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# Stereopsis Cueing Effects on Hover-in-Turbulence Performance in a Simulated Rotorcraft

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## Summary

The efficacy of stereopsis cueing in pictorial displays was assessed in a real-time piloted simulation of a rotorcraft precision "hover-in-turbulence" task. Seven pilots endeavored to maintain a hover by visually aligning a set of inner and outer wickets (major elements of a "real-world" pictorial display) to attain the desired hover position. A full factorial experimental design was used. The display conditions examined included the presence or absence of a velocity display element (a velocity head-up display) as well as the stereopsis cueing conditions, which included nonstereo (binoptic or monoscopic, i.e., no depth cues other than those provided by a real-world display, such as perspective, size, shape, interposition, and motion parallax), three-dimensional stereo, and hyperstereo (telestereoscopic). The latter condition exaggerated the depth cues present in the display (as might be encountered with forward-looking infrared cameras mounted on each side of a cockpit for a binocular display). The performance metrics for the study included root-mean-square values of the radial displacement from the desired hover point as well as the pilot control inputs.

Subjective and objective results indicated that the depth cues provided by the stereo displays enhanced the situational awareness of the pilot and enabled improved hover performance to be achieved. The velocity display element also improved the hover performance, with the best hover performance being achieved with the combined use of stereo and the velocity display element. Additionally, less pilot control action was required to attain the improved hover performance with the stereo displays.

## Introduction

Current electronic display technology can provide high-fidelity, "real-world" pictorial displays under flicker-free conditions that incorporate true depth in the display elements. Advanced pictorial flight display concepts that incorporate three-dimensional (3-D) images are being conceived of and evaluated at various flight display research laboratories, including the Langley Research Center. Innovative concepts are sought that exploit the power of modern graphics display generators and stereopsis cueing, not only in situational awareness enhancements of pictorial displays, but also in displays for the declutter of complex informational displays and in providing more effective alerting functions to the flight crew.

The intuitively advantageous use of three-dimensional display of three-dimensional information, rather than the conventional two-dimensional display of such information, has been investigated for years within the flight display community (refs. 1 to 7). These efforts have been particularly intense for helmet-mounted head-up display applications, as stereopsis cueing is an almost natural byproduct of binocular helmet systems (refs. 1 to 4). Additional investigations with electronic shutters or polarized filters (rather than helmet optics) used to present separate left- and right-eye views have also been conducted (refs. 5 to 7). Most of these investigations have reported favorable subjective opinions concerning the value of stereopsis cueing, and when objective data were presented, they generally demonstrated modest performance gains, or at least no degradations, in comparison with data for nonstereo displays.

Most of these investigations have focused on the stereoptic enhancement of situational awareness in the head-up, out-the-window visual environment of the fighter or rotorcraft pilot. In most cases, the displays were autostereoscopic, with the viewing direction being slaved to the head movement of the subject pilot. The flight tasks have generally been either target acquisition-recognition tasks or complex flight maneuvers. Pilot-vehicle performance measures which compare nonstereo and stereo presentations in a highly structured experiment utilizing a realistic and demanding (but relatively simple) task are sparse. References 6 and 7 report results from a simple situation recognition task in a simulated transport aircraft application, but it was a non-real-time study .

The purpose of the effort reported herein was to quantitatively determine, through simulation, the efficacy of stereopsis cueing in enhancing the situational awareness of pilots conducting precision tasks. Specifically, the study addressed the effects of stereopsis cueing in a real-world pictorial display for a rotorcraft precision "hover-in-turbulence" task. The display environment presented a pictorial out-the-window scene without autostereoscopsis (i.e., the pilot's head position was fixed). The display conditions examined included the presence or absence of a velocity display element (a velocity head-up display) as well as the stereopsis cueing conditions, which included nonstereo, 3-D stereo, and "hyperstereo."

## Participating Pilots and Task

Seven active-duty and operationally experienced U.S. Army helicopter pilots participated in this study. With one exception, each pilot had extensive experience in helicopters of various types, including both light, highly maneuverable vehicles with teetering rotors and heavy vehicles with articulated rotors. The one exception among the pilots had experience only with heavy, articulated-rotor helicopters.

The task chosen for the evaluation of stereopsis cueing in a real-world pictorial display was a precision hover-in-turbulence task. The pilots endeavored to fly to a point and maintain a hover above that point by visually aligning sets of inner and outer wickets, shown in figure 1. Errors in altitude and lateral position were made apparent by the center-wicket-pair alignment, as shown in figure 2, while the fore-aft (longitudinal) error would be apparent from the alignment of either side wicket pair (which define error relative to at least two radials, shown in fig. 3). Thus, attaining the desired hover position required the alignment of at least two wicket pairs to place the vehicle at the point of intersection of the radials. Figure 4 is the display as viewed by the pilot. The task was initiated in a hover condition at a location displaced from the desired position in all three directions (behind the hover point by 250 ft longitudinally, 10 ft to the right laterally, and 25 ft up in altitude). The pilot was required to fly to the perceived intersection position and reacquire a hover. Two minutes were allowed for the pilot to achieve the new position, with warning buzzers sounding at 1 minute to go, 30 sec to go, and the begining of data collection. The performance metrics for the study included root-mean-square (rms) values of the 3-D radial displacement from the desired hover point (radial error) and of the pilot control inputs, taken for a period of 1 minute. The rms pilot control input measures were computed for cyclic pitch and roll inputs, rudder pedal activity, and collective inputs. If the pilot felt he had achieved the desired condition before the final buzzer indicating the start of data collection, he could initiate data collection at any time by closing the trigger switch in the cyclic controller. This feature was added early in the task familiarization process, as the pilots experienced little or no difficulty in reaching the desired point early and wished to initiate the data collection process themselves.

The main factor of interest in the experiment was, of course, the display condition. The display conditions examined included the presence or absence of a velocity display element (a velocity head-up display) as well as the stereopsis cueing conditions, which included nonstereo (binoptic or monoscopic, i.e., no depth cues other than those provided by a real-world display, such as perspective, size, shape, interposition, and motion parallax), 3-D stereo, and hyperstereo (telestereoscopic). The last condition exaggerated the depth cues present in the display (as might be encountered with forward-looking infrared cameras mounted on each side of a cockpit for a binocular display).

