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EVALUATION OF SEVERAL TV DISPLAY SYSTEMS FOR VISUAL SIMULATION OF THE LANDING APPROACH

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16. Abstract

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The use of color had two main effects on pilot performance in the landing approach. The touchdown distance and standard deviations increased more for the monitor displays, and the touchdown rates of descent were slightly lower. With quasicollimation, the standard deviations of touchdown distance increased, and the rate-of-descent standard deviations decreased in a direction more favorable with the actual flight data; an association between the standard deviations of rate of descent and touchdown distance suggests that a corresponding decrease in the deviation of rate of descent will be offset with an increase in the deviations of touchdown distance. The time outside the glide-slope error limits was less with the monitor display than with the projector display, and the lateral localizer error was smaller for the projector display because the pilots intercepted the runway center line at a greater distance from the threshold. With reduced resolution, there was a slight change in the touchdown distance and the standard deviation; for the flights made without color, the landings were predominantly to the right of the runway center line with twice the standard deviation.

The pilots were more critical of the black and white variation for either display, and favored more use of a color system. Advantages cited for a color system included greater pilot relaxation, decreased fatigue, better picture quality, and more realistic depth perception, particularly with the monitor display. With regard to the reduced-resolution monitor display, the pilots also noted a loss in depth perception and height references, increased visual fatigue, and increased efforts for a reasonable approach in comparison with the projector display. The objective performance measures of the study were reasonably consistent with the pilots' subjective evaluations and comments.

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NOTATION

A	angular magnification, dimensionless
D	diameter of lens, in.
D'	exit window of lens and monitor display, in.
f	lens focal length, in.
h	pilot's eye-to-lens principal plane distance, in.
h_e	altitude error from given glide slope, ft
h'	pilot's eye-to-lens distance, in.
$\bar{\dot{h}}$	mean touchdown rate of decent, fps
K	flight director feed forward lateral channel compensating gain, rad/rad
K_{h_e}	altitude error gain, 1/ft
K_ϵ	lateral localizer beam error gain, rad/rad
K_ϵ'	flight director lateral channel feed forward localizer beam error gain, rad/rad
K_θ	pitch gain, rad/rad
K_ϕ	roll gain, rad/rad
K_θ'	flight director lateral channel feed forward bank angle gain, rad/rad
K_ψ	heading gain, rad/rad
R	horizontal width of the television CRT face, in.
s	Laplace operator, 1/sec
t	time outside longitudinal flight path (±0.5°), sec
u	object distance, in.
V_T	total image distance from pilot's eye, ft
$\bar{X}$	mean touchdown distance from threshold, ft
$\bar{Y}$	mean touchdown center-line offset, ft

α	direct view subtended angle of the monitor display, deg
α'	collimated image field of view, deg
γ	aircraft longitudinal flight path, deg
δ	thickness of lens, in.
ϵ'	lateral localizer beam error, rad
$\epsilon_{lat_{rms}}$	lateral localizer beam error (rms), deg
$\epsilon_{long_{rms}}$	longitudinal glide-slope error (rms), deg
θ	body axis pitch attitude angle, rad
θ_c	flight director vertical channel pitch command, rad
$\sigma_{\dot{h}}$	standard deviation of touchdown rate of descent, fps
σ_X	standard deviation of touchdown distance from threshold, ft
σ_Y	standard deviation of touchdown center-line offset, ft
ϕ_c	flight director lateral steering channel roll command, rad
ω	flight director pitch command dominant root, rad
ω_1	flight director lateral channel feed forward numerator root, rad
ω_2	flight director lateral channel feed forward denominator dominant root, rad
ω_3	flight director lateral channel feed forward denominator dominant root, rad

EVALUATION OF SEVERAL TV DISPLAY SYSTEMS FOR VISUAL SIMULATION OF THE LANDING APPROACH*

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SUMMARY

A study has been conducted to determine the effect of several variations of two types of visual display systems on subjective pilot evaluations and objective measures of performance in the landing approach. Two types of flight approaches were made with either a projector or quasicollimated monitor visual display: (1) the instrument approach, and (2) the visual approach without the normal cockpit instrumentation assistance. The variables examined were color; differences between displays due to quasicollimation of the monitor display; and reduced resolution as related to brightness, contrast, and sharpness.

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INTRODUCTION

In most actual aircraft landings, pilots view a realistic scene comprising natural visual cues. The most common type of visual simulation attachments recreate scenes, analogs of the real world, which are displayed to the pilot by means of a television monitor or projection screen. Most visual simulation systems inherently lack the realism of actual flight, particularly for the critical maneuvers of aircraft takeoff and landing. Presently, because of limitations in state-of-the-art television resolution and related problems in optical technologies, these systems fail to provide, with sufficiently high fidelity, all the visual cues found in the real world. These visual simulation attachments nevertheless are progressively assuming an important position in research and training programs for advanced aircraft and spacecraft.

There is an increasing demand for higher visual simulation fidelity (refs. 1 and 2) to substitute for a greater portion of flight training as a means of offsetting the high cost of current pilot training programs. For the most part, experience with many of the visual simulation attachments and aircraft simulators has not demonstrated adequate agreement between simulator and actual flight performance data (ref. 3). The disparity between simulator and flight appears greatest in the touchdown rate of descent, which is normally 1 to 2 fps (refs. 4-6) in actual flight compared with 4 to 16 fps in the simulator (ref. 3). These excessive rates also may be due, in part, to lack of motion feedback and vestibular and kinesthetic cues. Experienced test pilots performing the final approach and touchdown maneuver required up to 10 hr of practice with the simulation to attain a consistent level of performance equal to flight (ref. 7).

Since little work has been done to adequately explain these and other differences between the aircraft simulator and actual flight data, it is necessary to establish the research and training effectiveness of the visual simulation and to relate the display characteristics with man-system performance. Such information along these lines would provide a useful basis for defining specifications and requirements for more advanced simulators with visual simulation attachments.

Many variables influence the fidelity of the visual simulation. To determine which particular variables are most useful in achieving a higher level of realism, the relative importance of some of the basic visual display properties was evaluated. The display properties are closely related to some of the visual cues, which, in turn, may also be intimately related to the image fidelity. Therefore, the study included variations in pilot performance and pilot acceptance measures or opinion as related to such properties as color, resolution, and collimation.

The following displays were evaluated for the effects of color versus black and white, and differences in resolution, brightness, and contrast: (1) a projection-type display now used in aircraft simulators, and (2) an approximately (quasi) collimated television monitor display. The influence of further degradation of resolution was controlled with the use of the television monitor display. The variations of performance and pilot opinion obtained with a simulated DC-8 jet transport in the landing approach are presented for each type of display.

EQUIPMENT AND METHOD

Experimental Setup

The DC-8 jet transport dynamics were simulated on an Applied Dynamics, Inc., 256 analog computer programmed to represent a six-degrees-of-freedom simulation (ref. 8). The principal dynamics included a longitudinal response (both the phugoid and short period), the lateral response (including the spiral, roll subsidence, and dutch roll modes), and ground effect characteristics. The fixed-base cab and pilot's station (fig. 1) were also provided with a flight director guidance system (appendix A) and a typical instrument panel layout, variable flap position, variable throttle position, engine sound system, and a force-feel control system.

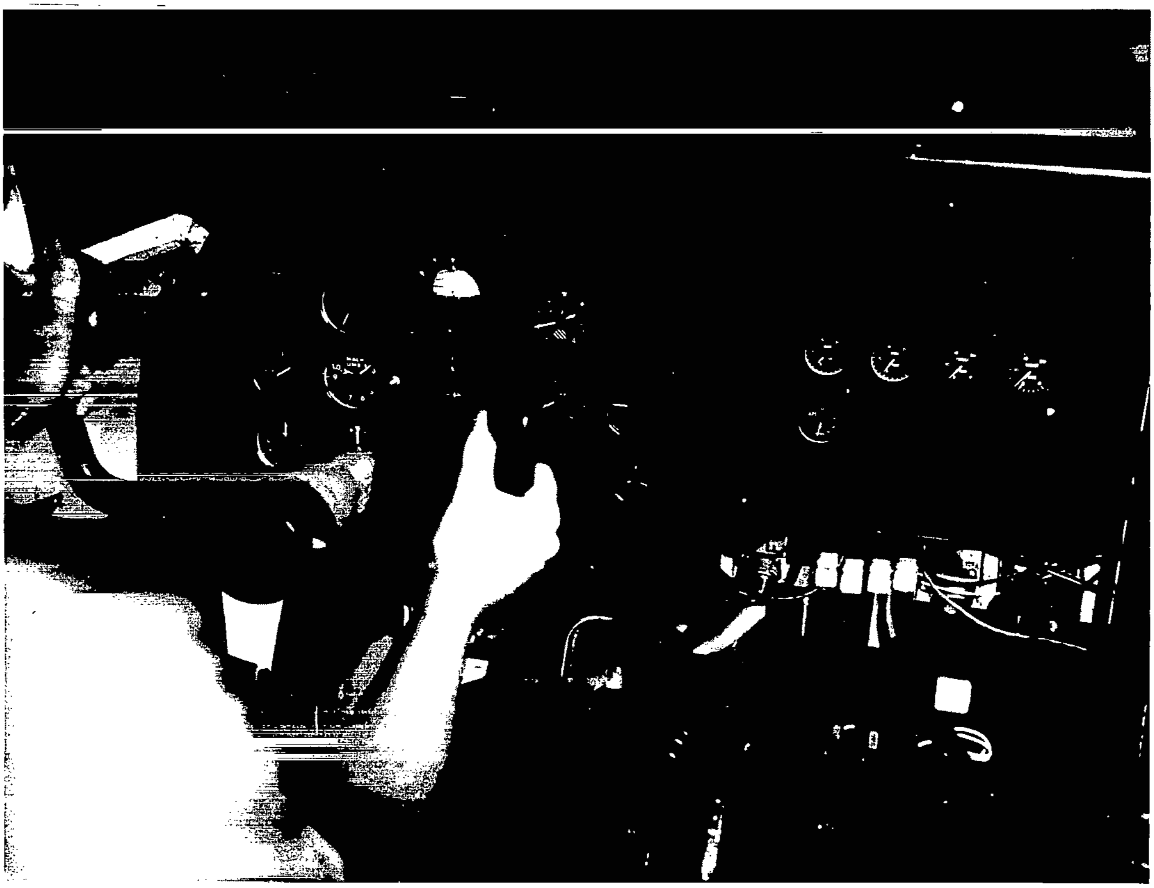


Figure 1.- Pilot's station and instrument panel.

