007x_3$	$+.059x_4$	$-.\underline{488}x_5$	$\underline{R} = .546$
y_M	=	$-.012x_1$	$+.061x_2$	$-.006x_3$	$+.051x_4$	$-.\underline{462}x_5$	$\underline{R} = .500$
y_F	=	$-.062x_1$	$+.016x_2$	$-.005x_3$	$+.038x_4$	$-.\underline{569}x_5$	$\underline{R} = .608$
Median Latency, All Responses:							
y_N	=	$-.098x_1$	$-.013x_2$	$-.043x_3$	$+.029x_4$	$-.\underline{520}x_5$	$\underline{R} = .582$
y_M	=	$.000x_1$	$+.056x_2$	$+.021x_3$	$+.079x_4$	$-.\underline{499}x_5$	$\underline{R} = .540$
y_F	=	$-.039x_1$	$+.000x_2$	$-.002x_3$	$+.056x_4$	$-.\underline{620}x_5$	$\underline{R} = .656$
Percent Incorrect Responses, Lateral Deviation:							
y_N	=	$-.\underline{191}x_1$	$-.064x_2$	$-.\underline{132}x_3$	$-.064x_4$	$-.\underline{293}x_5$	$\underline{R} = .384$
y_M	=	$-.\underline{148}x_1$	$+.010x_2$	$-.069x_3$	$-.\underline{148}x_4$	$-.\underline{465}x_5$	$\underline{R} = .515$
y_F	=	$-.\underline{235}x_1$	$+.026x_2$	$-.\underline{204}x_3$	$-.108x_4$	$-.\underline{390}x_5$	$\underline{R} = .511$
Median Latency, Incorrect Lateral Responses:							
y_N	=	$-.072x_1$	$-.090x_2$	$-.\underline{155}x_3$	$+.020x_4$	$-.\underline{322}x_5$	$\underline{R} = .386$
y_M	=	$-.076x_1$	$+.054x_2$	$-.098x_3$	$-.079x_4$	$-.\underline{481}x_5$	$\underline{R} = .509$
y_F	=	$-.\underline{212}x_1$	$+.048x_2$	$-.097x_3$	$-.041x_4$	$-.\underline{414}x_5$	$\underline{R} = .488$
Percent Incorrect Responses, Vertical Deviation:							
y_N	=	$.\underline{133}x_1$	$-.011x_2$	$-.079x_3$	$+.056x_4$	$-.\underline{519}x_5$	$\underline{R} = .567$
y_M	=	$-.052x_1$	$-.018x_2$	$+.033x_3$	$+.\underline{163}x_4$	$-.\underline{574}x_5$	$\underline{R} = .600$
y_F	=	$-.057x_1$	$-.025x_3$	$+.083x_3$	$+.000x_4$	$-.\underline{621}x_5$	$\underline{R} = .630$
Median Latency, Incorrect Vertical Responses:							
y_N	=	$.000x_1$	$-.028x_2$	$-.\underline{110}x_3$	$-.020x_4$	$-.\underline{457}x_5$	$\underline{R} = .510$
y_M	=	$.042x_1$	$+.057x_2$	$+.039x_3$	$+.060x_4$	$-.\underline{532}x_5$	$\underline{R} = .568$
y_F	=	$-.043x_1$	$+.003x_2$	$+.004x_3$	$+.020x_4$	$-.\underline{649}x_5$	$\underline{R} = .654$

The findings from this study of final approach position judgments by flight instructors, in response to statically presented images of computer-generated skeletal "airport" scenes, can be summarized as follows:

1. The accuracy and speed of judgments are enhanced more by the presence of synthetic guidance information than they are by the perspective projections of any combination of four "contact analog" elements representative of the real-world visual scene on an approach to an airport. When the four T-bars that defined an imaginary Glideslope/Localizer beam (a "highway in the sky") were present, position judgments were rapid (less than 2 sec versus more than 3 sec, on average) and quite precise (in some conditions without error during 36 trials from various positions by each of eight pilots).
2. The relative contributions of the real-world cues varied as a function of range from runway aimpoint. Specifically, in the absence of the synthetic guidance symbols, judgments were consistently better when the contact analog elements included the Runway Outline, particularly at Far ranges from the touchdown aimpoint (which was always visible), whereas the presence of the Runway Centerline contributed more at Near ranges.
3. Neither the presence of Touchdown Zone markings (in addition to the ever present aimpoint) nor the surface Texture Grid

contributed reliably to the overall accuracy or speed of judgments. In fact, the presence of the Texture Grid was consistently accompanied by slower judgments, and at Medium range it resulted in reliably more incorrect responses in the vertical dimension.