The real-world pictorial display (fig. 4) consisted of a ground grid, a sky-ground horizon, and the wickets. The wickets were arranged to allow a visual alignment that would determine the hover position. The pictorial display, rather than a flight-director-type hover display (e.g., refs. 8 and 9), was chosen because of the desire to investigate the stereoptic enhancement of the situational awareness of pilots. The depth cues available in a synthetic, head-up, out-the-window visual environment seemed to lend themselves more naturally to such an investigation than did any display consisting of symbology elements.

Another factor in the design was the presence or absence of a velocity display element (a velocity head-up display), as shown in figure 5. The cross of the element remained fixed while the box moved vertically and laterally to represent fore-aft velocity and lateral velocity of the vehicle, respectively. Whenever the combined velocity components (airspeed, including vertical velocity) exceeded 5 knots in any direction, the box turned red. When airspeed exceeded 10 knots, the box turned black.

The inclusion or exclusion of this explicit velocity information, which had been made available as a simulation training aid for the pilots before the data collection phase of the experiment, was added as a factor in the experiment because of local experience with left- and right-eye image fusion. Subjects reported that fusion of the stereo pair was more difficult (required some exposure time) in a static-image environment than in a moving-scene environment. That is, when the real-time simulation was frozen at the task starting point (with no motion, all variables set to their initial conditions, and time held at zero) and the pilot was receiving his first exposure to a given display condition, fusion of stereo-pair images might not occur until the simulation went to the operate condition and the simulated vehicle and time began to move. Fusion of the images was never a problem once motion had started. Human factors literature (e.g., section 5.9, ref. 10) reports a decrease in stereo acuity (the ability to accurately judge depth differences) with motion. Therefore velocity effects on stereopsis cueing appeared to be of definite interest.

Training was initiated with no turbulence and with the velocity display element "on" for each of the three display conditions. Training then progressed through the inclusion of turbulence for each condition to the removal of the velocity display element. The rms radial error score was reported to the pilot following each trial. Each pilot achieved approximate asymptotic performance for the six experimental conditions before data collection was begun. Four replicates of each condition were obtained from each of the seven pilots during the experiment. The six experimental conditons were blocked across pilots to prevent the intrusion of any learning curve effects. Table 1 presents the test matrix used in the experiment.

## Simulator Description

The simulator was assembled with the following elements: mathematical model, computer implementation, stereo display system hardware, graphics generation hardware and software, and simulator cockpit.

### Mathematical Model

A six-degree-of-freedom total force and moment mathematical model of a teetering-rotor helicopter, including a modified blade element rotor model, was used in the study. It was a modified model of an AH-1 helicopter with a stability augmentation system tuned so that the rate command handling characteristics of an S-61 helicopter were closely duplicated. The development of the program of the model is documented in reference 11, and various applications of the model are documented in references 12 to 15.

Turbulence was introduced into the mathematical model through the direct addition of random numbers to the body-axis longitudinal and lateral velocity variables. No random vertical turbulence was added, as the other components induced vertical disturbances through vehicle coupling. The magnitude and direction of the disturbance were incrementally varied with random number generators during each iteration (31.25 iterations per second) of the math model. The magnitude of the disturbance was constrained between 0.02 and 0.04 units, with random increments varying uniformly between $\pm 0.005$. The uniformly random increments (for each iteration) of direction, used to apportion the disturbance between the longitudinal and lateral body-axis velocities, were constrained between $\pm 2.5^\circ$. Thus the vehicle, regardless of its inertial heading, was flying into a disturbance that resembled a headwind varying in magnitude and direction.

The seeds of the random number generators were based on the replicate number of the experimental trial, and the generators were initiated with these seeds both at the start of the trial and at the beginning of the data collection phase of the trial. Therefore each pilot flew with the same turbulence variation for each individual replication for all experimental conditions. The level of the turbulence was considered to be moderate by the participating pilots.

### Computer Implementation

The mathematical model of the helicopter and the simulation hardware drives were implemented on the Langley Flight Simulation Computing Subsystem. This system, consisting of a CDC® CYBER 175 computer and appropriate interface equipment, solved the programmed equations 31.25 times a second. The average time delay from input to output (1.5 times the sample period) was approximately 48 msec.

### Stereo Display System Hardware

The stereo display system hardware operated on the video signals supplied by the graphics generation system. These video signals presented a noninterlaced frame at 60 Hz consisting of both the left- and right-eye stereo-pair images. Figure 6 presents the display as drawn by the graphics generation system in a stereo-pair arrangement. The stereo display system hardware (fig. 7) separated the left- and right-eye scenes and presented each alternately, at 120 Hz, spread across the entire monitor screen (i.e., time-multiplexed stereo, which resulted in a loss in vertical resolution of 50 percent), as shown in figure 4. Liquid crystal device glasses were shuttered in synchronization with the stereo pair, such that the right eye saw only the right-eye scene and the left eye saw only the left-eye scene, each at 60 Hz, without flicker. The stereo display system hardware is described in reference 16.

### Graphics Generation Hardware and Software

Figure 8 illustrates the three-stage computer pipeline used for this study. The mathematical model of the helicopter and the simulation hardware drives were implemented on the CYBER 175. The graphics generation software resided within a Digital Equipment Corporation VAX 8650 computer and consisted of the necessary transformation equations and the graphics data base for the display. The Adage RDS-3000 graphics computer only made calculations directly related to drawing the display. Utilizing the three-stage computer pipeline architecture, the graphics displays could be produced at an update rate of 20 Hz. However, the communications link between the CYBER and the VAX limited the visual update rate to 15 Hz.

Figure 9 illustrates the geometric principle that was employed to produce the left- and right-eye views within the stereo-pair generation software. The heavy horizontal line represents the screen of the display monitor. To present an object that appeared at the depth of the screen, the object was drawn in the same location for both stereo-pair views. For objects to appear behind the screen, the object was displaced to the left for the left-eye view and to the right for the right-eye view (with the displacement reaching a maximum value to place an object at infinity). For objects to appear in front of the screen, a displacement to the right was used for the left-eye view and to the left for the right-eye view.

