Effect of Display Color on Pilot Performance and Describing Functions

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A study has been conducted with the full-spectrum, calligraphic, computer-generated display system to determine the effect of chromatic content of the visual display upon pilot performance during the landing approach maneuver. This study utilizes a new digital chromatic display system, which has previously been shown to improve the perceived fidelity of out-the-window display scenes, and presents the results of an experiment designed to determine the effects of display color content by the measurement of both vertical approach performance and pilot-describing functions. This method was selected to more fully explore the effects of visual color cues used by the pilot. Two types of landing approaches were made: dynamic and frozen range, with either a landing approach scene or a perspective array display. The landing approach scene was presented with either red runway lights and blue taxiway lights or with the colors reversed, and the perspective array with red lights, blue lights, or red and blue lights combined. The vertical performance measures obtained in this experiment indicated that the pilots performed best with the blue and red/blue displays, and worst with the red displays. The describing-function system analysis showed more variation with the red displays. The crossover frequencies were lowest with the red displays and highest with the combined red/blue displays, which provided the best overall tracking performance. Describing-function performance measures, vertical performance measures, and pilot opinion support the hypothesis that specific colors in displays can influence the pilots' control characteristics during the final approach.

Nomenclature

A_i	= amplitude of input disturbance, rad
h	= aircraft altitude, m
$\dot{h}$	= aircraft rate of descent, m/sec
h_d	= altitude input disturbance, rad
h_e	= altitude error referenced to glide slope, m
h	= aircraft altitude, m
H	= aircraft transfer function
s	= Laplace operator, 1/sec
$\overset{*}{Y}$	= total describing function of pilot, rad/rad
Y_h	= altitude describing function of pilot, rad/m
Y_θ	= attitude describing function of pilot, rad/rad
Y_{OL}	= open-loop describing function, rad/rad
δ	= elevator controller deflection, rad
δ_d	= input disturbance, rad
δ_E	= error control deflection, rad
η	= pilot remnant, rad
θ	= aircraft pitch attitude, rad
τ	= input disturbance tracking time, sec
τ_{TOT}	= time outside glide slope error limits (± 0.5 deg γ), sec
ω_c	= open-loop crossover frequency, rad/sec
ω_i	= input disturbance frequency, rad/sec

I. Introduction

CURRENT visual display systems for piloted simulators provide out-the-window scenes either by means of movie systems, televized views of airport models, or by digitally generated display techniques. Most experience has been obtained with either black-and-white or color TV systems. Recent studies have shown that color is preferred by pilots and that landing performance is significantly improved for both the TV and calligraphic color display systems.[1,2] In spite of the current improvements in both research and training simulators, the pilot's visual cue requirements are not well understood. This lack of understanding of the pilot's needs in terms of the various visual-display color cues may be related to the inherent limitations in realism present in the simulator display scene. A device now in use (which represents a significant improvement in color fidelity) is the Computer-Generated, Calligraphic, Full-Spectrum Color System invented by this author. This device provides a color display system with the capability and fidelity to study the effects of color as specified by hue, value, and chroma. The important characteristic of this display is its capability to generate over 500 colors at high brightness levels and resolution. This chromatic display system has been shown to produce both better performance and confidence, particularly when presented as an aerial image.[2] The pilots reported that this enhancement was due to the perceived three-dimensional characteristics of the color night landing scene. They also indicated that the red colors appeared to be in front of and above the blue colors. This effect has been commonly referred to as "color stereoscopy,"[3] but has not been observed in current night landing, computer-generated, visual display devices because of inadequate means of generating the blue spectrum. Although this investigation was not concerned with studying the stereo effect directly, there is at least one experimental condition that includes these characteristics in the display scene. Because of the color stereoscopy effect, two small equidistant light sources with red and blue dominant hues will appear as if at unequal distances, to some extent in monocular vision and markedly so in binocular observation. Red always appears nearer, and blue appears more distant. The effect is without question a phenomenon of stereoscopic depth perception.[3] The only study that supports the color stereoscopy phenomenon was a recent experiment conducted with a Bausch and Lomb "Modified" Model Orthorater in an attempt to demonstrate the apparent depth of colors and to quantify the results.[4] In this investigation, the luminances for both red and blue rods were varied and found to be independent of the perceived position of the rods, the red rod always appearing closer to the observer than the blue.

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Another factor that could affect performance is found in a recent study concerned with the response time to colored (blue, yellow, green, red) stimuli imaged upon or near the fovea, which showed that the response time within a 30 deg field of view was approximately 18% faster for blue (280 msec) than for red (330 msec) light.[5] These results indicate that the pilot's performance of a closed-loop control task could be affected by the color content of a display.

Because subjects were shown to respond differently to both blue and red light, as indicated above, it was suspected that the pilot's performance might be subject to chromatic visual-cue variations in the display, and likewise to chromatic influences in the real world. Since the computer-generated, calligraphic, full-spectrum color system can precisely control the colors, an experiment was formulated to examine how variations of the red and blue colors in the display scene might influence pilot performance and opinion. Providing that differences can be shown, a direct application can be realized in the areas of head-up displays and in modification of the landing approach lighting systems.

In order to examine in greater detail how the pilot's performance and dynamics vary with color visual-cue influences, a new or modified measurement technique should be developed. A technique that has proven to be an invaluable engineering tool in the analysis of manual control of a wide variety of vehicles is the measurement of pilot-describing functions.[6,7] The reason for using describing functions as a measurement technique is to look for differences in pilot dynamics and tracking performance prior to the final touchdown maneuver. The application of describing function techniques to measure pilot variations due to chromatic influences has not previously been attempted to our knowledge. Specifically, this paper describes an experiment that was conducted to determine differences in pilot performance and pilot-describing functions due to the following display configurations: 1) two landing approach scenes, one with red approach lights and blue taxiway lights and the other with the colors reversed, and 2) three perspective arrays of either red, blue, or red and blue lights.

II. Equipment and Method

The essential components of the computer-generated system are 1) a Systems Engineering Laboratories SEL 840 digital computer, 2) an Evans and Sutherland Line Drawing System (LDS-2), and 3) the supporting optical collimating lens arrangement and Full-Spectrum Calligraphic Projector.[2] The visual scene was generated with the use of the above components. Although the optical system can operate in either of two modes, a rear projection scene or an aerial image scene, the aerial image was utilized because of its superior brightness, resolution, and three-dimensional color stereoscopy qualities. This visual display system was placed in the windscreen of a fixed-base cockpit cab. The aerial image scene was a virtual image, which was obtained directly from the scene on the cathode-ray tube, and was located 3.048 m from the pilot's eye. Because the virtual image plane was not located at optical infinity, the true collimation was changed to quasicollimation. The field of view was 40 deg both horizontally and vertically, and scene magnification was determined to be unity. According to the previous experiment,[2] the brightness of the display was adjusted for the white spectrum to about 1884 cd/m^2, for the green spectrum (550 N·m) to about 1302 cd/m^2, for the red spectrum (620 N·m) to about 343 cd/m^2, and for the blue spectrum (450 N·m) to about 274 cd/m^2. These values produced the maximum scene brightness, for which no retrace lines were visible in the display scene. The corresponding resolution for each color normally varies as a function of the wavelength of the particular color. These brightness levels were found to be satisfactory to the pilots. Although threre is a 20% difference in the brightness between the red and blue colors, it has previously been found to be independent of the perception of depth.[4] The resolution varied from 1200 lines per picture height for the blue spectrum to about 800 lines per picture height for the red spectrum. Both the green and white spectra were about 1000 lines resolution per picture height. In calculating the size of the retinal blur circles for both the red and blue spectra, it was found that the red image would be 1.55 times the size of the blue image. This is in good agreement with the measured resolution about which has a ratio of 1200/800, i.e., 1.5 times larger for red than for blue images.