4. There were several statistically reliable first-order interactions between visual elements as indicated in Tables 4, 6, 8, and 9: most notably, the presence of the Runway Outline contributed less when the Glideslope/Localizer T-bars were present than when they were absent, and the Texture Grid contributed favorably in the presence of the Runway Outline whereas it interacted unfavorably with the Touchdown Zone markers, and the latter resulted in disproportionately slow responses in the absence of the Runway Centerline.

DISCUSSION

The generalizability of these findings is qualified by several factors. The pilots' judgments were made in response to the sudden appearance of static projections of skeletal visual scenes. The sudden appearance of the scene can be considered roughly analogous to breaking out of an overcast on a final instrument approach to a runway. The dynamics of movement toward the runway were not represented, and the scene disappeared immediately following the pilot's response with no indication of the correctness or incorrectness of the repsonse.

The superior performance associated with a synthetic perspective representation of an extended Glideslope/Localizer approach path illustrates the effectiveness of including specific guidance information, clearly encoded, relative to the perspective representation of real-world "contact analog" scenes. This is not to say that dynamic contact analog presentations alone do not contribute to spatial orientation, but it appears that such displays do not support the precise position and projected flight path discriminations required for all-weather instrument flight. The inclusion of guidance and/or prediction information in addition to the essential real-world elements in contact analog displays supports both rapid orientation and accurate control.

The linear regression equations presented in Table 10 account for a substantial proportion of the experimental variance observed but not for all of the variance that can be isolated. In view of the several reliable interactions among some of the visual elements, revealed by the analyses of variance, regression equations that included the corresponding higher-order terms would similarly account for additional increments of variance and thereby yield higher multiple correlation coefficients. The values of these higher-order regression coefficients can be determined directly from the analyses of variance for dichotomous variables.

The use of a central-composite design, in conjunction with a conventional factorial combination of experimental display variables, served a somewhat different purpose from that for which CCDs are normally used. In this case, its purpose was to provide an efficient sampling of flight variables likely to affect the pilots' discrimination task, namely, three positional variables (lateral and vertical deviation from desired flight path and range from runway aimpoint) and two flight attitude variables (pitch and bank). Thus the task variables sampled in accordance with the CCD were not experimental variables in the usual sense, although they could be treated as such, and the data obtained could be submitted to overall regression analyses in which the dependent performance variables would be related to these continuous task variables as well as to the discrete display variables of primary interest.

The testing of pilots' responses to static presentations of computer-generated visual displays was a logical initial step in the screening of elements of real-world airport scenes that support judgments of flight attitude and position on final approaches to landings. The logical next step is the measurement of dynamic, closed-loop pilot performances in response to a relatively limited subset of the 32 displays studied statically in this experiment. In fact, research currently in progress has already shown that the four essential contact analog elements — horison, runway outline, runway centerline, and landing aimpoint (or target) — do result in consistently accurate simulated landings by skilled pilots.

Furthermore, as would be predicted from the results of this experiment, the inclusion of synthetic guidance information, encoded in a form similar to that studied in this experiment, has a comparably beneficial effect upon dynamic, closed-loop landing performance. When presented and withdrawn automatically in accordance with an appropriate adaptive logic, the synthetic guidance cues also appear to facilitate the initial acquisition of landing skills and the subsequent transfer of those skills to situations in which synthetic guidance is not presented (Lintern, doctoral research in progress).

In view of the evident benefits of the integrated presentation of guidance information within true-perspective contact analog scenes, the possible interactive benefits of including dynamic flight-path prediction symbology in the same integrated display should also be investigated. An illustration of how flight-path prediction and a modified "highway in the sky" might be combined in a computer-generated contact analog is shown in Figure 6. If flight-path prediction is presented in this way, the resulting flight control task becomes one of pursuit rather than compensation. Pursuit displays, by definition, have at least two moving indices within a common reference system, one representing the pilot's own airplane or projected flight path and the other representing his desired position or flight path.