To generate this lateral displacement, which is known as lateral disparity, left- and right-eye coordinate systems were transformed from the viewer coordinate system of the visual scene. The nonstereo condition used a lateral disparity of zero, and the stereo and hyperstereo conditions used disparities resulting from the stereo-pair transformations. Simple perspective division was used to transform the three-dimensional viewing volumes to two-dimensional viewports, for which the centers were offset from the center of the display screen by half of the maximum-allowed lateral disparity (i.e., that used to represent objects at infinite distance). Figure 10(a) illustrates the mapping of a real-world scene to the stereo viewing volume. Conventional asymptotic transformations, which were used to map the visual scene into the stereo viewing volume, allow the display designer to fix a specific scene distance at the screen location in the viewing volume. Additional control within the transformation allows some shaping of the asymptotic curve. Figure 10(b) represents the mapping of the visual scene to the 3-D stereo viewing volumes for the stereo and hyperstereo display condition cases.

Clipping was employed to limit each eye view to the display surface boundaries. Asymmetric clipping, which provides an increased monocular field of view (FOV) for each eye when compared with symmetric clipping (with accompanying increases in the binocular fields of view), was implemented in the graphics software. Figure 11 presents an illustration of symmetric and asymmetric clipping as well as the effects of using each algorithm. Symmetric clipping dictates a smaller monocular FOV for each eye for a fixed screen distance and size (shown in the top view for the left eye). Combining the monocular FOV's for both eyes results in different stereo overlap regions and single-eye viewing regions at different scene distances for the two clipping approaches. The perceived FOV's for the stereopsis regions and also the total horizontal FOV's provided by the asymmetric clipping algorithm are greater throughout the scene viewing envelope than those of the symmetric algorithm.

### Simulator Cockpit

The general-purpose fighter-helicopter portion of the cockpit of the Langley Visual/Motion Simulator (VMS) was used in a fixed-base mode for this study. The cyclic center stick and the rudder pedals were loaded by a hydraulic system coupled with a special-purpose analog computer to provide realistic control forces. The collective stick is a counterbalanced, friction-controlled stick, and it is representative of a helicopter collective. No instrumentation other than the primary display monitor was used. Because of structural limitations within the cockpit, the 19-in. monitor was mounted on the top of the instrument panel, approximately 19 in. from the pilot's eyes.

## Results and Discussion

The investigation was designed as a full-factorial, within-subjects experiment, with pilots, display conditions, velocity display element, and replicates as the factors. The objective results are presented and discussed first, with the subjective results discussed thereafter.

### Analysis of Objective Results

Univariate analyses of variance for each metric were used on the data collected in the full-factorial experiment. A detailed presentation of these analyses can be found in the appendix.

### Discussion of Objective Results

Each of the main factors of the experiment is discussed relative to the analyses of the main factors and the interaction terms presented in the appendix for the main performance measures of interest, radial error and the four control inputs. The interaction of display $D$ and velocity display element $E$ is also discussed in these terms within both main factors (as $D \times E$ for the display condition and as $E \times D$ for the velocity element factors; $D \times E$ and $E \times D$ are the same interaction term).

***Pilots.*** The main factor of pilot variability was highly significant for all performance measures. This result is always expected in a precision task, and the pilot variability was therefore isolated from the rest of the analyses by its inclusion as a main factor in the experiment.

***Display condition.*** After consideration of interaction terms (and the exclusion of data biases resulting from a single pilot), the analyses revealed that the main factor of display condition was highly significant for every measure, with the exception of the rms pitch input. The pitch input activity did not change as a function of display condition. This result was somewhat surprising, since pitch control is used to maintain fore-aft position with respect to the desired hover point, and one might expect any depth cueing effects to be realized along the fore-aft axis (the "depth" axis). However, none of the other factors in the analysis of the rms pitch results was significant either, with the exception of variablility between pilots. The handling characteristics of the simulated vehicle were such that the lateral control task was much more difficult than longitudinal control. Another contributing factor to the lack of a stereo effect may have been that the pilots used the two-dimensional wicket alignment cues (centering the outer wickets within the inner wickets) rather than depth perception cues for fore-aft control.

The other measures did change as stereopsis cues were added to the display. Table 2 summarizes the results in terms of percent reductions of rms errors from the nonstereo display condition for each of the measures. For the four measures that showed changes, the rms level for the nonstereo condition was significantly greater than that of either stereo condition. There were no statistically significant differences detected between the stereo and hyperstereo performances for three of these measures. The addition of stereopsis cueing to the display reduced the radial error about 28 percent, the roll activity about 16 percent, and the collective activity about 10 percent compared with those values for the nonstereo display. The reductions in rms roll and collective activities were not consistent across all the pilots, while the radial error reduction was consistent. For the fourth measure, rms pedal input, differences were detected between the input levels for the stereo and hyperstereo displays, both of which were significantly less than the input levels for the nonstereo display.

A significant reduction in pedal activity was detected between the stereo and the hyperstereo display conditions. The activity for the hyperstereo display was significantly less than that for the stereo display (about a 10-percent reduction), and the activity for the stereo display was less than that for the nonstereo display (about an 8-percent reduction). This reduction between the stereo and hyperstereo display conditions was the only difference detected in the objective data for these two display conditions as main factors. The reductions in rms pedal activity were not consistent across all the pilots. One explanation for the pedal activity reduction is that, with the closer appearance of the wickets with the hyperstereo presentation, perhaps the pilots could detect a directional error earlier and thus required a smaller rms pedal input to ensure correction.

All these results are considered to indicate that the depth cues provided by the stereo displays enhanced the situational awareness of the pilot and enabled greatly improved hover performance to be achieved with less control action. The velocity display element also greatly improved the hover performance, with superior hover performance being achieved with the combined use of stereo and the velocity display element.