The essential components of the General Precision Systems visual flight attachment are a servo-driven television camera and optical probe servoed to provide the rotational motions of the aircraft (appendix B), runway model (scaled at 2000 ft = 1 ft), and projection or monitor viewing

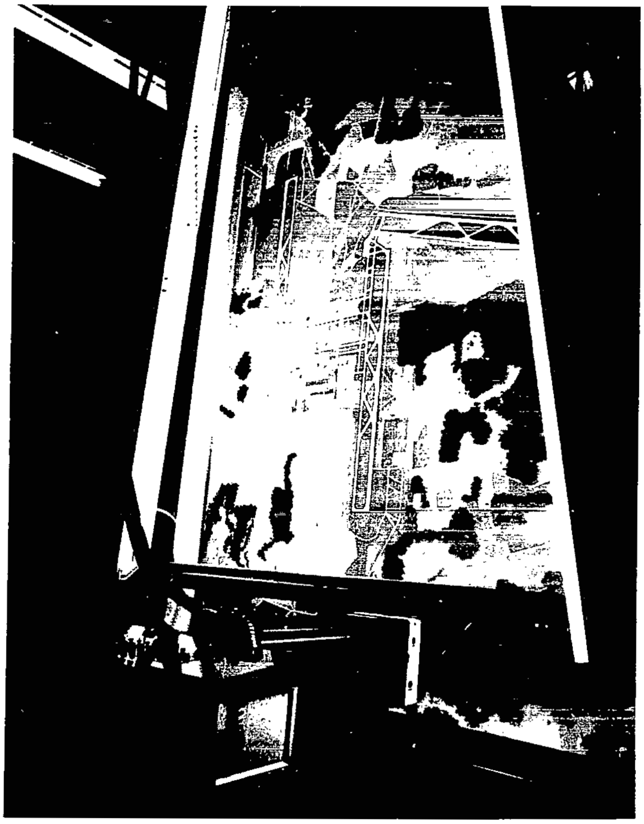


Figure 2.- Landing approach model assembly.

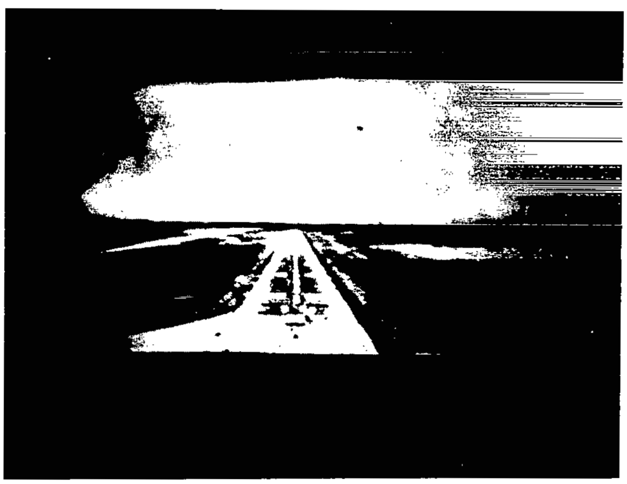


Figure 3.- Pilot's eye view of the projector approach runway display.

systems. The visual scene was created from a runway model of Dulles International Airport on a one-degree-of-freedom movable belt driven past a five-degrees-of-freedom camera and optical probe assembly (fig. 2). The Marconi television camera, capable of either color or black/white (monochrome) signal transmission, was a 625-line, 50 fields per second, 2:1 interface, 4:3 aspect ratio system.

One of the two display systems used was a Marconi (Schmidt type) screen-projection system with a unity picture perspective, color or black and white viewing capability, and a screen brightness gain of 2.5. The field of view afforded the pilot, located 10 ft from the screen, was 48° horizontal and 36° vertical (appendix C). A negligible keystone effect from the tilt of the screen, observed from the pilot's position, was adjusted. Figure 3 is a photograph of the landing approach scene taken at the pilot's eye position for the projector display.

The second display system comprised two 25-in.-diameter, 50-in.-focal-length, planoconvex, acrylic collimating lenses, and a Conrac 21-in. monitor with color or black and white viewing capability (fig. 4). For completely relaxed eye accommodation, this viewing system normally would be considered a true collimating, virtual-image optical system with the image located at infinity, provided the monitor was positioned at the focal plane of the lens system; for purposes of this experiment, however, the image plane was located 10.88 ft (appendix C) from the pilot, resulting in changes of true collimation to that of an approximate (quasi) collimation. The pilot was afforded a 40.6°-horizontal, 30.4°-vertical field of view, as well as a unity picture perspective (appendix C). Figure 5 is a photograph of the landing approach scene taken at the pilot's eye position for the quasicollimated monitor.

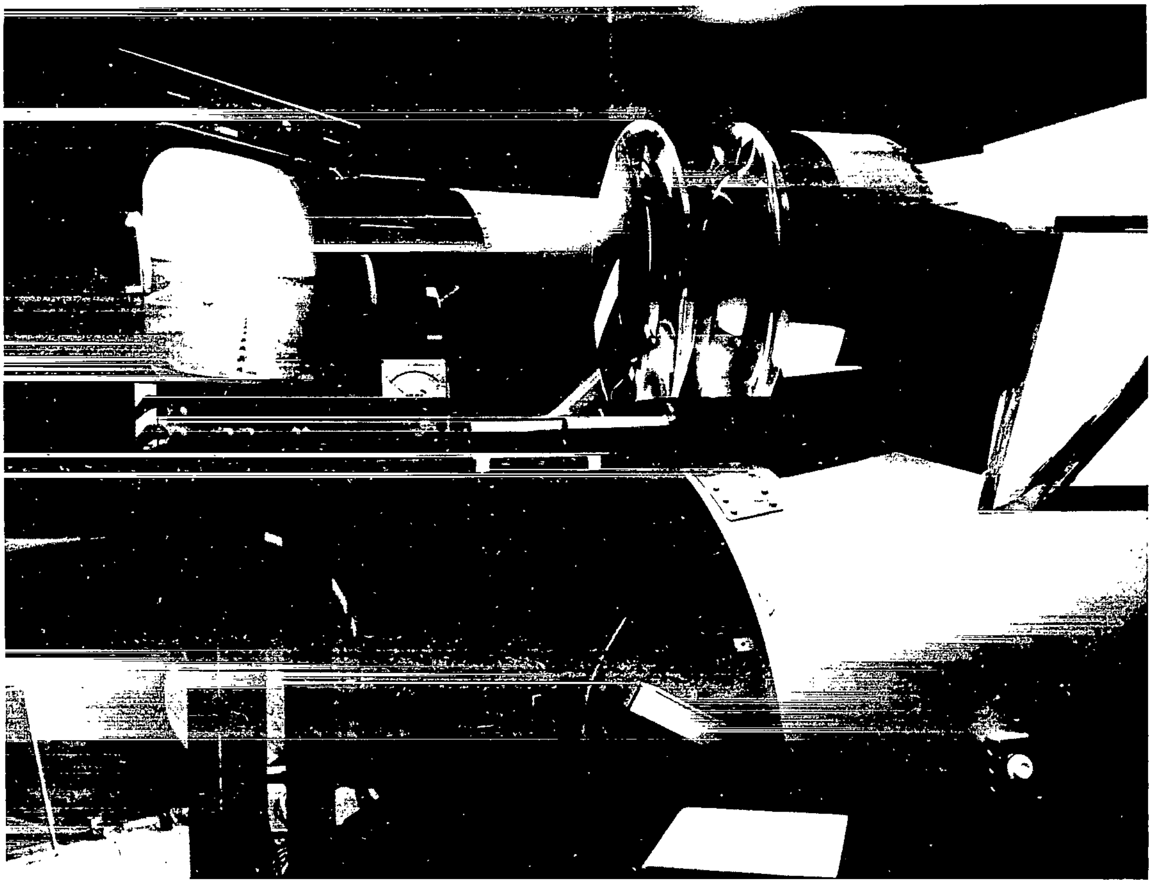


Figure 4.- Fixed base cab, collimating lenses, and monitor display assembly.

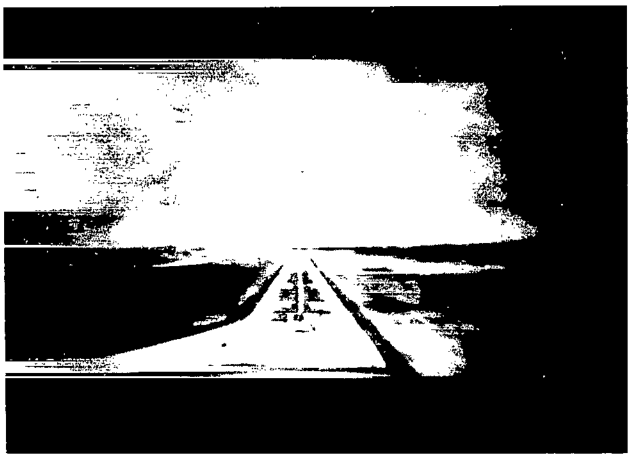


Figure 5.- Pilot's eye view of the monitor approach runway display.

Reduced resolution was accomplished by adjusting the monitor CRT focusing coil to defocus the TV line scan format of the monitor. This adjustment does not affect the bandwidth, beam current, or intensity, but does affect the overall sharpness of the display (appendix D).

Table 1 summarizes the significant display configuration variables, showing differences in resolution, brightness, and contrast, for the conditions between the two visual displays; these variables are discussed in greater detail in the appendixes.

TABLE 1.- DISPLAY SYSTEM VARIABLES

Variable	Display system: Monitor, Color	Monitor, B/W	Projector, Color	Projector, B/W	Monitor, Reduced resolution, Color	Monitor, Reduced resolution, B/W
Maximum vertical resolution (TV lines)	356	356	304.8	304.8	228.6	228.6
Maximum horizontal resolution (TV lines)	474	474	395	395	305	305
White brightness (ft-L)	24.3	22.7	18.3	15	24.3	22.7
Runway brightness (ft-L)	20.5	17	15.5	10.5	20.5	17
Contrast, percent	17.7	20.7	11.4	13.3	17.7	20.7

EXPERIMENTAL PROCEDURES

Seven professional pilots participated in the experiment, all of whom are currently flying. Each pilot's flight and simulator experience is briefly summarized in table 2. Two were qualified in the DC-8; the rest were qualified in the Boeing 707, 720, and B-52 or B-47 aircraft. It should be noted that the pilots had little or no exposure to visual simulation attachments in aircraft simulators.