Computer-Generated Chromatic Display

The combined SEL 840 digital computer and LDS-2 were used to 1) compute the aircraft dynamics, 2) provide the stored data base for the scene to be displayed, and 3) perform all the computations pertaining to matrix multiplication, translation, rotation, and display clipping. The full-spectrum calligraphic projector provided synchronization and color field pulses to the LDS-2.

The resulting simulated scene of the San Jose Municipal Airport, as viewed by the pilot, can be seen in Fig. 1. This scene, which contained green, white, orange, and blue-green lights as well as both red and blue lights, was made for viewing in two modes: 1) red approach lights and blue taxiway lights, and 2) a reversed color scene – blue approach lights and red taxiway lights. Figure 2 is a second display that was programmed to display three variations of a perspective array of lights positioned on the ground. They were all lights of red, all lights of blue, and red and blue lights combined in alternate rows. These displays were refreshed above critical flicker frequencies at 30 Hz.

A DC-8 jet transport aircraft was simulated with dynamics that included longitudinal responses (both plugoid and short-period modes), lateral responses (including the spiral, roll-subsidence,and Dutch-roll modes), and ground effect characteristics.[7] The longitudinal transfer functions are

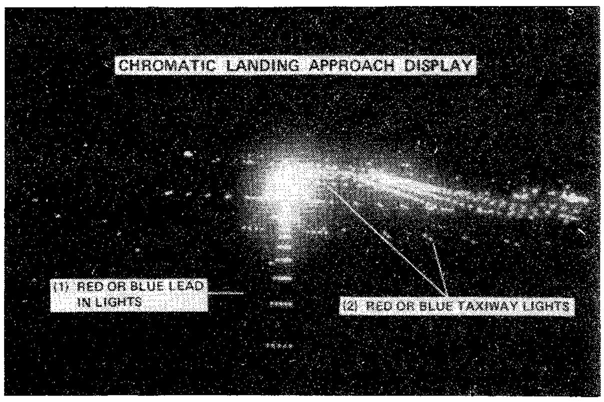

Fig. 1 Chromatic landing approach display.

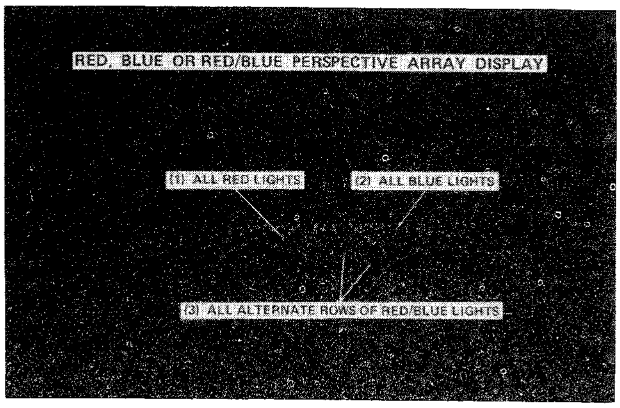

Fig. 2 Red, blue, or red/blue perspective array display.

provided in the Appendix. A variable throttle-position, side-arm controller and a rudder pedal, force-feel control system were also incorporated in the simulation.

Experimental Procedures

To obtain information on how pilots respond to chromatic influences by measurement of describing functions, six airline pilots participated in a fixed-base simulation study involving the landing approach phase of flight. Two of the pilots were Captains and the remaining four were First Officers, all of whom were on current flight status and qualified in similar aircraft.

The order of presentation of the experimental conditions is shown in Table 1. All flights were conducted with the aerial image display. The landing approach scene had the following two visual display variations: 1) a normal scene with red approach lights and blue taxiway lights (Fig. 1), and 2) a reversed-color scene with blue approach lights and red taxiway lights. In order to further test the effect of specific colors upon pilot performance, three perspective arrays of red, blue, and red/blue, which are representative of lights on the ground, in place of the normal approach scene were also provided (Fig. 2). Two different positions were chosen for performing the approach maneuver during the required tracking task from which the describing functions were calculated in order to determine if differences in phase or amplitude could be observed with changes in the chromatic display conditions. These positions were standardized for 1) dynamic flights with the pilot in command of six degrees of freedom of the aircraft and 2) a frozen-range flight whereby the pilot was positioned above the approach lights (Fig. 1) and in command of only five degrees of freedom of the aircraft. The frozen-range flights were utilized to more accurately provide details in tracking performance in the vicinity of the runway threshold. From this frozen-range position, the nonstationary aspects of the maneuvers are removed, and hence a more valid representation of the transfer function influence, while viewing the display at this range and altitude, can be realized.

To obtain consistent precision, the initial standardized positions for the dynamic flights were an altitude of 415.32 m above the runway, an approach speed of 69.5 m/sec, flaps extended 25 deg, landing gear down, 7.92 km ground distance to the touchdown point on the runway, and a flight path of −3 deg from the horizontal. For the frozen-range situation, the altitude was changed to 79.86 m, and the range was changed to 914.4 m from the threshold.

The pilots performed 15 dynamic training flights each with both the red and blue landing-approach-light scene. During this training period, the approaches were made with the airspeed and altitude presented digitally in the upper corners of the display and monitored at the pilot's discretion. During the criterion flights, no airspeed or altitude information was presented. A throttle was also provided, but it was emphasized that the speed should be adjusted only to maintain a uniform terminal velocity, and thereafter the pilots should make no further adjustments for the criterion dynamic or frozen-range flights. To avoid influencing the data by concerted pilot efforts on any particular performance measure, the pilots were not provided performance feedback at any time during the training or experimental flights.