***Interaction of display condition and velocity display element.*** This second-order interaction ($D \times E$) remained significant for three of the input measures (roll activity at the 1-percent level and pedal and collective activities at the 5-percent level). Table 3 summarizes the results in terms of percent reductions in levels from the nonstereo display condition for each velocity display element condition for all measures. From the table, it is evident that for the velocity display element "off" condition, stereopsis cues enabled improved hover performance with less control activity (although rms pitch input levels remained constant). However, for the velocity display element "on" condition, superior performance was achieved with the same level of input control for the stereo display as for the nonstereo display. For the hyperstereo display, superior performance was achieved with somewhat reduced input levels, although rms collective and pitch input levels remained constant.

The stereopsis enhancement was particularly effective (i.e., resulted in reduced control activity) when the velocity element was absent from the display, the implication being that some velocity information, as well as positional information, can be readily extracted from the depth presentation. With the velocity information already provided by the velocity display element, the anticipated reduction in control activity with the addition of stereopsis cues was perhaps no longer available.

***Velocity display element.*** One would expect that the direct display of velocity information would result in improved performance (with lower control activity) regardless of the display condition (i.e., the $E$ main factor would be significant and the $E \times D$ interaction term would not). After consideration of interaction terms, the analyses revealed that the main factor of velocity display element was highly significant only for the radial performance error and pedal activity measures. Table 4 summarizes the results in terms of percent reductions from the velocity display element "off" condition for each of the measures. There was a 34-percent reduction in the rms radial error and a 22-percent reduction in the pedal activity measure when the velocity display element was presented to the pilots. However, these reductions were not consistent across all pilots.

***Interaction of velocity display element and display condition.*** This second-order interaction ($E \times D$) remained significant for three of the input measures (roll activity at the 1-percent level and pedal and collective activities at the 5-percent level). Table 5 summarizes the results in terms of percent changes from levels for the velocity display element "off" for each display condition for all measures. As alluded to previously, one would expect that the direct display of velocity information would result in improved performance (with lower control activity) regardless of the display condition (i.e., the $E$ main factor would be significant and the $D \times E$ interaction term would not). And this expectation was realized for the radial error and rms pedal input measures. Improved hover performance (the radial error measure) was obtained with the addition of the velocity display element to the display, regardless of the display condition. The differences across display conditions were not statistically significant (a 36-percent reduction with the addition of the velocity display element to the nonstereo display, a 27-percent reduction with the stereo display, and a 38-percent reduction with the hyperstereo display). However, the amount of reduction in pedal activity did vary significantly with display condition (i.e., the $D \times E$ interaction term remained statistically significant). For the nonstereo display condition, a 30-percent reduction in pedal activity occurred, while for the stereo and hyperstereo display conditions the reductions were 8 and 26 percent, respectively.

However, for the roll and collective activity measures, $E$ was not significant and $D \times E$ was significant. The expectation that the direct display of velocity information would result in reduced activity levels was met for the nonstereo display condition with both the rms roll and the rms collective inputs, with a reduction in both cases of 12 percent. However, for these two measures, there was no significant reduction in activity for the hyperstereo display condition when the velocity element was "on," and for the stereo display condition, there were actually increases in activity (a 23-percent increase in roll activity and a 9-percent increase in collective activity). The reductions and increases acted to cancel the significance of the main effect for these two measures.

In summary, these results indicate that the direct addition of velocity information provided by the velocity display element enhanced the situational awareness of the pilots and enabled greatly improved hover performance to be achieved consistently across all display conditions. However, the lack of a consistent effect on control input activity for the addition of velocity information was unexpected. The expected effect was realized for the nonstereo display condition for most of the input measures (reduced activity with the addition of velocity information). For the hyperstereo display condition, the expected effect was realized for one measure (pedal activity), with no effect occurring for the other measures. The effect for the stereo display condition was very ambiguous, with control activity decreasing, increasing, or remaining the same, depending upon the particular measure. No explanation is offered for this result. The fact that the expected effect of velocity cues on control activity was realized for the nonstereo display condition but not for the stereopsis display conditions suggests that some differences exist in the velocity information inherently imparted by the addition of stereo depth cues.

***Replicates.*** The main factor of replicates was significant for only the rms pedal and rms collective measures. For both measures, there was no difference between the levels of replicates 1 and 2. For the rms pedal measure, there was a reduction of 13 percent between the mean of replicates 1 and 2 and the mean of replicates 3 and 4 (with no difference detectable between replicates 3 and 4). For the rms collective measure, there was a significant reduction of 8.5 percent between the mean of replicates 1 and 2 and the level of replicate 3. There was an additional reduction of 9 percent between the level of replicate 3 and the level of replicate 4. These results are not really surprising, as the overall direction of reductions in control activity with increasing replications is a classic pattern associated with learning a task.

### Subjective Results

Unstructured pilot comments recorded throughout the experiment indicated that every pilot preferred the stereo display condition. They felt that they were aware of where they were relative to the desired hover point and that they could detect upsets from the turbulence earlier and make the necessary corrections more readily with that display. The nonstereo display sometimes became just a conglomeration of lines that required mental sorting to achieve situational awareness. The hyperstereo display was not liked by most of the pilots, although they acknowledged that the display provided the same increased situational awareness that the stereo display provided. The dislike was attributed by some pilots to the positioning of the front-center wicket when they were flying near the hover point. The exaggerated depth of the hyperstereo display allowed the front-center wicket when they were flying near the hover point. The exaggerated depth of the hyperstereo display allowed the front-center wicket to appear to be in front of the display screen, penetrating into the cockpit with the pilot, a situation that they found to be somewhat distracting.

## Concluding Remarks

The purpose of the effort reported herein was to quantitatively determine, through simulation, the efficacy of stereopsis cueing in enhancing the situational awareness of pilots conducting precision tasks. Specifically, the study addressed the effects of stereopsis cueing in a "real-world" pictorial display for a rotorcraft precision "hover-in-turbulence" task. The display conditions examined included the presence or absence of a velocity display element (a velocity head-up display) as well as the stereopsis cueing conditions, which included nonstereo, three-dimensional stereo, and hyperstereo. The investigation was designed as a full-factorial, within-subjects experiment, with pilots, display conditions, velocity display element, and replicates as the factors.