TABLE 2.- PILOT RÉSUMÉ

Pilot	Present rating	Jet, hr	Reciprocating, hr	Simulator experience, hr
A	1st off., B-707 Capt., B-727	1500	2.400	130
B	1st off., B-720	1700	2,500	150
C	A.F. aircraft cmdr., B-47, B-52, B-36	4300	4,000	200
D	1st off., flt. engr., DC-8	3100	1,900	250
E	Capt., B-707	3500	30,000	250
F	Capt., DC-8	4000	19,700	240
G	Capt., B-707	1500	13,000	750

Visual and instrument final approaches were studied. The visual approach was made with only two instruments available, airspeed and altitude, which were monitored at the pilot's discretion. The purpose of this approach was to force the pilot into establishing visual dependence on the out-the-window visual cues of either display system during the final approach. Data obtained from the visual approaches provided the basis for direct comparisons between the two displays and an evaluation of the effects of color and degraded resolution. The purpose of the instrument approach was to generate baseline data similar to flight data obtained with the normal flight management, procedures, and instrumentation [including an instrument landing system (ILS) and a flight director] usually available for an instrument final approach. The visual display system continued to operate without restriction and was available to the pilot at any time according to the individual piloting techniques used in monitoring the instrument panel during the approach.

Prior to any simulator flying, the following set of instructions was given to each subject pilot to familiarize him with the study and the steps used during the experimental sessions:

> This simulator system includes a fixed-base instrumented airline type cab that has several methods of providing a closed-circuit TV color or black and white visual simulation of a typical landing approach or takeoff scene, and a computer complex to provide the appropriate simulation of a DC-8 aircraft and visual display dynamics. The objectives of this study requiring the use of this simulation system are: the evaluation and importance of color in TV display systems, both for screen projection and collimated TV monitor displays, and the effect of reducing the resolution of the collimated TV monitor display.
>
> The two following types of flights, which will be studied in order to evaluate the conditions between the two visual displays, are: (1) a visual flight with only the airspeed and altimeter instruments, and (2) an instrument flight with a complete instrument complement, including a flight director system. For the visual approaches, each pilot is to use his best judgment in trying to converge on the position normally supplied by the ILS system based on the available display system visual cues; execute a stable, well-controlled approach to the runway threshold; and make a termination maneuver including a flare and touchdown. For the instrument final approaches, each pilot is to use his own flight management and instrument procedures normally employed during a typical approach and landing.

The experimental initial conditions for all flights required four incremental altitude changes (±100 ft and ±200 ft) and four incremental lateral offset changes (±600 ft and ±1200 ft) established according to a Latin square experimental design for each instrument and visual approach. The initial flight, standardized for all pilots, was conducted at an altitude of 1387 ft above the runway at an approach speed of 135 knots, flaps extended 25°, landing gear down, 25,000-ft ground distance to runway threshold, flight path angle of -3° from the horizontal, and 5 miles visibility. The ILS glide slope and localizer transmitters were located 1500 ft and 11,000 ft, respectively, beyond the runway threshold. The beam width of the localizer transmitter was 4°, whereas the beam width of the glide slope transmitter was 1°.

Table 3 indicates the order of presentation of the experimental conditions. The experimental design was not balanced for serial effects; however, one subject (pilot G) was run in a different order to determine if there were any sequence effects in the experimental results.

TABLE 3.- EXPERIMENTAL CONDITIONS

Resolution	Display system	Chroma	Type of approach	Landings per session, each pilot	Experimental sequence	
					Pilots A-F	Pilot G
305.8 TV lines	Projector	Color	Instrument	17	1	6
			Visual	34	2	7
		Black/white	Visual	34	3	8
356 TV lines	Monitor	Color	Instrument	17	4	1
			Visual	34	5	2
		Black/white	Visual	34	6	3
228.6 TV lines	Monitor	Color	Visual	34	7	4
		Black/white	Visual	34	8	5

Initially, each pilot made 34 practice flights for both the instrument and visual approaches using the color projector display. Each pilot made two practice flights during the first portion of each session for checkout and familiarization purposes before the data flights. All instrument flights were conducted with color for each display system. To avoid distortion of the data through concerted pilot efforts on any performance measure, the pilots were not told of their in-flight or terminal performance.

A total of 238 instrument-approach and 952 visual-approach data flights were made with the monitor and projector display systems. An additional 476 visual-approach flights were made with the monitor to investigate the effects of reduced resolution on pilot performance.

Five flight performance measures were obtained for all the simulated landings: (1) vertical flight path alinement, (2) lateral flight path alinement, (3) touchdown dispersion, (4) touchdown rate of descent, and (5) standard deviation of touchdown distance and correlation with standard deviation of touchdown rate of descent. The values of these criteria are the result of the experimental initial conditions, guidance systems, and the pilots' adaptive intentions for both the visual and instrument type flights. The performance measures were sampled digitally every 10 sec in flight, as well as at the moment of touchdown. The 10-sec interval was used to validate the properties of stationarity (i.e., to determine if the data of interest are invariant with time translations and do not vary substantially from one interval to the next, ref. 9). Pilot performance as measured in actual landing approaches (refs. 4, 5, and 6) was compared with the applicable simulator data of this study.

RESULTS AND DISCUSSION

Instrument-Approach Pilot Performance Measures

In a perfectly executed instrument approach, an aircraft would descend along the localizer beam and glide path with very little deviation. However, few pilots can consistently execute an instrument approach perfectly because of variations in their adaptive capabilities and differences in their experience. In reviewing the instrument approaches made with monitor and projector displays, consideration was given to the demands of normal flight procedures and management of the aircraft on the pilot. Both displays were assisted by ILS and flight director systems to provide the pilot an additional source of high-accuracy positional information. While making the instrument approaches, the pilots were also concerned that the degree of information available in the visual display would influence their decision altitude in the complete transition from instruments to a visual reference.

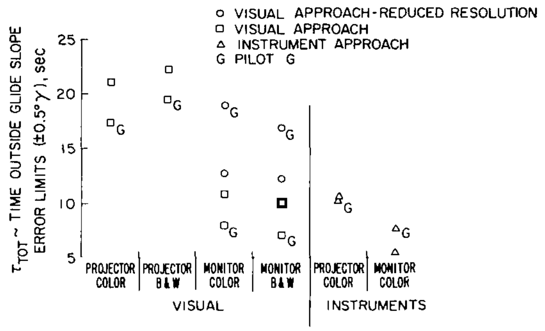


Figure 6.- Pilot's time outside flight path (±.5°γ).

Vertical flight path alinement- A measure of pilot performance can be observed from the vertical error relative to the approach flight path envelope, shown in figure 6 as a function of time outside the flight path (±0.5°γ). There is approximately 5 sec difference between the projector and monitor displays; however, this variability was not considered significant ($P > 0.05$)[1] for this performance measure. Pilot G showed a similar tendency for this performance measure.

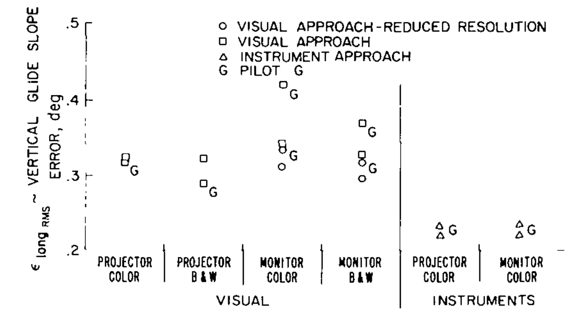


Figure 7.- Pilot's longitudinal glide-slope error (RMS).

The overall instrument flight was also used to generate an estimate of glide-slope errors. This is shown in figure 7 by the root mean square (rms) of the vertical glide-slope errors ($\epsilon_{long_{rms}}$) for both the projector and monitor. Essentially, no difference is noticeable ($P > 0.05$). Pilot G also exhibited the same characteristics for this performance measure. To ensure that this error was consistent, the properties of stationarity (ref. 9), showing little variation between intervals for this performance measure, were analyzed and validated by digital samples conducted at 10-sec intervals and by inspection of the analog recordings.

[1] Probability tests were conducted for main effects, allowing for differences between displays, color, or pilots, as determined by the analysis of variance; these variations were found to be not significant (i.e.. the acceptance of chance occurrences of the treatment differences was accepted for rejection of the null hypothesis when greater than 5 out of 100).

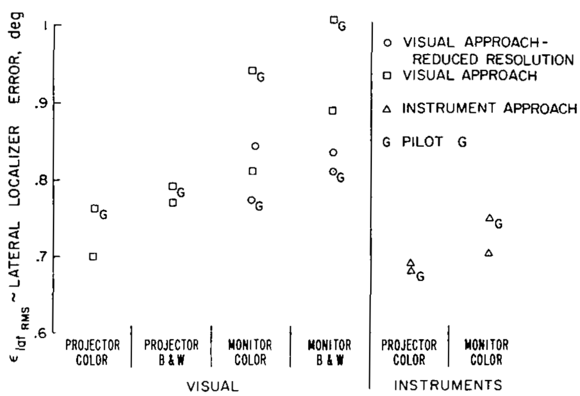


Figure 8.- Pilot's lateral localizer beam error (RMS).

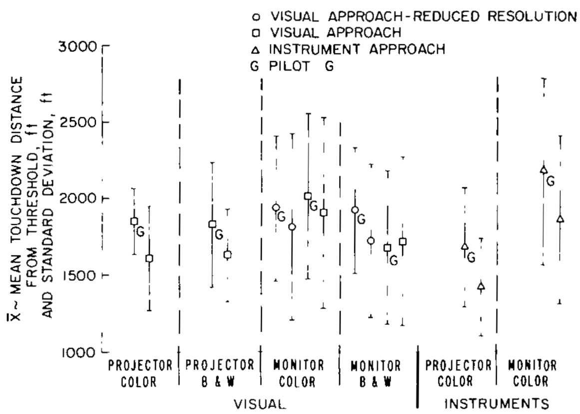


Figure 9.- Pilot's mean touchdown distance from threshold.

Lateral flight path alinement- An overall accumulation of lateral errors for the total flight time was represented by the rms of lateral localizer beam errors ($\epsilon_{lat_{rms}}$), as shown in figure 8. Little difference in error ($P > 0.05$) is evident for either the monitor or projector visual display. Pilot G also very nearly shows the same tendency for this performance measure. Because of the initial offset positions of the aircraft, tests were conducted for stationarity at 10-sec digitially sampled time intervals and by inspection of analog recordings; nearly all this error was generated within approximately the first minute of flight, and hence was nonstationary (ref. 9). The error did not increase over the remaining period of the flight, indicating that the aircraft was properly lined up with the runway center line.