At the conclusion of each landing approach scene and perspective array display scene, two additional flights were made with disturbance inputs resembling wind gusts for

Table 1 Experimental conditions

Collimated display system	Runway approach condition	Type of approach	Chroma of display scene: Perspective arrays	Chroma of display scene: Land approach scene and approach lights	Landings per session each pilot	Chromatic describing function flights	Experimental sequence
Aerial image	Dynamic	Visual training flights		Red	15		1
Aerial image		Visual training flights		Blue	15		2
Aerial image	Dynamic	Visual		Red	15		3
Aerial image	Dynamic			Red		2	4
Aerial image	Dynamic			Blue	15		5
Aerial image	Dynamic			Blue		2	6
Aerial image	Dynamic		Red-Blue-Red/Blue			3	7
Aerial image	Dynamic		Blue-Red/Blue-Red			3	
Aerial image	Dynamic		Red/Blue-Red-Blue			3	
Aerial image	Frozen range			Red-Blue		2	8
Aerial image	Frozen range			Blue-Red		2	
Aerial image	Frozen range		Blue-Red/Blue-Red			3	9
Aerial image	Frozen range		Red/Blue-Red-Blue			3	
Aerial image	Frozen range		Red-Blue-Red/Blue			3	
Aerial image	Dynamic			Blue	15		10
Aerial image	Dynamic			Red	15		11

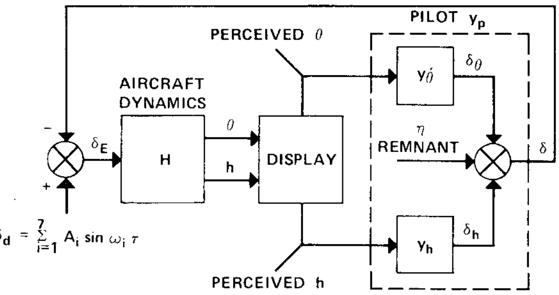

Fig. 3 Block diagram of pilot-describing-function method.

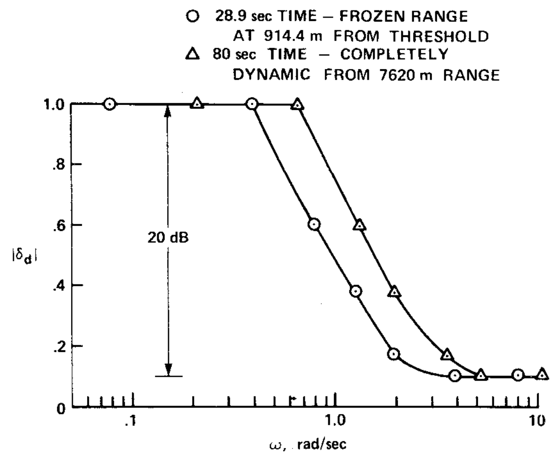

Fig. 4 Power spectra of input disturbance forcing function.

calculating the pilot-describing functions. As shown in Table 1, those flights for both the dynamic and frozen range and for the perspective arrays were balanced by a Latin Square experimental design to test for main effects due to color differences or for order effects. At the conclusion, a series of 15 dynamic flights each was made with the two landing approach display scenes to test for learning effects.

Pilot-Describing Function Method

One of the most common man/machine systems in use today is the airplane. Yet, remarkably little is known about the details of pilot dynamic visual responses and how these interact with the aircraft dynamic characteristics. In order to provide more enlightenment on the nature of the pilot in conjunction with the visual simulation display scene, it was necessary to attempt to measure two separate control loops, pitch attitude, and altitude. Figure 3 shows the block-diagram method for measuring the pilot-describing function with a single disturbance input δ_d. It is commonly accepted that the pitch attitude θ is referred to as the inner loop and that the altitude h is referred to as the outer loop. The pilot will perceive changes in both pitch attitude and altitude through his display and in turn is expected to make changes through his control stick δ to adjust the airplane through its dynamics H to a desired position. The single input disturbance δ_d serves to excite both the pitch loop and altitude loop in a manner that the pilot-describing function $\overset{*}{Y}$ can be obtained by Fast Fourier Transform Analysis.[8] In order to analyze the pilot's contribution through his control-loop equations of pitch attitude and altitude, the closed-loop and open-loop equations are briefly described in the Appendix to show the individual contributions within the cross-spectral transform ratios.

Figure 4 shows the power spectrum of the input disturbance forcing function for the two flight conditions. The actual input disturbance magnitude was based upon minimizing the contributions of both noise and remnant. Although this magnitude is about 3.6 times higher than that used in previous experiments,[6,7] it was not considered a difficult task, especially since the sidearm controller in the simulator had low inertia and minimal hysteresis and breakout characteristics. Since there were two initial aircraft positions requiring two different tracking times for each of the dynamic and frozen-range flights, there had to be two different and corresponding sets of power spectrum disturbance frequencies. For the dynamic flights, the run time was 80 sec. The effective bandwidth for these flights was 0.65 rad/sec with a second-order roll-off and a −20 dB shelf. The corresponding disturbance input frequencies were 0.078, 0.393, 0.785, 1.26, 1.93, 3.93, and 7.85 rad/sec. The remnant frequencies were measured at 0.157, 0.314, 0.628, 1.57, 3.14, and 6.28 rad/sec. For the frozen-range flights, the run time was 28.9 sec. The effective bandwidth for these flights was 0.40 rad/sec, also with a second-order roll-off and a −20 dB shelf. The corresponding disturbance input frequencies were 0.218, 0.654, 1.31, 1.96, 3.49, 5.24, and 10.47 rad/sec. The remnant frequencies were measured at 0.436, 0.872, 1.74, 2.62, 3.93, and 7.85 rad/sec. A 20-sec warmup period was allowed for each of the two aircraft positions prior to each respective 80- or 28.9-sec describing function computational analysis period. During the dynamic flights, the 80-sec disturbance was removed at about 30.48 m of altitude. In order to prevent any anomalous cross-talk between the lateral response of the aircraft and vertical measurements being taken on the pitch attitude and altitude loops, a lateral autopilot was incorporated for use only when describing-function flights were being performed.

A special preliminary test was required to be conducted prior to the criterion experiment in order to determine the degree of sensitivity of the describing-function contribution Y_h shown in Eqs. (A1) and (A8) of the Appendix through the altitude loop by itself. Referring to Fig. 3, the steering disturbance δ_d was removed and the altitude disturbance h_d was applied as shown in the first section of the Appendix. It was found that this contribution for both the frozen-range and dynamic conditions was negligible, since the pilots would not track this outer altitude loop, and hence the attitude-loop pilot-describing function could be successfully measured according to the method shown in the Appendix. This altitude contribution would normally be expected to approach zero at the higher frequencies.

A technique for checking the computed transform for the pilot model shown in Fig. 3 was accomplished by substituting the filter of the form $[4.5/(s+4.5)]$ for the aircraft dynamics and a gain of 5 into the pilot model. The resulting Fourier transform for the pitch attitude was formed and compared with the results of the original filter and gain. This was performed for both the two different run times of 28.9 and 80 sec. As a check for the pilot and aircraft dynamics model, the Appendix provides the aircraft dynamics transfer functions

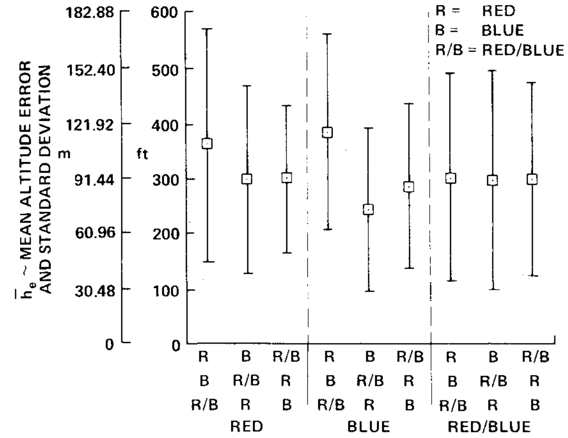

Fig. 5 Mean altitude error for the dynamic perspective array display.