The objective and subjective results of this experiment indicate that stereopsis cueing is an effective way to enhance the situational awareness of pilots utilizing pictorial displays. The depth cues provided by the stereo displays enhanced the situational awareness and enabled improved hover performance to be achieved. Control input measurement data revealed that less control activity was required to attain the improved hover performance with the stereo displays. The stereopsis enhancement was particularly effective (i.e., resulted in reduced control activity) when the velocity information element was absent from the display, and this finding implies that some velocity information, as well as positional information, can be readily extracted from the depth presentation. With the velocity information already provided by the velocity display element, the anticipated reduction in control activity with the addition of stereopsis cues is not realized.

The results also indicate that the direct addition of velocity information provided by the velocity display element increased the situational awareness of the pilots and enabled improved hover performance to be achieved. However, the lack of a consistent effect for the addition of velocity information on control input activity was unexpected, and no definitive explanation is offered for this result, although it is suggested that some differences exist in the velocity information inherently imparted by the addition of stereo depth cues.

Subjective and objective results indicate that the depth cues provided by the stereo displays enhance the situational awareness of the pilot and enable improved hover performance to be achieved. The velocity display element also improves the hover performance, with the best hover performance being achieved with the combined use of stereo and the velocity display element.

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# Appendix

## Analysis of Objective Results

The data collected were subjected to univariate analyses of variance for each metric. The investigation was designed as a full-factorial, within-subjects experiment, with pilots, display conditions, velocity display element, and replicates as the factors.

Table 6 is a summary of the results of these analyses for the five performance measures. The presentation of the results follows the statistically significant sources of variance identified in the table measure by measure.

### rms Radial Error

The rms radial error was the measure of primary interest in this investigation.

***Pilots.*** The main factor of pilot variability was highly significant. Figure 12 presents the mean rms radial error for each pilot. Pilot 7 had no experience with light, highly maneuverable helicopters with teetering rotors, having flown only heavy, slowly responding helicopters with articulated rotors.

***Display condition.*** The display condition factor was highly significant. Figure 13 presents the mean rms radial error for each display condition. Newman-Keuls t-test comparisons between the means for each display condition using the standard error of a mean (based on the mean square error from the analysis of variance, ref. 17) revealed that the performance error for the nonstereo display was significantly greater than the performance errors for either stereo display condition. There was no difference detected between the stereo and hyperstereo performances.

***Interaction of pilot and display condition.*** There was a highly significant interaction between pilots and display conditions, which further statistical analysis attributed to the extreme variation across display conditions for pilot 7. Figure 14 illustrates the difference in change of hover performance across the display conditions for pilot 7 compared with the overall pilot mean (both including and excluding pilot 7). The addition of stereopsis cueing to the display resulted in a reduction of about 43 percent from the performance error for the nonstereo display condition for the overall pilot mean (pilots 1 to 7), with no statistically significant performance difference between the stereo and hyperstereo display conditions. Pilot 7 exhibited a 54-percent reduction in error when using the stereo display instead of the nonstereo and a statistically significant 34-percent reduction in error when using the hyperstereo instead of the stereo (a 62-percent reduction using hyperstereo instead of nonstereo). Thus the display condition factor was much stronger for pilot 7 than for the average pilot. Excluding pilot 7, the addition of stereopsis cueing to the display resulted in a reduction of about 28 percent from the nonstereo performance error.

The results of excluding pilot 7 from the analysis are summarized in table 7. The interaction of pilot and display condition was no longer significant, even at the 5-percent significance level; however, the main factor display condition remained highly significant. Figure 15 presents the mean rms radial error for each display condition for only pilots 1 to 6. Newman-Keuls t-test comparisons between the means for each condition revealed that the error for the nonstereo display was significantly greater than that for either stereo display. There was no difference detected between the stereo and hyperstereo performances. The addition of stereopsis cueing to the display for these pilots resulted in a reduction in error of about 28 percent from that for the nonstereo display.

***Velocity display element.*** The effect of the velocity display element on hover performance was highly significant. Figure 16 shows a 46-percent reduction in the rms radial error measure when the velocity display element was presented to the pilots.

***Interaction of pilot and velocity display element.*** There was a highly significant interaction between pilots and velocity display element condition, and further statistical analysis attributed this largely to the extreme variation across velocity display element condition for pilot 7. Figure 17 illustrates the difference in change in hover performance across velocity display element condition for pilot 7 compared with that for the overall pilot mean (both including and excluding pilot 7). The addition of the velocity element to the display ("on" condition) resulted in a reduction in radial error of about 46 percent from that of the no-element ("off") condition for the overall pilot mean (pilots 1 to 7) compared with a 62-percent reduction for pilot 7. Thus, the effect of velocity display element was much larger for pilot 7 than for the average pilot. Excluding pilot 7, the addition of the velocity element to the display resulted in a reduction in radial error of about 34 percent from that of the no-element condition.

The results of excluding of pilot 7 from the analysis is again summarized in table 7. The main factor velocity display element remained highly significant. Figure 18 presents the average rms radial error for the velocity display element conditions averaged only across pilots 1 to 6. The addition of the velocity element to the display for these pilots resulted in a reduction in radial error of about 34 percent from that of the no-element display. The interaction of pilot and velocity display element was then reduced to significance at the 5-percent level. Figure 19 presents the average rms radial error for the velocity display element conditions for each pilot and reveals that the velocity display element had no effect on the performance of pilot 1. Further testing revealed no differences in the effect of the velocity display element on the performances of the other five pilots (i.e., that the addition of the velocity display element to the display for these pilots resulted in a reduction of about 37 percent from the "off" condition rms radial error).