Longitudinal dispersion of touchdown point- Figure 9 shows the mean touchdown distance from the runway threshold ($\overline{X}$) and the standard deviation (σ_X) for the projector and collimated monitor instrument flights. Table 4 summarizes the terminal touchdown dispersions for the simulator and actual flight data, and shows the mean distance from the center line ($\overline{Y}$) and its corresponding standard deviation (σ_Y). Although the mean touchdown distances differ between displays by 430 ft and the standard deviations by 230 ft ($P > 0.05$), in general the color monitor showed standard deviations (557 ft) similar to the flight data recorded in table 4 (593 and 497 ft). It should be noted that the ILS glide-slope simulator transmitter intercept point was located at 1500 ft instead of 1250 ft (nominal position at Dulles) from the runway threshold. This difference of 250 ft, when applied to the simulator data mean touchdown distance, would agree more closely with the flight data recorded in table 4, particularly for the color monitor. Figure 9 shows that pilot G's performance followed the same trend achieved by all pilots, except for a slightly higher mean touchdown distance.

Touchdown rate of descent- Another measure of touchdown performance for the instrument approaches is the mean touchdown rate of descent $\overline{\dot{h}}$ and its respective standard deviation $\sigma_{\dot{h}}$. Figure 10 shows $\overline{\dot{h}} = 3.58$ fps for the monitor, whereas $\overline{\dot{h}} = 4.33$ fps for the projector. Similarly, there is some improvement in the smaller standard deviations for the monitor flights over the projector flights, $\sigma_{\dot{h}} = 1.52$ fps and $\sigma_{\dot{h}} = 1.98$ fps, respectively. Statistically significant differences

TABLE 4.- INSTRUMENT AND VISUAL TOUCHDOWN DATA*

Resolution	Display system	Chroma	Type of approach	Terminal Landing Data: $\overline{X}$, ft	σ_X, ft	$\overline{Y}$, ft	σ_Y, ft	$\overline{\dot{h}}$, ft/sec	$\sigma_{\dot{h}}$, ft/sec	Experimental sequence: Pilots A-F	Pilot G
305.8 TV lines	Projector	Color	Instrument	1414	327	-4.8	17.1	4.33	1.98	1	6
		Black/white	Visual	1607	347	-5.3	17.7	4.05	1.70	2	7
			Visual	1620	307	-4.3	23.5	4.52	2.10	3	8
356 TV lines	Monitor	Color	Instrument	1844	557	-11.3	17.4	3.58	1.52	4	1
			Visual	1903	640	-0.3	19.8	3.82	1.58	5	2
		Black/white	Visual	1710	559	-1.6	18.3	3.90	1.82	6	3
228.6 TV lines	Monitor	Color	Visual	1808	622	-3.5	14.1	4.00	1.75	7	4
		Black/white	Visual	1720	506	+8.5	28.0	3.88	1.79	9	5
Flight data				1510-1560	593-497	--	--	2.00-1.65	0.90-0.88		

*The ILS simulator glide-slope intercept point is 1500 ft from the runway threshold. Normal intercept point for flight data is approximately 1250 ft from the runway threshold.

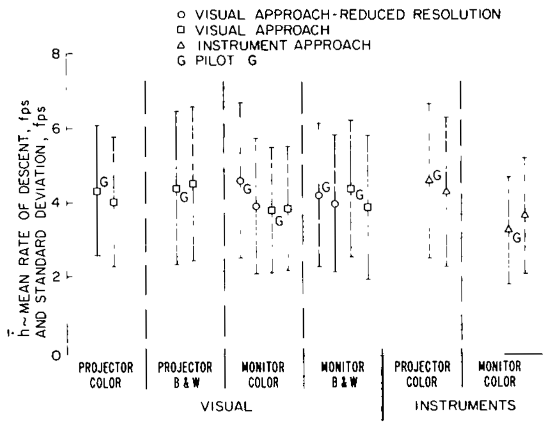


Figure 10.- Pilot's mean touchdown rate of descent.

do appear ($P < 0.05$)[2] when the monitor and projector displays are compared. Pilot G results also are very similar. Comparison with the flight data of table 4 shows $\overline{\dot{h}} = 1.62$ to 2.00 fps, with $\sigma_{\dot{h}} = 0.9$ fps. These figures vary by roughly a factor of 2 between the simulator and flight. Again, to avoid influencing the data, the pilots were not provided any relevant information regarding their touchdown performance.

Standard deviation of touchdown distance, and correlation with standard deviation of touchdown rate of descent- With each visual display system, the standard deviation of touchdown distance σ_X appears

[2]Probability tests were conducted for main effects, allowing for differences between displays, color or pilots, as determined by the analysis of variance; these variations were found to be significant (i.e., the acceptance of chance occurrences of the treatment differences was not accepted for rejection of the null hypothesis when less than 5 out of 100).

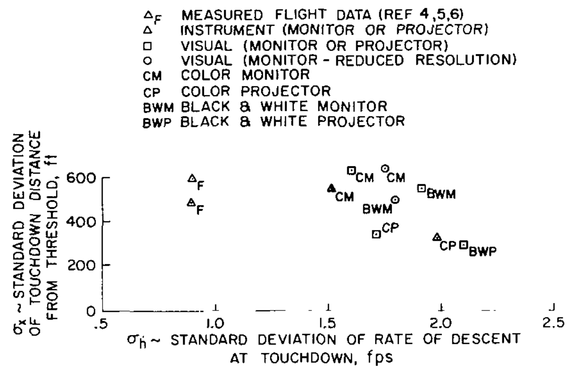


Figure 11.- Standard deviations of touchdown distance and rate of descent for simulator and flight.

to be associated with the standard deviation of touchdown rate of descent $\sigma_{\dot{h}}$ shown in figure 11. The projector flights indicate that a lower σ_X (327 ft) tends to increase $\sigma_{\dot{h}}$ (1.98 fps). The monitor flights show an apparent improvement by raising σ_X (557 ft) while lowering $\sigma_{\dot{h}}$ (1.52 fps). It is the experimenter's opinion that when the pilots were using the system of better resolution, brightness, and color contrast, they increased the touchdown dispersion and distance down the runway to exert better control on touchdown rate of descent.

Visual Approach Pilot Performance Measures

For the performance obtained without reliance on normal instrumentation, some errors can be expected to change when compared to an accurate instrument approach. These performance measures reflect the pilot's ability to attain what he thinks is the position normally supplied by the ILS and flight director system, and he proceeds to fly the aircraft according to the visual cues provided by the display system.

Longitudinal flight path alinement- Time outside the flight path ($\pm 0.5° \gamma$) for the visual approaches is also shown in figure 6. Little γ error is evident ($P > 0.05$) between color or black and white for either the projector or the monitor display; however, a greater difference ($P < 0.01$)[3] of about 10 sec is evident between the projector and monitor displays. It is apparent from figure 6 that the pilots were able to maintain more precision (less time outside the flight path) with the monitor display. Pilot G maintained similar properties, with a proportional reduction of about 3 sec between displays compared to the other pilots.

The estimate of glide-slope errors ($\epsilon_{long_{rms}}$) for the overall flight is shown in figure 7. No differences ($P > 0.05$) between the projector and monitor displays were apparent for this performance measure. The differences between color and black and white also are considered negligible. Pilot G, however, did exhibit slightly larger errors, possibly because of pilot technique, but with similar properties for this performance measure. The properties of stationarity were also analyzed to show that there was no unusual variation from one 10-sec digitally sampled interval to the next.

For the condition of reduced resolution, the pilot's performance showed a negligible increase ($P > 0.05$) of several seconds error in the time outside the flight path. Essentially no differences were found between color and black and white. The increase in time outside the flight path experienced by pilot G resulted in some loss of precision for the reduced-resolution display. Glide-slope error with reduced resolution was found to change significantly ($P < 0.05$) from 0.35°

[3]Probability tests were conducted for main effects, allowing for differences between displays, color, or pilots, as determined by the analysis of variance; these variations were found to be very significant (i.e., the acceptance of chance occurrences of the treatment differences was less than 1 out of 100).

to 0.33°. Although this change does not appear significant, it is important to point out that there were variations between sampling intervals that not only violated the properties of stationarity but showed an increase of 1.5 times the standard deviation of the higher resolution system.

Lateral flight path alinement- Lateral localizer beam error $\epsilon_{lat_{rms}}$ is shown in figure 8. Most of this error occurred within approximately the first minute of flight. An investigation as to the apparent increase of this performance measure error with the monitor showed that during the first minute of flight, the lateral flight path to the runway center line intercept point was more nonlinear with the projector and more linear with the monitor (i.e., more like a direct line-of-sight maneuver). Furthermore, the intersection distance with the localizer beam was always approximately 11,800 ft from the runway threshold for all the monitor flight conditions (including those for reduced resolution), and was consistently 500 ft farther away with the same conditions for the projector flights. Thus, a larger $\epsilon_{lat_{rms}}$ resulted from a more direct lateral flight path flown with the monitor when compared with the projector. The resulting errors (fig. 8), which vary between 0.7° and 0.9°, were considered very important ($P < 0.01$). There were no significant differences between pilots in the individual effects of color and black and white.

Although the smaller projector $\epsilon_{lat_{rms}}$ appears to indicate superior performance, it is the experimenter's opinion that it is associated with the time outside the vertical flight path (fig. 6) in that the establishment of an early runway lineup with the projector display may have been responsible for the loss in precision of control in the vertical flight path. Similarly, pilot performance with the monitor indicates a larger $\epsilon_{lat_{rms}}$ but less time outside the vertical flight path. The performance of pilot G also appears to maintain these same characteristics (figs. 6 and 8). In support of the above opinion, the pilots remarked that they were having greater difficulty in obtaining initial runway lineup information with the projector displays early in the flight, particularly with the black and white configuration for both displays; however, the pilots did feel the lineup approach was more relaxing as the monitor display required less effort.

Longitudinal dispersion of touchdown point- Table 4 summarized terminal touchdown dispersions for mean distance from threshold $\overline{X}$, mean distance from centerline $\overline{Y}$ and their respective standard deviations, σ_X and σ_Y. Figure 9 presents the touchdown data for both the projector and monitor displays. Note that the instrument flights, which were performed first, were conducted with the guidance system glide-slope transmitter beam intersecting the runway 1500 ft beyond the threshold. This influence should be considered when the touchdown distance $\overline{X}$ data is observed because the pilots were instructed to try to use the reference points they used in making instrument approaches. A comparison of the pilot performance with the projector and monitor for touchdown distance shows that for color, the pilots flew 296 ft farther before touchdown with the monitor, with a 293-ft increase in the standard deviation. For black and white, the pilots flew 90 ft farther before touchdown with the monitor, with a 252-ft increase in the standard deviation. The individual variations between displays and relative importance of color compared to black and white were found to differ significantly ($P < 0.05$) because of the further increases in the mean touchdown distances and standard deviations. Furthermore, the overall variability in performance between pilots was found to differ significantly ($P < 0.01$), mostly because of the variation in the standard deviations. The performance of pilot G is shown to be in general agreement for this performance measure, except in the case of the color projector where the touchdown standard deviation was the smallest (250 ft).