θ/δ and h/δ. The θ/δ transfer function was used to help check the open-loop δ/δ_E transfer function and crossover frequencies with those obtained by measuring the δ/θ and θ/δ_E ratios.

A total of 156 pilot chromatic describing-function flight was made. Besides the 180 training flights, there was also a total of 180 criterion flights made only with the landing approach scene. An additional 180 flights were made to investigate possible learning effects.

In addition to the two usual performance measures of touchdown distance from threshold and touchdown rate of descent, four additional performance measures were obtained for all the simulated flights. They were altitude error, time outside glide-slope limits, ratio of pilot output power to input disturbance power, and open-loop crossover frequency. The values of these performance measures are the result of the initial experimental conditions and the pilots' adaptive tendencies for the visual approaches. These criteria were categorized as 1) vertical-approach performance and 2) pilot-describing-function performance. A pilot opinion survey was also collected and used to correlate with the visual display scenes and to provide positive direction for future experiments.

III. Results and Discussion

Most pilots are accustomed to flying a Visual Flight Rules (VFR) approach with the normal complement of cockpit instruments. Forcing the pilot to use the out-the-window visual cues during the entire course of the simulator flight produces changes in visual cockpit procedures. The pilots' initial concerns were that of finding correct power settings and establishing adequate airspeed. These were usually accomplished within the 15 visual training flights, and thereafter the pilots could concentrate on the final approach visual display scene. The two terminal performance measures, touchdown distance and touchdown rate of descent, were found to be in very good agreement with a previous experiment by this author.[2] From this earlier experiment, the mean touchdown distance was 406.3 m, and the mean touchdown rate of descent was 1.29 m/sec. The standard deviations were 96.62 m and 0.50 m/sec, respectively. They are referred to only at this point because the nature of this experiment is to concentrate on the two principal performance measures discussed earlier. For the current experiment, the mean touchdown distance was 474.9 m, and the mean touchdown rate of descent was 1.2 m/sec. The standard deviations were 106.7 m and 0.51 m/sec, respectively. The above data were obtained for the flights conducted with the landing approach scene and without the disturbance input.

Vertical Approach Performance (Dynamic Landing Approach Scene)

Table 2 shows performance measures that are closely related to the pilot-describing-function performance. They are 1) mean altitude error referenced to the command glidepath h_e and its standard deviation σ_{he}, 2) time outside glide-slope error limits τ_{TOT}, 3) ratio of control elevator power to the disturbance δ^2/δ_d^2, and 4) open-loop crossover frequency ω_c. Although Table 2 contains discrete values of the above performance measures, it should be emphasized that this approach sequence would not be expected to show much difference in performance because of the large distance and high altitude with respect to the chromatic runway scene. At this position, the colors would not be expected to have much influence during the major portion of the flight. As expected, Table 2 shows essentially no major differences between the two display conditions for the dynamic flights.

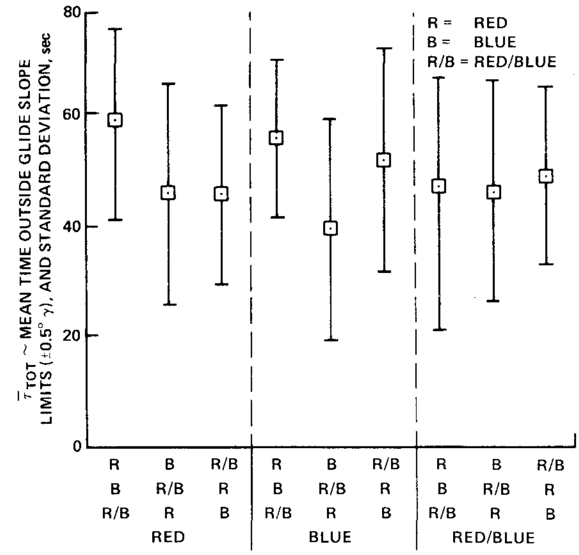

Fig. 6 Mean time outside glide-slope limits for the dynamic perspective array display.

Vertical Approach Performance (Dynamic Perspective Arrays)

Table 3 and Figs. 5-7 show details in relation to the order effects of altitude error, time outside glide-slope error limits, and control power. Each of these figures shows that the largest value occurs initially with either the red or blue array, independent of the order of presentation. The least effect is observed with the red/blue perspective array, which appears to have no variation due to the order of presentation. Although there appears to be a consistent trend for these three performance measures, none of these was found to be significantly different in order effects or main effects as determined by an analysis of variance ($p > 0.05$). Figure 8 also shows that the open-loop crossover frequency is highest for the red/blue perspective display condition and is also highest for any of the display conditions at 2.3 rad/sec.

Table 2 Pilot performance measures for the chromatic landing approach display scene

Runway approach condition	Landing approach scene chroma	$\bar{h}_e$, m	σ_{h_e}, m	$\bar{\tau}_{TOT}$, sec	σ_τ, sec	$\bar{\delta}^2/\delta_d^2$	$\sigma_{\delta^2/\delta_d^2}$	$\bar{\omega}_c$, rad/sec
Dynamic	Normal with red approach lights	21.32	12.97	26.83	26.21	11.16	2.24	1.95
Dynamic	Reversed color with blue approach lights	20.83	11.12	20.17	23.73	11.06	2.10	2.0
Frozen range	Normal with red approach lights	9.94	3.85	12.17	15.64	16.15	2.01	1.9
Frozen range	Reversed color with blue approach lights	9.57	3.67	7.33	7.55	14.62	1.12	2.1
Frozen range	Reversed color with blue approach lights	9.40	4.45	9.17	8.28	19.14	5.63	2.1
Frozen range	Normal with red approach lights	21.43	12.05	31.00	15.21	18.28	8.40	1.9

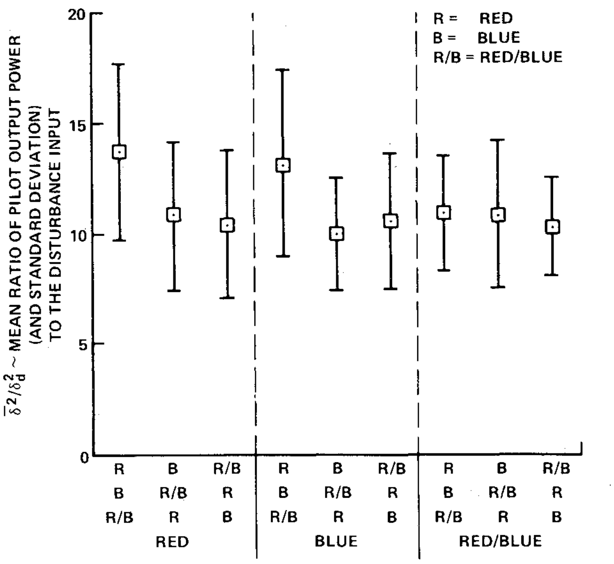

Fig. 7 Mean ratio of pilot output-to-input power for the dynamic perspective array display.