***Interaction of display condition and velocity display element.*** There was a change in the display condition effectiveness across the velocity display element, as indicated by the highly significant $D \times E$ interaction. Figure 20 presents the mean rms radial error for each display condition with the velocity display element "on" and "off." Newman-Keuls t-test comparisons between the means for each display condition within each velocity display element condition revealed that the error for the nonstereo display was significantly greater than the error associated with either stereo display. There were no differences detected between the errors for the stereo and hyperstereo displays for either velocity display element condition. The addition of stereopsis cueing to the display resulted in a reduction in error of about 30 percent from the nonstereo display for the velocity display element "on" condition and a 49-percent reduction for the velocity "off" condition. Thus, the display condition effect was much stronger when the velocity display element was not presented to the pilots.

This interaction can also be viewed as indicating a significant change in the velocity display element effectiveness across the display condition (as $E \times D$), as both main factors $D$ and $E$ are significant. Figure 20, when examined in this light, can be replotted as figure 21, and examination of it reveals that the addition of the velocity display element reduced radial errors 54 percent for the nonstereo display, 32 percent for the stereo display, and 43 percent for the hyperstereo display conditions. Thus, the effect of adding velocity information to the display was strongest for the nonstereo display condition, less strong for the hyperstereo display condition, and weakest, but still quite evident, for the stereo display condition.

***Interaction of pilot, display condition, and velocity display element.*** There was a highly significant interaction between pilots, display conditions, and velocity display element conditions, which further statistical analysis attributed largely to the extreme variation across display and velocity display element conditions for pilot 7. The results of excluding pilot 7 from the analysis are shown in table 7. The second-order interaction $D \times E$ and the third-order interaction $P \times D \times E$ were no longer significant, an indication that the effect of display condition on the radial error did not vary with the presence or absence of the velocity display element. Or conversely, the effect of the presence or absence of the velocity display element on the radial error did not vary with the display condition.

Indeed, Newman-Keuls t-test comparisons between the means for each display condition within each velocity display element condition (the means are shown in fig. 22) revealed that the error for the nonstereo display was significantly greater than that associated with either stereo display. There were no differences detected between the errors for the stereo and hyperstereo displays for either velocity display element condition. The addition of stereopsis cueing to the display resulted in a reduction in error of about 26 percent from that of the nonstereo display for the velocity display element "on" condition and a 29-percent reduction for the velocity display element "off" condition. Thus, the display condition effect was almost constant, regardless of the presence or absence of the velocity display element (disregarding the data of pilot 7).

Examining the velocity display element effectiveness across display conditions from the data of figure 22 reveals a 36-percent reduction in error with the addition of the velocity display element to the nonstereo display, a 27-percent reduction with the stereo display, and a 38-percent reduction with the hyperstereo display. These differences were not statistically significant, and therefore the velocity display element effect was almost constant, regardless of the display condition being utilized (only for pilots 1 to 6).

***Replicates.*** The replicate factor was not significant for the rms radial error. This result was expected, as each pilot achieved approximate asymptotic performance based on this measure for each of the six experimental conditions before data collection was begun.

### rms Pitch Input Activity

Cyclic pitch inputs were used by the pilots to maintain fore-aft (longitudinal) position and pitch attitude relative to the desired hover point.

***Pilots.*** The main factor of pilot variability was highly significant. Figure 23 presents the mean rms pitch input for each pilot.

***Display condition.*** The display condition factor was highly significant. Figure 24 presents the mean rms pitch input for each display condition. Newman-Keuls t-test comparisons between the means for each condition revealed that the input activity for the hyperstereo condition was significantly less than that for the other conditions. No differences were detected between the pitch input activities for stereo and nonstereo displays. The addition of hyperstereopsis cueing to the display reduced input activity by about 21 percent from the average of the other two conditions.

***Interaction of pilot and display condition.*** There was a highly significant interaction between pilots and display conditions. Figure 25 presents the average rms pitch input for each display condition for each pilot and reveals that the differences between display conditions varied a great deal from pilot to pilot, with particularly extreme variations for pilot 1. The pattern exhibited in figure 24 is clearly not representative of each pilot, but rather is the mean of all pilots.

The results of excluding pilot 1 from the analysis are summarized in table 8. The interaction of pilot and display condition and the main factor of display condition were no longer significant, even at the 5-percent significance level. Figure 26 presents the average rms pitch input for each display condition for pilots 2 to 7. Newman-Keuls t-test comparisons between the means for each condition revealed no significant differences between display conditions.

***Velocity display element.*** This factor was not significant for the rms pitch input measure.

***Interaction of pilot and velocity display element.*** This second-order interaction term was not significant for the rms pitch input measure.

***Interaction of display condition and velocity display element.*** This second-order interaction was not significant for the rms pitch input measure.

***Interaction of pilot display condition and velocity display element.*** This third-order interaction term was not significant for the rms pitch input measure.

***Replicates.*** The replicate factor was not significant for the rms pitch input measure.

### rms Roll Input Activity

Cyclic roll inputs were used by the pilots to maintain lateral position and roll attitude relative to the desired hover point.

***Pilots.*** The main factor of pilot variability was highly significant. Figure 27 presents the average rms roll input for each pilot.

***Display condition.*** The display condition factor was highly significant. Figure 28 presents the average rms roll input for each display condition. Newman-Keuls t-test comparisons between the means for each condition revealed that the roll activity for the nonstereo display condition was significantly greater than that for either stereo display condition. There were no differences detected between roll activities for the stereo and hyperstereo display conditions. The addition of stereopsis cueing to the display reduced the roll measure for the stereo displays about 16 percent from that of the nonstereo display.

***Interaction of pilot and display condition.*** There was a highly significant interaction between pilots and display conditions. Figure 29 presents the average rms roll input for each display condition for each pilot, and Newman-Keuls t-tests reveal that the differences between display conditions varied a great deal from pilot to pilot, particularly for pilots 3 and 6. The pattern exhibited in figure 28 is clearly not representative of each pilot, but rather is the mean of all pilots.

***Velocity display element.*** This factor was not significant for the rms roll input measure.

***Interaction of pilot and velocity display element.*** This second-order interaction term was not significant for the rms roll input measure.