Flight performance with the reduced-resolution display was similar to that obtained for the other monitor flights in that, with color, the touchdown distance decreased by 95 ft and the standard deviation decreased by 18 ft; whereas, for black and white, there was an increase of 10 ft in the touchdown distance and a corresponding reduction of 53 ft for the standard deviation. Variability between pilots ($P < 0.05$) was also found for this performance measure.

Table 4 indicates the effect of the display conditions on the aircraft position at touchdown Y. All flights, except those flown with the black and white reduced-resolution display, landed to the left of the runway center line. Several of the subject pilots claimed that landings made from the left seat result in touchdowns that are predominantly to the left of the center line. However, for this study, not only did the aircraft land predominantly to the right of the center line for the black and white display but the standard deviation nearly doubled, perhaps indicating less confidence in the final lineup of the runway.

Standard deviation of touchdown distance and correlation with standard deviation of touchdown rate of descent- Figure 11 shows the relationship between the standard deviations of touchdown distance σ_X and standard deviation of rate of descent $\sigma_{\dot{h}}$. Visual flights made with the projector display for both color and black and white are consistent with the data obtained from the instrument flights for this performance measure. Flights made in color with the projector indicate that a lower σ_X (347 ft) tends to increase $\sigma_{\dot{h}}$ (1.70 fps). The flights made in color with the monitor show more improvement by raising σ_X (640 ft) while lowering $\sigma_{\dot{h}}$ (1.58 fps). The improvement is considered relative to the performance obtained from the actual flight data. Flights made with the black and white monitor, as well as those for reduced resolution, also show a similar trend. Figure 11 also shows the flight data, which, in general, appear to agree more closely with all monitor data than projector data.

Touchdown rate of descent- Figure 10 shows the mean touchdown rate of descent; performance with the monitor varies from 3.82 fps (color) to 3.90 fps (black and white), while performance with the projector is not as good, varying from 4.05 fps (color) to 4.52 fps (black and white). The standard deviations were lower for the monitor than the projector (by 7 percent) for color and 13 percent for black and white.

These differences, although small, were further analyzed by display, and were not found statistically important; however, there was some variability ($P < 0.05$) in individual pilot performance. Pilot G maintained similar characteristics for this performance measure.

The mean rates of descent obtained from the reduced-resolution flights were 4 fps (color) and 3.88 fps (black and white), while the standard deviations were 1.75 fps and 1.79 fps, respectively. The variations in performance were not considered significantly different from the other monitor flights except that there was also some variability ($P < 0.05$) in performance between the individual pilots.

GENERAL PILOT COMMENTS

The pilot's "subjective opinions" (appendix E) comprised both the pilot's rating and his informative comments and were useful in evaluating each display configuration. Figure 12 shows the dispersion of the pilot ratings, relative to the real world fidelity and ranging between 1 and 5,

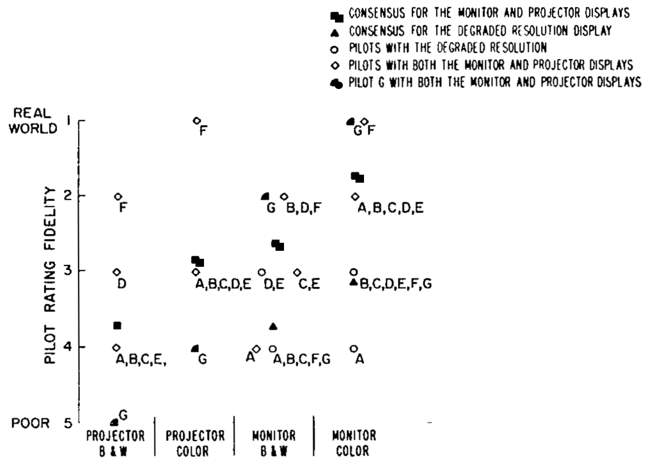


Figure 12.- Pilot opinion for visual simulation displays compared to real-world fidelity.

for all the display configurations. The pilots rated the projector black and white display as having the poorest fidelity (4 rating); the projector color display and monitor black and white display were somewhat better (3 rating), while the monitor color display was considered the best (2 rating). Note that the maximum television resolutions of the monitor and projector displays are approximately 5 and 7 min of arc (appendix D), respectively, both of which are considerably less than the resolvability of the human eye, which normally is accepted as 1 min of arc (refs. 1 and 10).

Figure 12 also shows that the pilots rated the monitor reduced-resolution configuration poorly for black and white (4 rating) and slightly better for color (3 rating); similar ratings were obtained for the projector display. The pilots' comments are summarized below.

Color Versus Black and White

Projector- It is easier to determine the flare point and to judge the rates of descent when the display is in color; there is no problem with the color cues; it takes much more concentration and effort to fly without color; there are problems in getting height and runway lineup information for the black and white display; the use of color is more relaxing; more eye strain and blinking are noticeable when the display is in black and white; the black and white visual cues are perceived a little more slowly than color; the aircraft is coming in higher with the black and white display than with the color display.

Monitor- The height reference is good prior to the touchdown; blinking occurs more often than for the color display; there is a tendency to wait on the lineup with the black and white system; however, for the color system, it is a little easier; with the use of color, a more natural interpretation of the various cues reduces the effort to maintain the profile; the fatigue factor compared to the black and white display is much less; there is more consistency, with a color display, in the flair and touchdown maneuver; blinking the eyes occurs more often with the black and white display; with a black and white display, it was much harder to achieve the result obtained with a color display.

Monitor Versus Projector

It is easier to ease into the glide-slope path with the monitor display than with the projector display; the picture quality is better for the monitor display; the improvement in depth perception for the monitor display is very helpful; some eye blinking occurs but not as much as with the projector display; the depth perception is very strong near the ground such that everything stands out more realistically and can really be analyzed very similar to actual flight; this was not possible with the projector display; there is a better feeling for lining up with the monitor display.

Reduced-Resolution Monitor

Both the color and black and white displays effect losses in depth perception and in height references; there is more visual fatigue and a greater need for concentration in the final moments of the approach; the workload is greater with the black and white display than with color; the intercepts and corrections to the course and glide path are delayed until the runway appears clearer; the poor picture quality requires above average effort to achieve even reasonable approach techniques; the landings seem harder than normal; the touchdown occurs before it is expected; lack of color definitely makes a more difficult flare and touchdown.

CONCLUDING REMARKS

Present methods of reproducing visual scenes with television displays achieve considerably less fidelity than is normal in actual flight. To help understand the effects of visual cues on image fidelity due to color, resolution, and perceptual differences arising from quasicollimation, two display systems, each capable of color or black and white transmission, were compared. One was a typical projection system commonly used in aircraft simulators with visual attachments; the other was developed especially for this experiment from a pair of collimating lenses and a television monitor. The experimental results were obtained from seven trained jet pilots viewing four scenes displayed by projector in color and black and white, and by monitor in color and black and white. Two types of flights were flown as a means of identifying the true effects of the visual cues under investigation: a visual flight designed to show the influence of the visual cues on the performance measures and pilot opinion, and an instrument flight to measure pilots' performance with their usual flight management procedures.

The experimental results obtained from the performance measure differences, although small, are identifiable. Comparison of the effects of color and black and white by these differences showed that the touchdown distance and standard deviation increased for both the color monitor and color projector displays; however, for the same performance obtained with the color monitor, the agreement was more favorable with the actual flight data. The performance for rate of descent at touchdown was also lower for color, particularly with the monitor display, but still higher than for actual flight.

The pilots were able to achieve better performance in minimizing the time outside the vertical glide-slope beam with the monitor display compared to the projector display. However, for the lateral flight path performance, the error was smaller for the projector display. The reason for the smaller projector display error is that the pilots, while trying to line up with the runway, tended to correct the lateral offset error more quickly, and consistently intercepted the runway center line about 500 ft farther from the threshold as compared with the identical flight conditions applied to the monitor display.

Degradation of the monitor display resolution tended to reduce the touchdown distance and slightly increase the corresponding standard deviation. In addition, the landings were made predominantly to the right of the center line for the black and white display, and with nearly twice the standard deviation as obtained for the color display.

It is the experimenter's opinion that there is a correlated difference between the two display systems when the standard deviations of touchdown distance and touchdown rate of descent are compared with similar flight data. When using the monitor display, pilots were able to exert better control in reducing the touchdown rate-of-descent deviations, while tending to increase the standard deviations of the touchdown distance.

The pilots were more critical of the black and white configuration and favored the use of color for either displays. Their comments were also more favorable toward the monitor display because of better picture quality and depth perception.

From performance measure results and their confirmation by trained commercial pilots, a quasicollimated monitor appears to be a more satisfactory device than the projector for this model television system. Although there has been some improvement in the fidelity of the visual scene obtained from the quasicollimated monitor, these results are not necessarily sufficient to determine specification requirements for additional improvements in other special-purpose visual simulation systems. More study is needed on such things as changing the degree of collimation on the monitor or collimating the projector, and to relate those results to the test results obtained here.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Dec. 7, 1970

APPENDIX A

FLIGHT DIRECTOR EQUATIONS AND MECHANIZATION

The instrument-type landing approaches were made with the aid of a Bendix 300 flight director. The study results are related to both the guidance systems and initial conditions. There is a wide variation, however, in manufactured flight director instruments, and therefore it was necessary to generate a precise transfer function of the steering computer commands that responded in the simulator in much the same manner as during actual flight.

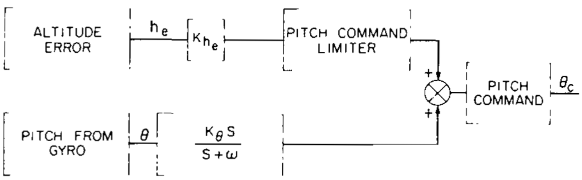


Figure 13.- Block diagram of flight director computer for vertical channel (S is Laplace operator).