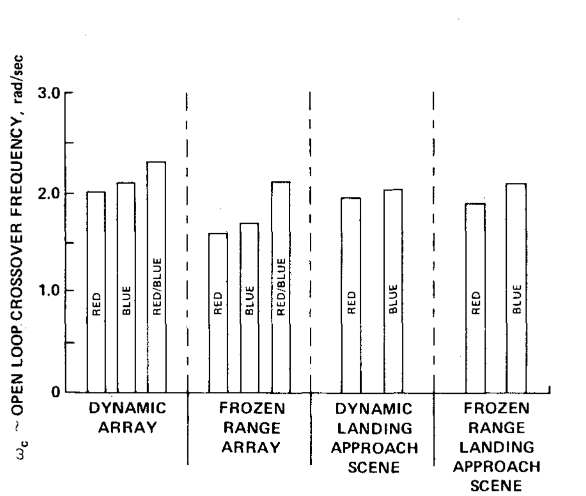

Fig. 8 Open-loop crossover frequency.

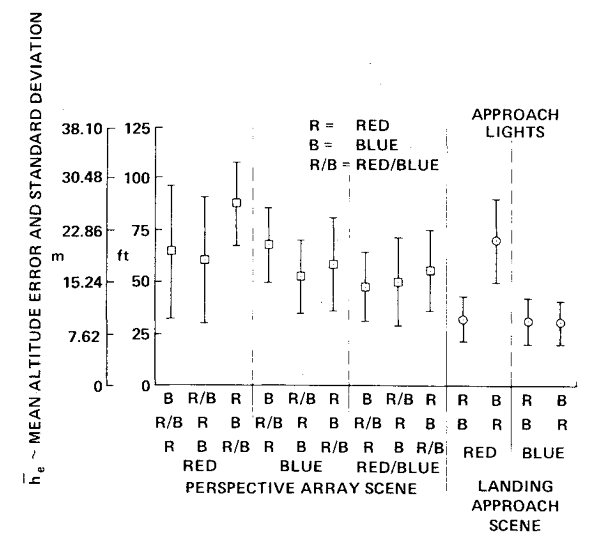

Fig. 9 Mean altitude error for the frozen-range display.

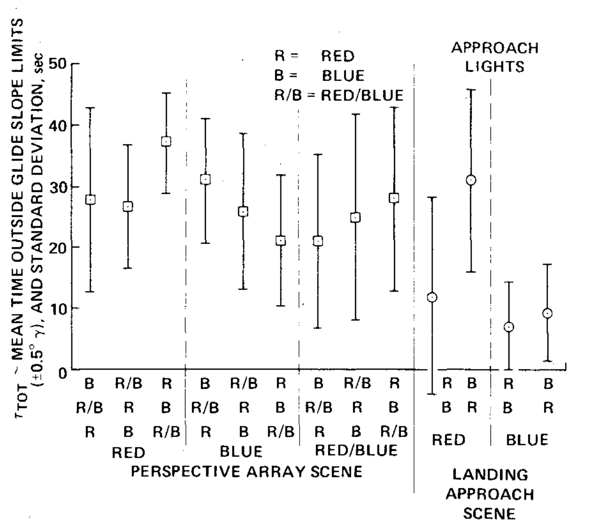

Fig. 10 Mean time outside glide-slope limits for the frozen-range display.

Table 3 Pilot performance measures for the perspective array display scene

Order of presentation	$\bar{h}_e$, m	σ_{h_e}, m	$\bar{\tau}_{TOT}$, sec	σ_τ, sec	$\bar{\delta}^2/\bar{\delta}_d^2$	$\sigma_{\delta^2/\delta_d^2}$	$\bar{\omega}_c$, rad/sec
				Dynamic			
Red	112.60	65.67	59.50	17.13	13.95	4.00	2
Blue	120.28	55.25	56.17	15.64	13.25	4.33	2.1
Red/Blue	92.93	57.99	47.17	22.50	10.85	2.83	2.3
Blue	74.80	45.11	39.67	19.92	10.09	2.80	2.1
Red/Blue	91.54	61.92	46.0	22.54	10.76	3.57	2.3
Red	91.89	52.68	46.50	20.70	10.97	3.32	2
Red/Blue	91.77	54.22	49.17	17.17	10.25	2.23	2.3
Red	92.12	41.67	46.00	16.14	10.50	3.38	2
Blue	87.61	45.07	51.83	22.67	10.38	3.09	2.1
				Frozen range			
Blue	20.71	5.24	30.67	9.99	16.43	2.11	1.7
Red/Blue	14.75	5.27	21.33	14.08	16.37	2.42	2.1
Red	19.85	10.34	27.83	14.80	15.88	2.14	1.6
Red/Blue	15.80	7.06	25.00	17.57	15.39	1.89	2.1
Red	18.69	8.71	26.50	10.33	16.86	4.61	1.6
Blue	16.12	5.17	25.67	12.63	17.25	3.28	1.7
Red	26.54	6.03	37.17	7.73	14.69	3.03	1.6
Blue	17.92	7.86	21.17	10.68	17.23	4.34	1.7
Red/Blue	17.53	5.86	28.00	15.26	16.77	2.83	2.1

Vertical Approach Performance (Frozen-Range Landing Approach Scene)

Table 2 and Figs. 9, 10, and 11 show that the best performance is obtained with the blue approach-light display. Among the three performance measures, altitude error, time outside glide-slope error limits, and output power, there were significant order effects. The altitude error was significantly different for the red approach lights ($p<0.05$), and the time outside the glide-slope error limits were also significantly different ($p<0.01$). It is the author's opinion that these differences, particularly for the second red approach-light condition, are the result of the pilots biasing their flight path either high or low, which in turn has resulted in both larger altitude error and greater time outside the glide path. It should also be noted that with a biased altitude, the pilots can still perform a satisfactory tracking task as evidenced by noting no change in the crossover frequencies shown in Table 2. In testing for the main effects between the red approach-light and blue approach-light display, both the above performance measures were found to be significantly different ($p<0.05$). Although the control power shown in Fig. 11 shows more variance with the red approach lights compared to the blue approach lights, it was not significant ($p>0.05$). Figure 8 shows the open-loop crossover frequency to be slightly higher for the blue approach-light condition at 2.1 rad/sec versus 1.9 rad/sec for the red approach-light conditions.

Vertical Approach Performance (Frozen-Range Perspective Arrays)

Table 3 and Figs. 8, 10 and 11 also show the performance obtained for the red, blue, and red/blue perspective arrays. The red array had the highest altitude error and time outside the glide-slope error limits. The order effects were found to be significantly different between the red, blue, and red/blue arrays ($p<0.05$). In contrast to either the red or blue altitude error, the red/blue altitude error and time outside glide-slope error limits had the lowest values, averaging about 15.24 m and 25 sec, respectively. Figure 11 shows that there are no order effects and essentially no differences due to color for the control power. The crossover frequencies shown in Fig. 8 are the lowest with the red array at 1.6 rad/sec, slightly higher with the blue array at 1.7 rad/sec, and highest with the red/blue chromatic array at 2.1 rad/sec. When the frozen-range landing approach scene and the frozen-range perspective array scenes are compared, a trend of the blue crossover frequency being higher than the red crossover frequency can be observed, with the red/blue crossover frequency representing the highest value. This trend appears to be preserved when comparing those dynamic array flights for the same color conditions as also observed in Fig. 8. This trend seems to indicate that the higher crossover frequency is related to the least amounts of both altitude error and time outside glide-slope error limits, which have been obtained with the red/blue chromatic displays.