***Interaction of display condition and velocity display element.*** This second-order interaction was significant at the 1-percent level. Figure 30 presents the mean values of rms roll input for the various conditions. The interaction term was examined both as a variation in effect of display conditions across the velocity display element condition and as a variation in effect of velocity display element across display conditions.

With the velocity display element "off," the addition of stereopsis cues to the display resulted in a 26-percent reduction in rms roll input, with no detectable differences between performance for stereo and hyperstereo displays. With the velocity display element "on," there were no detectable differences between the performances for the nonstereo and stereo displays. There was a 12-percent reduction in rms roll input from the mean of those two display conditions for the hyperstereo display condition.

The effect of the velocity display element was different for each display condition; it reduceed roll activity when it was "on" for the nonstereo display condition, it increased roll activity when it was "on" for the stereo display condition, and it had no effect on roll activity for the hyperstereo display condition. The overall effect of these differences across display conditions was to cancel any significance for the main factor in the analysis of variance for this measure.

***Interaction of pilot, display condition, and velocity display element.*** This third-order interaction term was not significant for the rms roll input measure.

***Replicates.*** The replicate factor was not significant for the rms roll input measure.

### rms Pedal Input Activity

Rudder pedal inputs were used by the pilots to maintain heading relative to the wickets of the display.

***Pilots.*** The main factor of pilot variability was highly significant. Figure 31 presents the average rms pedal input for each pilot.

***Display condition.*** The display condition factor was highly significant. Figure 32 presents the mean rms pedal input for each display condition. Newman-Keuls t-test comparisons between the means for each condition revealed that input activity for the hyperstereo display condition was significantly less than that for the stereo display condition (about a 10-percent reduction) and that the input activity for the stereo display condition was significantly less than that for the nonstereo display condition (about an 8-percent reduction).

***Interaction of pilot and display condition.*** There was a highly significant interaction between pilots and display conditions. Figure 33 presents the mean rms pedal input for each display condition for each pilot and reveals that the differences between display conditions varied a great deal from pilot to pilot. The pattern exhibited in figure 32 is clearly not representative of each pilot, but rather is the mean of all pilots.

***Velocity display element.*** There was a highly significant effect of the velocity display element on rms pedal input. Figure 34 shows a 22-percent reduction in the pedal activity measure when the velocity display element was presented to the pilots.

***Interaction of pilot and velocity display element.*** There was a highly significant interaction between pilots and the velocity display element, which further statistical analysis attributed largely to the extreme variation across velocity display element for pilot 7 and the lack of any variation for pilot 2. Figure 35 illustrates the difference in change of pedal activity across the velocity display element for each pilot.

***Interaction of display condition and velocity display element.*** There was a change in the display condition effectiveness across the velocity display element, as indicated by the interaction $D \times E$, which was significant at the 5-percent level. Figure 36 presents the mean rms pedal input for each display condition with the velocity display element "on" and "off." Newman-Keuls t-test comparisons between the means for each display condition with the velocity display element "off" revealed that pedal activity for the nonstereo display condition was significantly greater than that associated with either stereo display condition. There were no differences detected in rms pedal inputs between the stereo and hyperstereo display conditions. The addition of stereopsis cueing to the display resulted in a reduction in pedal activity of about 19 percent from activity for the nonstereo display with the velocity display element "off." With the velocity display element "on," there were no differences detected between rms pedal inputs for the nonstereo and stereo displays. There was a reduction in pedal inputs of about 18 percent from those display conditions to the hyperstereo display condition.

Examining the effect of velocity display element across display conditions from the data of figure 36 revealed a reduction in rms pedal input of 30 percent with the addition of the velocity display element to the nonstereo display, a 9-percent reduction with the stereo display, and a 26-percent reduction with the hyperstereo display. These differences were statistically significant (i.e., $E$ and $D \times E$ were both significant).

***Interaction of pilot, display condition, and velocity display element.*** This third-order interaction term was not significant for the rms pedal input measure.

***Replicates.*** The replicate factor was significant at the 5-percent level for the rms pedal input measure. Figure 37 presents the mean rms pedal input for each of the four replicates of the experiment. Newman-Keuls t-test comparisons revealed no differences between replicates 1 and 2 and between replicates 3 and 4. However, there was a reduction of 13 percent between the mean of replicates 1 and 2 and the mean of replicates 3 and 4.

### rms Collective Input Activity

Collective inputs were used by the pilots to maintain altitude relative to the desired hover point.

***Pilots.*** The main factor of pilot variability was highly significant. Figure 38 presents the average rms collective input for each pilot.

***Display condition.*** The display condition factor was highly significant. Figure 39 presents the mean rms collective input for each display condition. Newman-Keuls t-test comparisons between the means for each condition revealed that collective activity for the nonstereo display condition was significantly greater than that for either stereo display condition. There were no differences detected between collective activity for the stereo and hyperstereo display conditions. The addition of stereopsis cueing to the display resulted in a reduction in activity of about 10 percent from that for the nonstereo display condition.

***Interaction of pilot and display condition.*** There was a highly significant interaction between pilots and display conditions. Figure 40 presents the mean rms collective input for each display condition for each pilot and reveals that the differences in input between display conditions varied a great deal from pilot to pilot. The pattern exhibited in figure 39 is clearly not representative of each pilot, but rather is the mean of all pilots.

***Velocity display element.*** This factor was not significant for the rms collective input measure.

***Interaction of pilot and velocity display element.*** This second-order interaction term was not significant for the rms collective input measure.

***Interaction of display condition and velocity display element.*** This second-order interaction was significant at the 5-percent level. Figure 41 presents the mean values of rms collective input for the various conditions. The interaction term was examined both as a variation in effect of display condition across the velocity display element and as a variation in effect of velocity display element across display conditions.

With the velocity display element "off," the addition of stereopsis cues to the display resulted in a reduction in mean rms collective input of 18 percent, with no detectable differences in performance between stereo and hyperstereo display conditions. With the velocity display element "on," there were no detectable differences in performance between the nonstereo, stereo, and hyperstereo display conditions.