The vertical and lateral channels of the flight director steering computer are shown in figures 13 and 14, respectively. For the vertical steering channel, the pitch command θ_c is

$$\theta_c = K_{h_e} h_e + \theta\left(\frac{K_\theta S}{S + \omega}\right) \tag{A1}$$

with coefficients

$$K_{h_e} = 5 \times 10^{-4}$$

$$K_\theta = 0.5$$

$$\omega = \frac{1}{12}$$

$$\theta_c = 5 \times 10^{-4} h_e + \left(\frac{0.5S}{S + \frac{1}{12}}\right) \tag{A2}$$

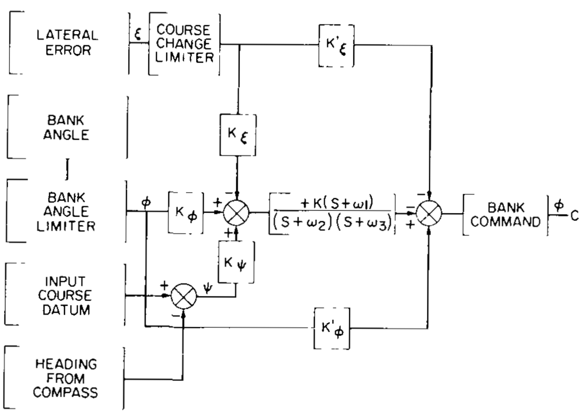


Figure 14.- Block diagram of flight director computer for lateral channel (S is Laplace operator).

The instrument display scaling was 1 rad θ_c = 6 rad of displayed θ. For the lateral steering channel, the roll command (ϕ_c) is

$$\phi_c = \left[K_\psi \psi + K_\phi \phi - K_\epsilon \epsilon\right]\left[\frac{-K(S + \omega_1)}{(S + \omega_2)(S + \omega_3)}\right] + K'_\phi \phi - K'_\epsilon \epsilon \tag{A3}$$

with coefficients

$K_\psi = 0.1431$ $\qquad$ $K_\phi = 0.90$

$K_\epsilon = 97.5$ $\qquad$ $K = -0.638$

$K'_\phi = 2.7$ $\qquad$ $K'_\epsilon = -22.92$

$\omega_1 = 0.0227$ $\qquad$ $\omega_2 = 0.163$

$\omega_3 = 1.05$

The instrument display scaling was 1 rad $\phi_c = 0.1$ rad of displayed ϕ.

These two steering commands (θ_c and ϕ_c) provided the requirements for attitude control and regulation, path command or stiffening, and path damping terms.

APPENDIX B

DESCRIPTION OF THE FLIGHT SIMULATOR OPTICAL PROBE SYSTEM

The optical system, or optical relay, transfers the image formed by an objective lens positioned near the model surface to the photosensitive plumbicon in the television camera.

Dynamic control of focus as a function of altitude, pitch, or velocity is provided by automatic adjustment of the focusing wedges behind the objective lens. In addition to the complexity involved in the transfer of radiant flux from the object to image plane, a lens has important geometric properties with respect to the focus of the image.

It is important to know the optimum range of distances as delineated by the lens system depth of field, within which objects in the scene may move without requiring adjustments in the focus of the camera. In general, for this system the depth of field increases as the stop opening of the lens is decreased (i.e., the smaller the focal length of the lens, the greater the depth of field).

APPENDIX C

DESCRIPTION OF DISPLAY SYSTEMS

The Marconi projection system used in this study uses three in-line Schmidt optical systems with specially developed 5-in. projection tubes. Individual phosphors used are green, blue, and orange, the latter being corrected by a suitable red filter. The projector operates on the same 625-line television standards as does the television camera, accepting either separate red, green, and blue signals for color viewing, or composite green television signals in equal proportions for black and white (monochrome) viewing. The Schmidt optical system consists of an accurately alined, spherically concave mirror and an aspherical corrector plate to permit projection of the object plane image, which has a spherical curvature, on a flat screen. Figure 15 shows the layout of the projector and screen, and the distances required for alinement of the screen relative to the pilot.

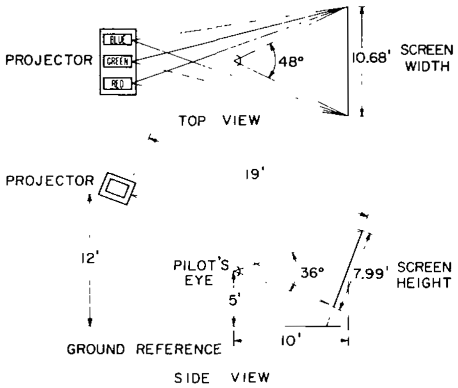


Figure 15.- Position of projector and screen with respect to the pilot's eye.

QUASICOLLIMATED MONITOR DISPLAY

The components of the quasicollimated monitor display system include a Conrac 21-in. monitor and two 25-in.-diameter, 50-in.-focal-length planoconvex acrylic collimating lenses. In addition, a light baffle shroud was provided to reduce the effects of stray light radiation.

The monitor operates on the same 625-line television standards as does the television camera, accepting either separate red, green, and blue signals for color viewing, or composite green television signals for conversion to black and white (monochrome) viewing.

The arrangement of the collimating lenses with respect to the pilot's eye, windscreen, and television monitor is shown in figure 16. Normally, the image should be located at infinity for completely relaxed eye accommodation; however, for the lenses used in a test system of this type for an image located at infinity, there is a reduction of the image area of sharp focus because of increases in astigmatism and several types of aberrations that tend to disturb the pilots when making normal head movements. For these tests, these restrictions were effectively avoided by the adjustment of (1) image distance, (2) angular magnification, (3) field of view, and (4) exit window diameter. For the purpose of this paper, adjustment of these parameters does result in changes of true collimation to that of near-collimation and will be referred to as quasicollimated.

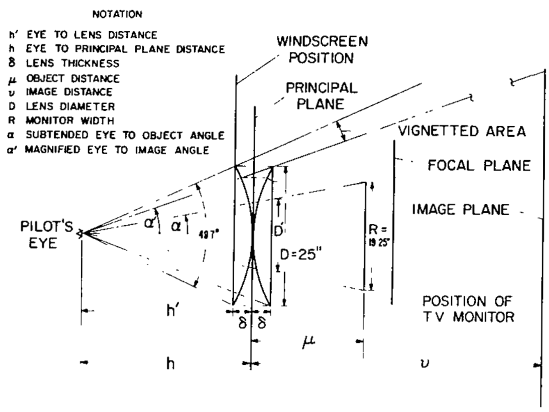


Figure 16.- Position of lenses with respect to the pilot's eye, windscreen, and television monitor.

Image Distance

Figures 4 and 16 show the physical arrangement of two 25-in. planoconvex collimating lenses that were inserted into the simulator aircraft windscreen. Thickness of each lens (δ) was 3-1/2 in. The pilot's eye-to-lens distance (h′) was 27 in. The object distance (u) from the principal plane of the lens to the face of the television monitor was 20 in. Location of the image distance (v) is related to the focal length of a lens (f) (ref. 11) by

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \qquad \text{(C1)}$$

where f = 25 in. (combined focal length of two 50-in.-focal-length lenses with zero separation distance). Transforming and solving for v yields

$$v = \frac{fu}{u-f} = \frac{(25)(20)}{-5} = -100 \text{ in.} \qquad \text{(C2)}$$

The total image distance (v_T) from the pilot's eye is

$$v_T = |v| + h' + \delta = 100 + 27 + 3.5 = 130.5 \text{ in.} = 10.88 \text{ ft}$$

This total image distance is very nearly the same as the pilot eye-to-projection screen distance, which was 10 ft. Ideally, for a perfect comparison, the image distances should be the same between displays; however, because other parameter adjustments command a greater degree of influence, this slight difference can be considered negligible.

Angular magnification

Angular magnification (A) is related to the object distance (u), eye-to-lens principal plane distance (h), and focal length (f) by (ref. 12)

$$A = \frac{1 + (h/u)}{1 - h\,[(1/f) - (1/u)]} \qquad \text{(C3)}$$

The angular magnification is maximum when the combined focal length is equal to the object distance and is

$$A_{max} = \frac{1 + (30.5/25)}{1} = 2.22$$

However, to satisfy the compromised simulator arrangement by appropriately setting the object distance to 20 in., the angular magnification is

$$A = \frac{1 + (30.5/20)}{1 - 30.5\,[(1/25) - (1/20)]} = 1.935$$

Although this is a reduction from A_{max}, its significance will be seen later.

Field of View

Since the television camera optics are designed for approximately a 48° horizontal field of view and the photosensitive system is adjusted accordingly, the quasicollimated monitor should display the same visual field to help preserve the linear picture perspective as seen by the pilot. The angular magnification previously computed was the parameter used to help accomplish this requirement.

From figure 16, the unaided direct view subtended angle of the monitor display (α) is related to the quasicollimated image field of view (α') as a function of angular magnification by

$$A = \frac{\tan \alpha'}{\tan \alpha} \tag{C4}$$

Since $h = h' + \delta$

$$\tan \alpha = \left(\frac{R/2}{u + h}\right)$$

where R equals the horizontal width of the television monitor viewing surface, then:

$$\tan \alpha' = A\left(\frac{R/2}{u + h}\right) \tag{C5}$$

Therefore, the total field of view is

$$2\alpha' = 2 \tan^{-1}\left[\frac{A\,(R/2)}{u + h}\right] \tag{C6}$$

Furthermore, the final relationship of the total field of view ($2\alpha'$) by substituting equation (C3) for A in (C5) is given as

$$2\alpha' = 2 \tan^{-1}\left(\left\{\frac{1 + (h/u)}{1 - h[(1/f) - (1/u)]}\right\}\left(\frac{R/2}{u + h}\right)\right) \tag{C7}$$

A comparison of field of view using equation (C7) for a specific object distance and focal length as related to the 27-in. reference (h) of the pilot's head shows: that a field of view of 42.2° is the result of an angular magnification of 2.22, which was previously computed for an object distance equal to the focal length of the lens; and that the final adjusted position corresponds to a field of view of 40.6° as a result of an angular magnification of 1.935 and an object (monitor) distance of 20 in. This field of view is nearly the same as if the television monitor CRT face were inserted directly into the windscreen (40.4°).

Since a 40.6° field of view has been shown to be nearly maximum as a result of equation (C7), it is still less than that of the optical field of view of the simulator television camera (48°) which must be matched to maintain a linear picture perspective. This perspective was maintained by overscanning the television camera photocathode, and was verified by measuring, at the pilot's eye position, the subtended angles of various positions of the runway.

Exit Window Diameter

Little attention has been given to the relative importance of the size of the exit window diameter of display systems and its effect on the display quality. From figure 16, the exit window (D′), as seen from the observer, is actually the entrance window of the display image and is found to be related to the angular magnification (A) and lens diameter (D) by

$$\frac{D'/2}{h+\delta} = \tan\ \alpha \tag{C8}$$

and

$$\frac{D/2}{h+\delta} = \tan\ \alpha' \tag{C9}$$

From equation (C4), the ratio of tan α' to tan α is the angular magnification

$$A = \frac{\tan\alpha'}{\tan\alpha} = \frac{D}{D'} \tag{C10}$$

Therefore, from equation (C7), the exit window diameter is

$$D' = \frac{D}{A} \tag{C11}$$

Substitution of equation (C3) shows the final relationship to be

$$D' = \frac{D}{[1 + (h/u)]/[1 - h\,(1/f) - (1/u)]} \tag{C12}$$

Expression (C12) was derived to enable the experimenter to adjust the other lens variables in terms of a known lens diameter. These adjustments were also responsible for properly integrating the collimating lenses with the television monitor display.