Effect of Color on the Pilot-Describing Function

For this experiment, the most complex technique of measuring pilot performance is the calculation of the describing functions based upon the model of the pilot illustrated in Fig. 3, and the equations in the Appendix. The Fourier transform of the pitch attitude loop was calculated for all the display conditions. The resulting pilot-describing function $\overset{*}{Y}$ was obtained while the pilots observed the various color displays. The corresponding open-loop crossover frequencies were calculated by the same method and were reported previously in Tables 2 and 3 and Fig. 8. Therefore, more attention is directed toward the presentation of chromatic effects upon the pilot as determined from his describing functions. In referring back to Table 1 for the order of presentation, the dynamic flights with the landing approach scene would normally come first, followed by dynamic flights for the perspective arrays. However, since the landing approach scene dynamic flights began at such a distance range and high altitude, it was expected that there would not be any significant difference in performance. The data for these flights has already been presented in Table 2 and Fig. 8 in terms of the four performance measures. As shown in Fig. 12, these particular describing functions did not reveal any differences, as was suspected above. The most notable features, however, are the very low and flat gains throughout the spectrum. The gain was compared with all other transfer functions and was found to be significantly different ($p<0.01$).

Describing Functions with the Dynamic Perspective Array Display

An overall performance measure in terms of both amplitude or pilot gain and phase angle difference is shown in Fig. 13. This figure is the total contribution ($\overset{*}{Y}$) of the pilot for the three perspective array displays of red, blue, and red/blue combined. As shown in this figure, the gain and phase for the blue array appear to be higher than for the red or red/blue array up to the vicinity of the crossover frequency. The red/blue array gain appears to be an average between the red or blue arrays. Also provided are the standard deviations for each color at each frequency of interest. The largest deviations are shown to occur at both the high and low ends of the spectrum, with the smallest deviations occurring in the neighborhood of the crossover frequency. The highest crossover frequencies were obtained with the red/blue array

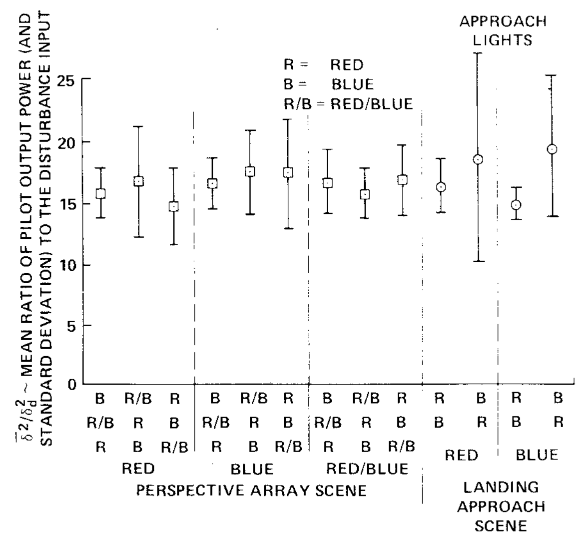

Fig. 11 Mean ratio of pilot output-to-input power for the frozen-range display.

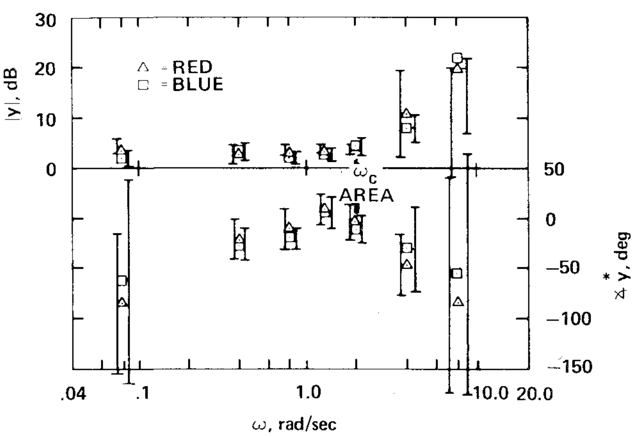

Fig. 12 Pilots' describing functions for the dynamic landing approach display.

display. The phase for the red/blue array has the most favorable phase lead or lag throughout the spectrum when compared to that for the red or blue array display. Assuming that an analysis of variance can be applied to these spectral data for both gain and phase, it was found that in testing for main effects there was no significant difference ($p>0.05$) between any of the displays. Although the above differences in the describing functions may seem minor, it is believed by this author that they are reflected in the trends noted previously in Figs. 5, 6, and 7, whereby the best performance appeared with the red/blue display.

Frozen-Range Landing Approach Display Describing Function

According to Table 1, those flights following the dynamic perspective arrays were the frozen-range flights conducted in the vicinity of the lead-in approach lights. Figure 14 shows the results for the two landing approach display conditions with red and blue approach lights in terms of the pilots' describing functions ($\overset{*}{Y}$). As can be seen, the variation of gains for the two display conditions is very similar with only about a 2-4 dB separation in gain, except at the high-frequency end. A gain difference of 7 dB is evident between these displays at 10.5 rad/sec with the highest gain of 33 dB obtained with the blue approach-light display. The midspectral region is the crossover frequency area where crossover in the neighborhood of 2 rad/sec was found to be higher for the blue approach-light display. At this point, it can be observed that the gain and phase for both display conditions are about 16 dB and +10 deg, respectively. These values are higher by about 4 dB and +12 deg than those for the previous perspective array describing functions. Over most of the spectrum, the blue approach display tends to lead the red approach-light display in phase by approximately 15 deg. The greatest difference, however, occurs at the high-frequency end, where the phase and gain for the red display have reversed by as much as 50 deg and 7 dB, respectively, due to pilot control reversals. The phase standard deviations are shown to be the smallest through the spectrum up to 5.2 rad/sec. They are about half for the blue display compared to the red display through this portion of the spectrum and are actually the smallest in the area of crossover frequency. Assuming that a valid analysis of variance can be applied to these spectral data for both gain and phase, it was found that in testing for main effects there was no significant difference ($p>0.05$) between the two displays. Again, although the above differences in the describing functions may seem minor, it is believed by this author that they are reflected in the performance noted previously in Figs. 9, 10, and 11. These data were found to be significantly different and are the product of the pilots' tracking abilities with a disturbance input. The pilots performed best with the blue approach-light display.