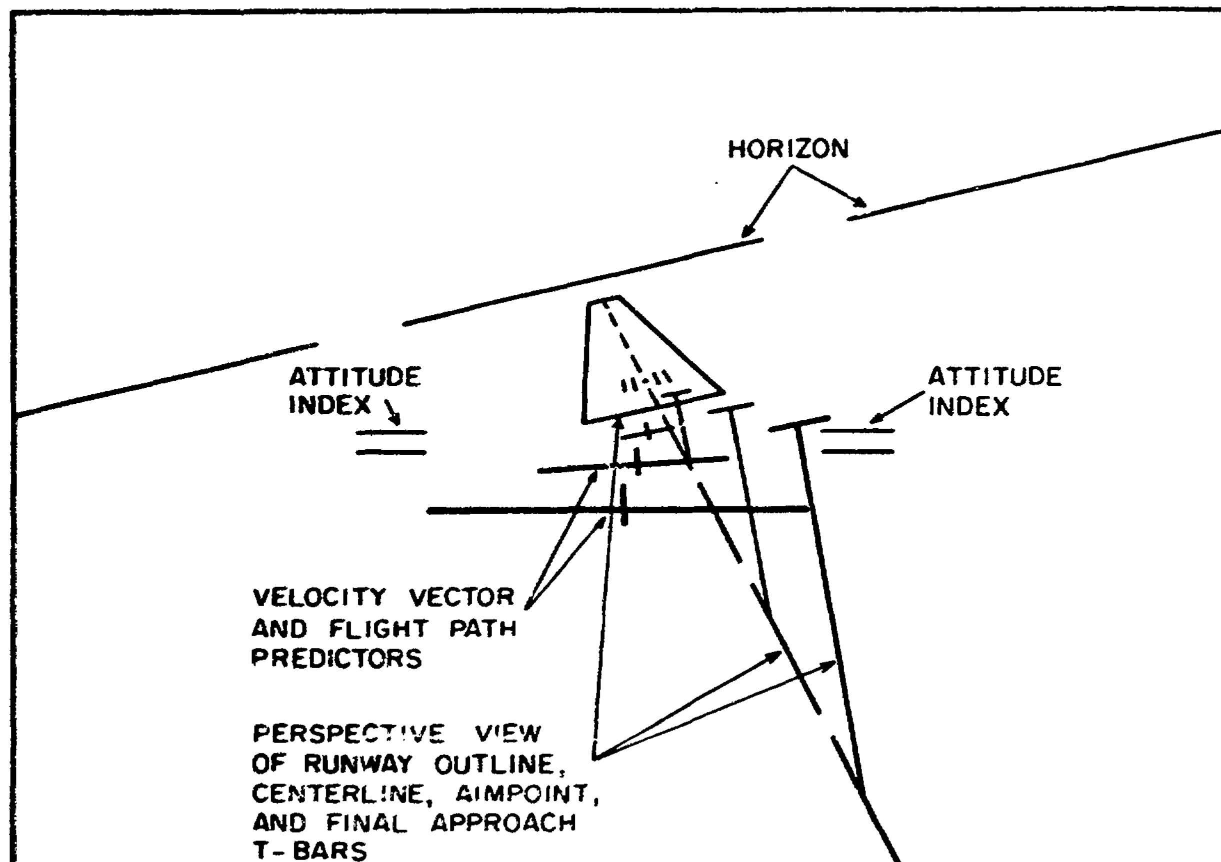

Figure 6. Integrated display of flight-path prediction, desired final approach path, and essential contact analog elements.

Any flight maneuver, including ones defined in relation to surface objects such as airport runways or ground targets, can be reduced to an abstract, error-nulling task with appropriate sensing, computing, and symbolic display devices. However, when the pilot's tracking task is reduced to that of a simple amplifier providing control inputs proportional to displayed error signals, his unique potential contributions can be lost, namely: resolving uncertainty, judging the reasonableness of the situation, and adjusting his <u>indices of desired performance</u> accordingly. It is by facilitating his intelligent action in the face of opportunity or adversity that pictorial situation displays of the type developed and tested in this program may contribute most directly to flight safety and mission success.

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