If the monitor display is located at the focal plane, the image is located at infinity with an angular magnification of 2.22 (computed previously by equation (C3)). With a lens diameter (D) of 25 in. the exit window diameter is approximately equal to

$$D = \frac{25}{2.22} = 11.25 \text{ in.}$$

Similarly, for the adjusted position of the monitor display image located at 10.88 ft from the pilot's eye, and with an angular magnification of 1.935 (also previously computed by equation (C3)), the exit window is approximately equal to

$$D' = \frac{25}{1.935} = 12.91 \text{ in.}$$

The reason for increasing D′, which results from a smaller angular magnification and image height, is that some of the undesirable lens aberrations and astigmatism have been minimized. This compromise has allowed larger lateral and vertical head movements by the subject pilot when viewing the display without introducing other undesirable effects. In addition, better uniform brightness has resulted because of an increase in the light bundle image intensities over a larger area of the adjusted display.

APPENDIX D

DESCRIPTION OF DISPLAY VARIABLES

In discussing the display variables, it is necessary to describe the display in terms of (1) resolution, and (2) brightness and contrast.

RESOLUTION

Resolution is a measure of detail that can be obtained with an imaging system. This property can be measured by test charts containing line patterns of different spacings. The maximum resolution of this television system was obtained from a National Bureau of Standards Test Chart (refs. 13, 14), normally located at a distance of 26 times the lens focal length, and by observing the closest line spacing (highest spatial frequency) that can be distinguished through the imaging system. In observing a square wave test chart and physically measuring the magnitude of the beam current generated for each spatial frequency set of square waves, a square wave response was obtained and converted to a sine wave response as a quantitative measure of overall system performance according to the analytical techniques described in references 2 and 15. According to reference 16, the sine wave response was replaced by the term modulation transfer function (MTF) on the recommendation of the Subcommittee for Images Assessment Problems of the International Commission for Optics. Normally, television resolution varies as a function of servo-driven focus ranges and altitudes in flight simulators with visual attachments. The following measurements are for the position that provides the maximum resolution. Figure 17 shows the MTF obtained for this model television system, including the viewing conditions of either color or black and white. From both the beam current measurement and the observation of the test chart, the maximum resolution for the monitor was 28 TV lines (14 optical lines/mm), and the maximum resolution for the projector was 24 TV lines (12 optical lines/mm). The MTF was seen to be lower for black and white because the television camera, which is basically a color system, has a lower spectral distribution of transmitted light when operating on the green video signal for black and white viewing.

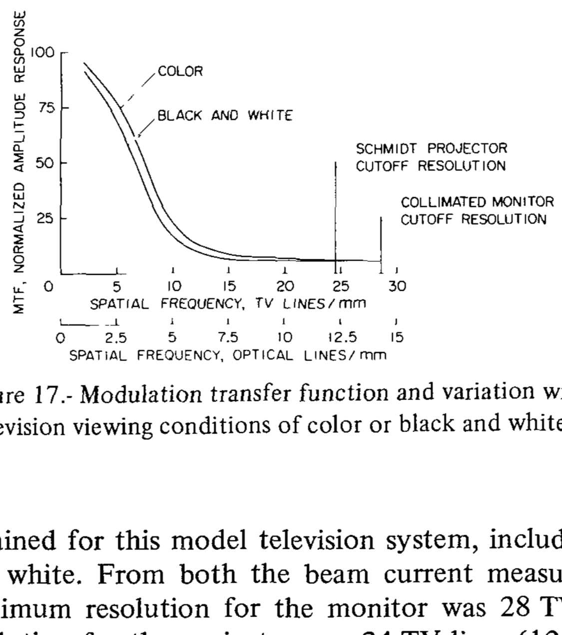
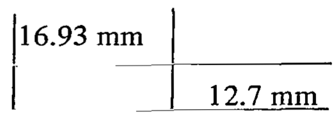


Figure 17.- Modulation transfer function and variation with television viewing conditions of color or black and white.

Conversion of TV lines to TV lines per picture height is based on an image falling upon the following plumbicon photoconductor dimensions.



Since the maximum cutoff resolution for the monitor was 28 TV lines/mm, the maximum vertical resolution displayed to the pilot was 356 TV lines (28 TV lines/mm X 12.7 mm). This corresponds to a limiting resolution over the 30.4° field of view of 5.12 min of arc. Likewise, the maximum resolution displayed to the pilot with the projector is 304.8 TV lines (24 TV lines/mm X 12.7 mm). This corresponds to a limiting resolution over the 36° field of view of 7.08 min of arc.

The maximum horizontal resolution of the monitor was 474 TV lines (28 TV lines/mm X 16.93 mm). This is equivalent to a limiting resolution over the 40.6° field of view of 5.13 min of arc. Similarly, the maximum resolution of the projector was 395 TV lines (24 TV lines/mm X 16.93 mm). This corresponds to a limiting resolution over the 48° field of view of 7.3 min of arc.

The resolution is also affected by the response of the focus system. Automatic focusing is achieved by varying the position of two focusing wedges in response to the pitch, belt (aircraft) speed, and height signals connected to a servo-drive motor. The position of the focus servo and wedges was observed during the final approach phase and landing to determine the point of maximum focus and resolution. Figure 18 shows the resolution variation with respect to the distance from the runway threshold. The focus servo maintains this position for altitudes less than 200 ft with the optical probe positioned at the threshold. A maximum resolution is observed at a distance of approximately 1415 ft. The falloff in resolution at either end can be attributed to the depth of field characteristics.

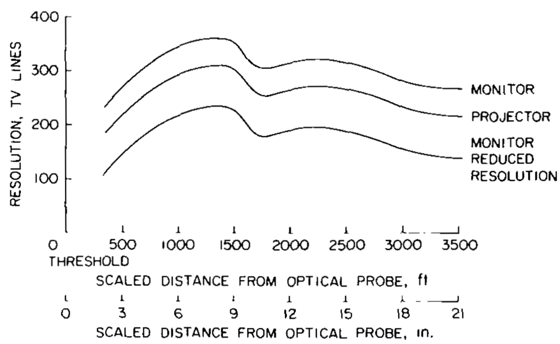


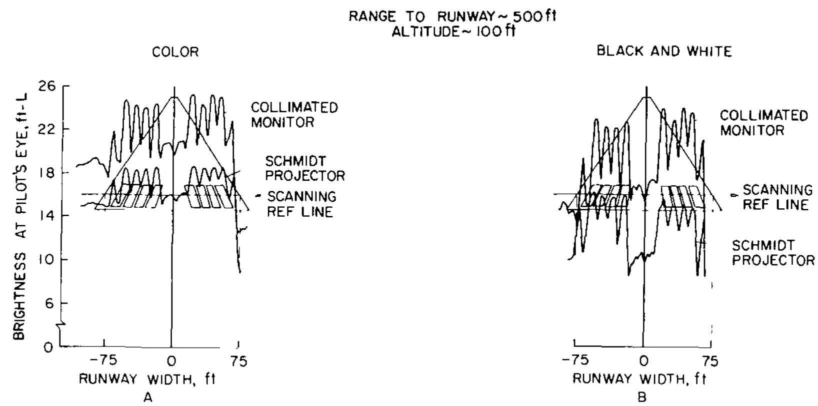
Figure 18.- Variation of resolution with distance.

Reduced Resolution

The reduced resolution variation was accomplished by adjusting the focusing coil of the monitor. A 36-percent change in resolution by changing the focus was calibrated to a peak resolution of 228.6 TV lines (18 TV lines/mm X 12.7 MM) (fig. 18). This procedure does not alter the beam current, bandwidth, or brightness, but does affect the focus and sharpness of the resulting monitor display.

Brightness and Contrast

The brightness for both the projector and monitor displays was analyzed by measuring the light intensities of the approach runway as observed by the pilot. Figures 19(a) and (b) show the brightness for an identical scanning line across the threshold zone hash marks for both conditions of color and black and white as seen at the pilot's eye position. The average white brightness for the color monitor is 24.3 ft-L and 17.7 percent contrast. The average white brightness for the black and white monitor is 22.7 ft-L and 20.7 percent contrast. For the color projector, the average white brightness is 18.3 ft-L and 11.4 percent contrast. The black and white projector average white brightness was only 15 ft-L and with only 13.3 percent contrast. The results show that there is about 56 percent better uniform contrast, and nearly a 40 percent increase in brightness with the monitor display. It can also be observed that the contrast is less for both black and white displays than for both color displays (and in agreement with the MTF of fig. 17).



(a) Color display. (b) Black and white display.

Figure 19.- Brightness for monitor and projector display.

Brightness and contrast measurements for the reduced resolution flights were maintained at the same levels as for the higher resolution condition, except that the focus and quality of the resulting picture was affected.

APPENDIX E

PILOT OPINION OF THE MONITOR AND PROJECTOR DISPLAYS AND THEIR VARIATIONS

TABLE EI.- PILOT OPINION OF THE PROJECTOR DISPLAY CONFIGURATION

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Projector	Black and white Vert. res. = 304.8 TV lines Brightness = 15 ft-L Contrast = 13.3 percent	A	4	1. Perspective looks good; trying for touchdown point 1000 from the runway threshold. 2. Height reference is good when using the terrain; the approaches seem consistently low on the glide slope, and the landings seem shorter than usual. 3. Height reference near the ground is confusing and forces me to glance more often at the instrument panel for an altitude reference.
↓	↓	B	4	1. The final touchdown rate of descent seems harder. 2. The approaches seem to be low on the glide slope. 3. The runway does not appear too distinct. 4. There seems to be a problem in deciding when to flare.
↓	↓	C	4	1. The height reference over the threshold seems too high. 2. The terrain features are not very prominent. There is some difficulty in establishing a runway lineup. 3. There is much more eye blinking and a lot more fatigue while trying to establish height references. Sweeping vision from end of runway for better depth perception.