Frozen-Range Perspective Array Display Describing Function

According to Table 1, the final displays presented to the pilots for which the describing functions were calculated were the perspective arrays of red, blue, and red/blue combined. These were also positioned in the vicinity of the runway lead-in approach lights. Figure 15 shows the results for the above-mentioned display in terms of the pilot-describing function $\overset{*}{Y}$. The gain for all three display conditions is essentially the same over the entire frequency spectrum. The standard deviations show the same trend as noted previously, with the smallest deviations occurring in the midfrequency area or region of crossover frequency. The red/blue array has the highest crossover frequency. The crossover frequency area for these three display conditions averages about 1.8 rad/sec. In contrast, the average dynamic crossover frequency was slightly higher at 2 rad/sec. The phase at 1.8 rad/sec is +10 deg. This is 12 deg more in phase lead than that for the dynamic approach. It can be seen that the red array display lags the blue array display by about 15 deg from the low-frequency to the midspectrum range. The blue array display allows the largest phase lead throughout the spectrum. In testing for main effects, there was no significant difference ($p>0.05$) between the three color array display conditions and their describing functions. However, it is again the author's opinion that what appear to be minor differences in the describing functions are reflected in the tracking performance noted previously in Figs. 10 and 11. These data, although not significantly different, do show a trend with the altitude error and time outside glide-slope error limits lowest for the red/blue chromatic array.

General Pilot Comments

The pilots' informal subjective opinions, which were useful in evaluating each display configuration, indicated that chromatic variations of the display were in some cases pleasing and in others antagonistic. The displays that were the most pleasing or restful to the eyes were those associated with the blue colors. In fact, the blue lights, although less bright, seemed to be more effective in helping the pilot determine the geometric plane of the runway. In contrast, the pilots found that the red lights could be seen at a greater range than the blue lights, but that close in to the runway threshold the blue approach-light display provided better ground-plane orientation. When given the red, blue, and red/blue perspective array displays, the pilots were satisfied with only the blue and red/blue combined displays. The most notable complaint by all six pilots was that a peculiar hypnotic ten-

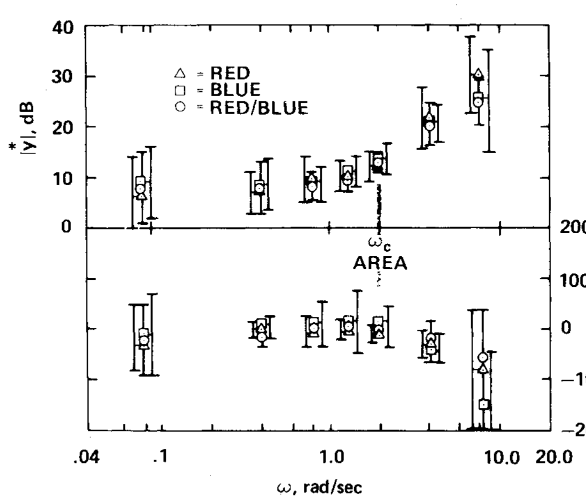

Fig. 13 Pilots' describing functions for the dynamic perspective array display.

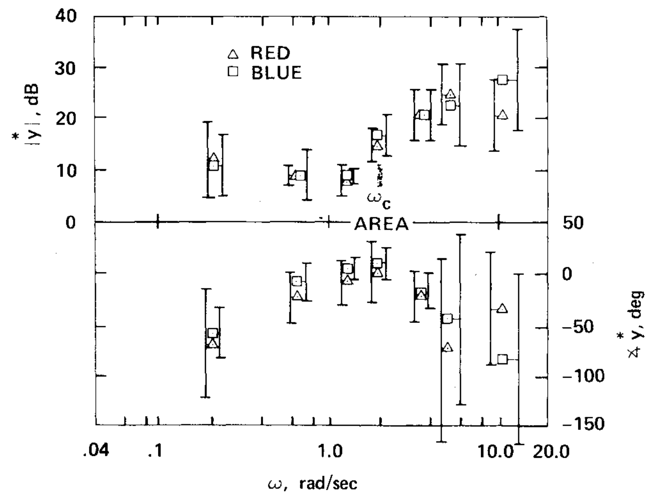

Fig. 14 Pilots' describing functions for the frozen-range landing approach display.

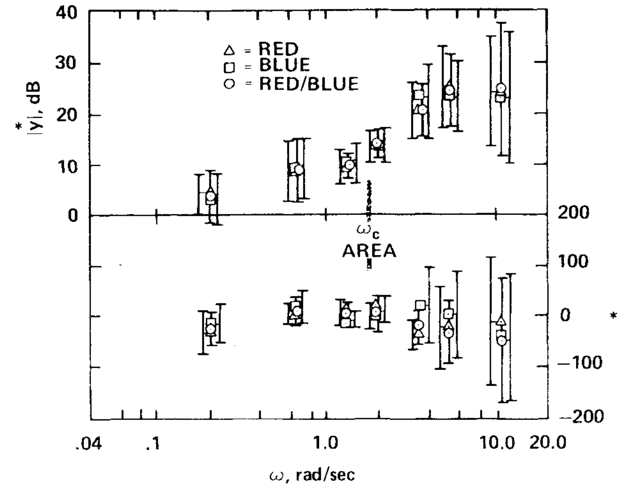

Fig. 15 Pilots' describing functions for the frozen-range and perspective array display.

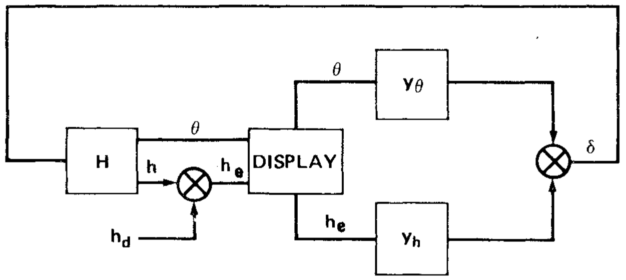

Fig. 16 Block diagram for determining the pilots' altitude describing function.

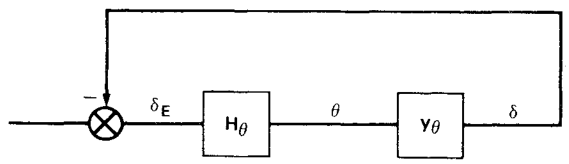

Fig. 17 Block diagram for measuring the open-loop crossover frequencies.

dency was produced with the red array scene. This tendency was not present nor commented upon while tracking with the blue or red/blue arrays. Pilots did mention that the red displays seemed to contribute toward control reversals, and perhaps this comment was prompted by their antagonism for these types of displays due to what they felt was a resultant poorer performance. All the pilots were particularly impressed by the realism of the display scene when presented the landing approach scene. They were aware of the three-dimensional qualities produced from the chromatic landing approach scene, and recognized a more apparent three-dimensional effect when the scene was presented in the form of a red/blue perspective array display.