TABLE EI.- PILOT OPINION OF THE PROJECTOR DISPLAY CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Projector	Black and white Vert. res. = 304.8 TV lines Brightness = 15 ft-L Contrast = 13.3 percent	C	4	4. There seems to be a lack of consistency on the final touchdown point. The reference point on the runway is different and thus feel the landings are farther down the runway.
		D	3	1. Depth perception is about the same as color but not as clear a picture is presented.
				2. Not getting sufficient information when initiating the flare.
				3. Workload, both mental and visual, seems to be harder. Visual references are more like the problems associated with an Alhskan "whiteout."
				4. Setting vision reference as far down the runway and shifting vision to closer point to give better depth perception.
		E	4	1. Visual references are not as usable when flying high because ground references do not stand out.
				2. There are problems in getting height information and runway lineup information. Also, it is difficult without sufficient information to initiate a proper flare.
				3. The final touchdown point seems to be farther. The use of more rudder power during the lineup is required.
				4. More eye strain and blinking are noticeable.
		F	2	1. It takes longer to get back to the command path flight profile. It is much harder to fly than with color.
				2. It requires much more concentration effort to fly without color.
				3. The aircraft seems to come upon the runway too soon, and then there is not enough time for a final correction.

TABLE EI.- PILOT OPINION OF THE PROJECTOR DISPLAY CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Projector	Black and white Vert. res. = 304.8 TV lines Brightness = 15 ft-L Contrast = 13.3 percent	F	2	4. The lineup is much more difficult and requires more rudder action. 5. The black and white visual cues are perceived a little more slowly.
		G	5	1. It is difficult to determine height or distance because of little contrast. 2. Maximum effort is required to detect visual deviation in the lateral displacement when approaching the runway. 3. When close in, it was difficult to determine height on a visual glide slope for real accuracy.
Projector	Color Vert. res. = 304.8 TV lines Brightness = 18.3 ft-L Contrast 11.4 percent	G	4	1. It definitely is easier to fly than with black and white. 2. Not as much blinking or scanning the altimeter for height reference is required. 3. The use of color is more relaxing. 4. Considerable effort is required to detect the lateral displacement in the final lineup of the runway.
		A	3	1. The approach is much easier. 2. Runway lineup is easier for what is needed to control the aircraft. It feels more like a normal approach. 3. The height reference is improved. Detail in color is more prominent. 4. It is easier to control the rate of descent with the use of color.
		B	3	1. The use of color does not present the problems encountered with the black and white system.

TABLE EI.- PILOT OPINION OF THE PROJECTOR DISPLAY CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Projector	Color Vert. res. = 304.8 TV lines Brightness = 18.3 ft-L Contrast = 11.4 percent	B	3	2. The approaches still seem to be always below the normal glide slope.
				3. With color, the runway is more distinct and is easier to judge the rates of descent when deciding to flare.
		C	3	1. The use of color is definitely better and easier to land the aircraft.
				2. The terrain features are more prominent, and are more useful in establishing a height reference.
				3. From a distance, the runway stands out more when in color.
		D		1. Color adds more realism. There is no problem with the color cues.
				2. There is not as much fatigue and eye strain with color.
				3. The runway is seen better initially when in color.
				4. Started to get strong visual cues for altitude and rate of descent when crossing the threshold.
		E	3	1. Color definitely gives better height information and depth perception.
				2. Using far end of the runway, at least 3000 ft, to establish a pitch flare reference.
				3. It seems that the final touchdown point is shorter.
				4. The final approach from the middle marker to touchdown is not as hard to lineup for position with color.
		F	1	1. Color seems to be more realistic, including the runway effects at termination of the flight.

TABLE EI.- PILOT OPINION OF THE PROJECTOR DISPLAY CONFIGURATION – Concluded

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Projector ↓	Color Vert. Res. = 304.8 TV lines Brightness = 18.3 ft-L Contrast = 11.4 percent	F	1	2. The color effect is much easier to fly with compared to the black and white effect. 3. The command path flight profile is easier to get back to.

TABLE EII.- PILOT OPINION OF THE MONITOR DISPLAY CONFIGURATION

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor	Black and white Vert. Res. = 356 TV lines Brightness = 22.7 ft-L Contrast = 20.7 percent	A	3	1. This looks like fog or rain; however, it still is missing information needed to properly line up the aircraft with the runway. 2. To get the correct lineup, more rudder control is required, but this was not noticeable with color. 3. There is a feeling that more of a duck under maneuver is taking place during the approach. 4. This is more tiring than color.
↓	↓	B	2	1. It is easier to ease into the glideslope path than for the projector system. 2. The height references near the ground are better. 3. The picture quality is better than the projector display, but it is still tiring on the eyes.
↓	↓	C	3	1. There still seems to be a lack of consistency upon the final touchdown point. 2. Use of the terrain features for an altitude check is improved. 3. Still blinking, but not as much as with the projector. 4. The inability to determine height over the threshold is disturbing due to the poorer runway definition.
↓	↓	D	2	1. The task was performed well, but there is still some moderate visual distress with a greater need for concentration in the final moments of the approach.
↓	↓	E	3	1. The approach with this system is much more natural than with the projector display.

TABLE EII.- PILOT OPINION OF THE MONITOR DISPLAY CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor	Black and white Vert. res. = 356 TV lines Brightness = 22.7 ft-L Contrast = 20.7 percent	E	3	2. The improvement in depth perception is very helpful. 3. Visual scanning of the scene is much easier. 4. Flights made with this system are more consistent.
		F	2	1. There is something different about the picture; looks better down close, but more distinct than the projector. 2. The lineup is more difficult without the color. 3. More rudder than normal is used.
		G	2	1. There is little initial height reference. 2. The height reference is good prior to touchdown. 3. It is hard to find the intercept (glide slope) point. 4. Blinking is occurring more often than for color.
	Color Vert. res. = 356 TV lines Brightness = 24.3 ft-L Contrast = 17.7 percent	G	1	1. There is not transition problem and can fly much easier than the black and white system. 2. With black and white, it was much harder to achieve the same result as obtained with color. 3. With the use of color, a more natural appearance affords a normal interpretation of various cues, thus reducing the effort required to maintain profile. 4. The fatigue factor compared with black and white is much less.
		A	2	1. This clearer picture traps you as is done in an actual VFR approach.

TABLE EII.- PILOT OPINION OF THE MONITOR DISPLAY CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor	Color Vert. res. = 356 TV lines Brightness = 24.3 ft-L Contrast = 17.7 percent	A	2	2. It feels much more normal VFR than for the projector VFR. 3. There is a better feeling for lining up. 4. There is overwhelming information during the last 500 ft altitude when needed and can really analyze things very similar to actual flight. This was not possible with the projector system.
		B	2	1. There was a tendency to wait on the lineup with the black and white system; however, with this system, it is a little easier. 2. These series of flights have been of considerable help in flying the actual aircraft. The flight experience and the simulator experience have been reciprocal. 3. There is no transition problem. 4. The aircraft motion is not missed.
		C	2	1. There is no transition problem. 2. The picture seems better. 3. There are stronger height information cues. 4. There is more consistency in the flair and touchdown with this series.
		D	2	1. This display is very impressive insofar as the resolution and clarity compared to the projector. 2. The depth perception is very strong near the ground. Everything stands out so much more clearly than for the projector display that it is much more realistic. 3. It seems much easier to learn with this system.

TABLE EII.- PILOT OPINION OF THE MONITOR DISPLAY CONFIGURATION – Concluded

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor	Color Vert. res. = 356 TV lines Brightness = 24.3 ft-L Contrast = 17.7 percent	E	2	1. The picture quality is much improved over the projector. 2. There is less of a transition problem – more consistent. 3. It is most easy and natural to fly right away. 4. There is a strong tendency to use a power-on approach (from the decision height on down) with this display.
↓	↓	F	1	1. This system seems very good. There is no transition problem, and it is easy to fly. 2. The picture looks very realistic from about 1000 ft on down. 3. The runway effects at termination are very good.

TABLE EIII.- PILOT OPINION OF THE MONITOR REDUCED RESOLUTION CONFIGURATION

Display System	Control Parameters	Pilot	Pilot Rating	Pilot comments
Monitor Reduced Resolution	Black and white Vert. res. = 228.6 TV lines Brightness = 22.7 ft-L Contrast = 20.7 percent	A	4	1. It is very tiring. 2. There is no altitude reference. 3. It feels like flying over a washboard. 4. It seems to affect the flare. 5. It feels like the touchdown point is closer to the threshold.
↓	↓	B	4	1. The approaches usually resulted in a worse position than for the better resolution system. 2. This display is very tiring.
↓	↓	C	4	1. There is very little height reference and depth perception.
↓	↓	D	3	1. There is more visual distress with a greater need for concentration in the final moments of the approach. 2. Control input was delayed because of the confusion of being either high or low relative to the glide slope. 3. The workload is greater for black and white than for color.
↓	↓	E	3	1. The depth perception seems to be affected. 2. There is a lot more eye strain.
↓	↓	F	4	1. There is a loss in depth perception.
↓	↓	G	4	1. The landings are harder. 2. In determining the flare point, there is a loss of an altitude reference. 3. There is a higher amount of fatigue by a factor of 4.

TABLE EIII.- PILOT OPINION OF THE MONITOR REDUCED RESOLUTION CONFIGURATION – Continued

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor Reduced Resolution	Black and white Vert. res. = 228.6 TV lines Brightness = 22.7 ft-L Contrast = 20.7 percent	G	4	4. There is more hesitancy in putting input control because of an indecisive knowledge of the true aircraft position. 5. A total gain requirement was needed to perform the required landing task.
	Color Vert. res. = 228.6 TV lines Brightness = 24.3 ft-L Contrast 17.7 percent	A	4	1. It is very tiring. 2. There is no altitude reference. 3. It seems to affect the flight path. 4. The flare is affected.
		B	3	1. The landings seem harder than normal. 2. The approaches resulted in a worse position than for the system with better resolution.
		C	3	1. The altitude cues near the runway were poor. 2. The touchdown occurs before it is expected.
		D	3	1. The intercepts and corrections to the course and glide path were delayed until the runway appeared more clearly. 2. The final 100-200 ft of the approach were slightly more difficult than with the better resolution system.
		E	3	1. The height information and depth perception are affected. 2. The control activity seems to be less.
		F	3	1. There is a loss in depth perception.
		G	3	1. More mental concentration is required. 2. The landings feel harder.

TABLE EIII.- PILOT OPINION OF THE MONITOR REDUCED RESOLUTION CONFIGURATION – Concluded

Display System	Control Parameters	Pilot	Pilot Rating	Pilot Comments
Monitor Reduced Resolution	Color Vert. res. = 228.6 TV lines Bri Brightness = 24.3 ft-L Contrast = 17.7 percent	G	3	3. The picture quality seemed to contribute greatly to goofing, especially from the threshold to touchdown. 4. The poor picture quality required above average effort to achieve even reasonable approach techniques.

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