IV. Concluding Remarks

Visual simulation is now advancing rapidly, especially with the new technique of constructing computer-generated images, a technique that provides high flexibility at lowered cost. However, the rationale for the contribution of color to visual simulation fidelity or realism has not been well established. None of the display devices now in operation have the ability to study the effects of color independently nor in a manner such that pilots may respond to the visual color cues during a closed-loop control task such as the landing approach maneuver. Recent studies have shown that blue colors represent a depth cue and red colors are a more proximal cue. The display system used in this experiment was designed to provide control of red and blue, as well as other colors within the display scene. Since the current technique for evaluating computer-generated as well as television-type displays has been to measure the display effectiveness based upon two principal measures of performance (namely touchdown distance and touchdown rate of descent), it was felt that this measurement technique was inappropriate to study in detail the effect of color on pilot performance and dynamics. In order to explore other techniques and ways of obtaining new information on how color in terminal-approach visual displays affects pilot performance dynamics and opinion, an experiment was developed to measure differences in pilot performance using vertical performance measures and pilot-describing functions. An experimental study utilizing six airline pilots was conducted in a fixed-base simulator to obtain data on selected vertical performance measures and on pilot-describing functions during the landing approach phase of flight. The two basic display variations were presented in two positions; at a distance of about 1609.3 m from which dynamic approaches could be accomplished, and at a frozen-range position in the vicinity of the approach lead-in lights. Two variations of the landing approach display were used: as a red approach-light and a blue taxiway-light display, and a blue approach-light and red taxiway-light display. Three variations of a perspective array display were also used; a red array, a blue array, and a chromatic red/blue array combined. The describing-function performance data as well as several other vertical performance measures were compared to each other in terms of the chromatic displays during the course of this experiment.

The results of this study are listed below.

1) Compared to the red approach-light display, both the altitude error and time outside the glide-slope error limits for the frozen-range flight were significantly lower for the blue approach-light display.

2) For the frozen-range perspective array flights, the two above-performance measures had similar significant order differences for both the red and blue displays, but no order differences for the red/blue array combined. The lowest altitude errors were obtained for the red/blue combined array display when compared to either the red or blue array displays alone.

3) Similar order effects were observed between the perspective red and blue dynamic array flights for altitude error, time outside glide-slope limits, and pilot control power. No order effects were observed for these same performance measures for the perspective red/blue arrays combined. The lowest vertical performance values were obtained with the perspective red/blue array display.

4) The crossover frequency consistently increased in going from red to blue to red/blue combined for each of the display conditions. The high crossover frequencies appeared to be associated with the blue scenes and were even higher when balanced with a red/blue display combination. The resulting altitude errors with this red/blue combination were also significantly lower.

5) When dynamic or frozen-range perspective array flights were made with the red, blue, and red/blue array display scenes, the pilot-describing-function gain and phase were not significantly different. However, both these gain and phase differences have been magnified by the pilot's tracking task and by his attempt to minimize other performance measures such as altitude error and time outside glide-slope error limits.

6) The frozen-range condition with the normal and reversed landing approach scene showed the largest differences in the pilot's describing-function gain and phase. The best describing-function performance was obtained for the blue approach-light scene when compared to the red approach-light scene, suggesting that the pilots were obtaining a

better perceptual visual definition of the ground plane. These describing functions, although not significantly different, are the result of the pilots' tracking and were found to produce very significant differences in both altitude error and time outside glide-slope error limits, with the best performance obtained for the blue approach-light display.

7) The pilots were critical of the red array display and favored the use of a combined red/blue display. Blue displays were more visually relaxing to the pilots. Their comments were also quite favorable toward the level of realism achieved in the visual simulation display scene, particularly the three-dimensional effect, resolution, and brightness.

These results support the hypothesis that improvement in visual simulation can be obtained through the use of specific colors within the display scene by influencing the pilot's control characteristics. It is possible that fruitful research can now be directed toward such areas as 1) chromatic display for heads-up landing applications, 2) the study of high-intensity approach lighting systems, and 3) the study of color stereoscopy in the visible spectrum at particular wavelengths.

Appendix

Derivation of the Pilot-Describing-Function Equations

Preliminary trials were required to be performed with an altitude disturbance as shown in Fig. 16, which is a modification of that shown in Fig. 3. This test was required to show that Y_h in Eq. (A8) was negligible. It was found that with the disturbance in the outer altitude loop, the pilots could not track latitude with the display as viewed through the windscreen and hence Y_h did not contribute to the pitch-describing function.

The pilot altitude describing functions were determined for the system shown in Fig. 3. For the pilot closures shown in Fig. 3, the pilot's stick deflection is given by

$$\delta=\delta_\theta+\delta_h+\eta \tag{A1}$$

The transfer functions across the airframe are

$$\theta=H_\theta\delta_E \tag{A2}$$

$$h=H_h\delta_E \tag{A3}$$

The transfer functions across the pilot are

$$\delta_\theta=Y_\theta\theta \tag{A4}$$

$$\delta_h=Y_h h \tag{A5}$$

Substituting Eqs. (A2)-(A5) into Eq. (A1) gives

$$\delta=Y_\theta H_\theta\delta_E+Y_h H_h\delta_E+\eta \tag{A6}$$

where η is the pilot's remnant. Forming the cross spectra between the pilot's stick deflection and disturbance input gives

$$\Phi_{\delta_d\delta}=Y_\theta H_\theta\Phi_{\delta_d\delta_E}+Y_h H_h\Phi_{\delta_d\delta_E} \tag{A7}$$

The cross spectra across the remnant is not formed because the remnant is uncorrelated with the input disturbance. Solving Eq. (A7) for Y_θ gives

$$Y_\theta=\frac{\Phi_{\delta_d\delta}-Y_h H_h\Phi_{\delta_d\delta_E}}{H_\theta\Phi_{\delta_d\delta_E}} \tag{A8}$$

The term Y_h in Eq. (A8) is actually very small at high frequency. It was shown to have no effect on the pilot's tracking ability according to the preliminary trials discussed above. Therefore, the second term in the numerator of Eq. (A8) may be neglected with little effect on the pilot's attitude describing function. The term Y_θ can be obtained as

$$Y_\theta=\frac{\Phi_{\delta_d\delta}}{H_\theta\Phi_{\delta_d\delta_E}}=\overset{*}{Y} \tag{A9}$$

Open-Loop Crossover Frequency Equation

From Fig. 3, the open-loop crossover frequency was derived across the attitude loop as shown in Fig. 17. The cross spectra for Y_θ were previously obtained as shown in Eq. (A9). The open loop is the ratio

$$Y_{OL}=\delta/\delta_E=H_\theta Y_\theta \tag{A10}$$

Therefore, in terms of the cross spectra, the open loop is

$$Y_{OL}=\frac{H_\theta\Phi_{\delta_d\delta}}{H_\theta\Phi_{\delta_d\delta_E}}=\frac{\Phi_{\delta_d\delta}}{\Phi_{\delta_d\delta_E}} \tag{A11}$$

The input disturbance frequency points were plotted for this cross-spectral ratio, and a linear interpolation was applied to the two closest points nearest the 0-dB line for the determination of the open-loop crossover frequencies.

Longitudinal Airframe Transfer Functions

The pitch attitude is given as

$$\frac{\theta}{\delta}=\frac{-0.915(s+0.101)(s+0.646)}{(s^2+0.0287s+0.0275)(s^2+1.5424s+1.5129)}$$

The altitude is given as

$$\frac{h}{\delta}=\frac{9.25(s-3.63)(s+0.0352)(s+4.42)}{s(s^2+0.0287s+0.0275)(s^2+1.5424s+1.5129)}$$

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