The effect of the velocity display element was different for each display condition; it reduced collective activity when it was "on" for the nonstereo display condition (12-percent reduction), it increased activity when it was "on" for the stereo display condition (8-percent increase), and it had no effect for the hyperstereo display condition. The overall effect of these differences across display conditions was to cancel any significance for the main factor $E$ in the analysis of variance for this measure.

***Interaction of pilot, display condition, and velocity display element.*** This third-order interaction term was not significant for the rms collective input measure.

***Replicates.*** The replicate factor was significant at the 1-percent level for the rms collective input measure. Figure 42 presents the mean rms collective input for each of the four replicates of the experiment. Newman-Keuls t-test comparisons revealed no differences between replicates 1 and 2. However, there was a significant reduction of 8.5 percent between the mean of inputs for replicates 1 and 2 and the input of replicate 3. There was an additional reduction of 9 percent between the inputs of replicates 3 and 4.

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Table 1. Test Matrix for Experiment

[Four replicates for each cell]

Display conditions:
- M—monocular
- S—stereo
- H—hyperstereo

Velocity display element conditions:
- F—velocity element off
- N—velocity element on

| Block | Factors for pilot— | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | H-N | S-N | S-N | H-F | S-N | M-F | M-F |
| 2 | H-F | S-F | S-F | H-N | S-F | M-N | M-N |
| 3 | M-N | M-N | M-N | S-F | H-N | S-F | H-F |
| 4 | M-F | M-F | M-F | S-N | H-F | S-N | H-N |
| 5 | S-N | H-N | H-N | M-F | M-N | H-F | S-F |
| 6 | S-F | H-F | H-F | M-N | M-F | H-N | S-N |

Table 2. Summary of Display Condition Effects

[Percent reductions from levels for nonstereo display]

| Display condition | Radial error | Pitch activity | Roll activity | Pedal activity | Collective activity |
|---|---|---|---|---|---|
| Nonstereo | Standard | Standard | Standard | Standard | Standard |
| Stereo | −28 | 0 | −16 | −8 | −10 |
| Hyperstereo | −28 | 0 | −16 | −18 | −10 |

Table 3. Summary of Display Condition Effects Across Velocity Display Element Condition

[Percent reductions from levels for nonstereo display]

| Velocity display element | Display condition | Radial error | Pitch activity | Roll activity | Pedal activity | Collective activity |
|---|---|---|---|---|---|---|
| Off | Nonstereo | Standard | Standard | Standard | Standard | Standard |
| | Stereo | −29 | 0 | −26 | −19 | −18 |
| | Hyperstereo | −29 | 0 | −26 | −19 | −18 |
| On | Nonstereo | Standard | Standard | Standard | Standard | Standard |
| | Stereo | −26 | 0 | 0 | 0 | 0 |
| | Hyperstereo | −26 | 0 | −12 | −18 | 0 |

Table 4. Summary of Velocity Display Element

[Percent reductions from levels for element "off"]

| Velocity display element | Radial error | Pitch activity | Roll activity | Pedal activity | Collective activity |
|---|---|---|---|---|---|
| Off | Standard | Standard | Standard | Standard | Standard |
| On | −34 | 0 | 0 | −22 | 0 |

Table 5. Summary of Velocity Display Element Effects Across Display Conditions

[Percent changes from levels for element "off"]

| Display condition | Velocity display element | Radial error | Pitch activity | Roll activity | Pedal activity | Collective activity |
|---|---|---|---|---|---|---|
| Nonstereo | Off | Standard | Standard | Standard | Standard | Standard |
| | On | −36 | 0 | −12 | −30 | −12 |
| Stereo | Off | Standard | Standard | Standard | Standard | Standard |
| | On | −27 | 0 | 23 | −8 | 9 |
| Hyperstereo | Off | Standard | Standard | Standard | Standard | Standard |
| | On | −38 | 0 | 4 | −26 | 2 |

Table 6. Summary of Analyses of Variance

| Factor | Degrees of freedom | Significance[a] of rms performance measures of— | | | | |
|---|---|---|---|---|---|---|
| | | Radial error | Pitch activity | Roll activity | Pedal activity | Collective activity |
| Pilot, $P$ | 6 | ** | ** | ** | ** | ** |
| Display condition, $D$ | 2 | ** | ** | ** | ** | ** |
| $P \times D$ | 12 | ** | ** | ** | ** | ** |
| Velocity display element, $E$ | 1 | ** | – | – | ** | – |
| $P \times E$ | 6 | ** | – | – | ** | – |
| $D \times E$ | 2 | ** | – | ** | * | * |
| $P \times D \times E$ | 12 | ** | – | – | – | – |
| Replicates, $R$ | 3 | – | – | – | * | ** |
| Error | 123 | | | | | |

[a]Significance:
– Not significant at levels considered.
* Significant at 5-percent level.
** Significant at 1-percent level.

Table 7. Summary of Analyses of Variance for Radial Performance Measure

| Factor | Significance[a] of rms radial performance for— | |
|---|---|---|
| | Pilots 1–7 | Pilots 1–6 |
| Pilot, $P$ | ** | ** |
| Display condition, $D$ | ** | ** |
| $P \times D$ | ** | – |
| Velocity display element, $E$ | ** | ** |
| $P \times E$ | ** | * |
| $D \times E$ | ** | – |
| $P \times D \times E$ | ** | – |
| Replicates, $R$ | – | – |

[a]Significance:
- – Not significant at levels considered.
- * Significant at 5-percent level.
- ** Significant at 1-percent level.

Table 8. Summary of Analyses of Variance for Pitch Performance Measure

| Factor | Significance[a] of rms pitch performance for— | |
|---|---|---|
| | Pilots 1 to 7 | Pilots 2 to 7 |
| Pilot, $P$ | * | ** |
| Display condition, $D$ | * | – |
| $P \times D$ | * | – |
| Velocity element, $E$ | – | – |
| $P \times E$ | – | – |
| $D \times E$ | – | – |
| $P \times D \times E$ | – | – |
| Replicates, $R$ | – | – |

[a]Significance:
- – Not significant at levels considered.
- * Significant at 5-percent level.
- ** Significant at 1-percent level.

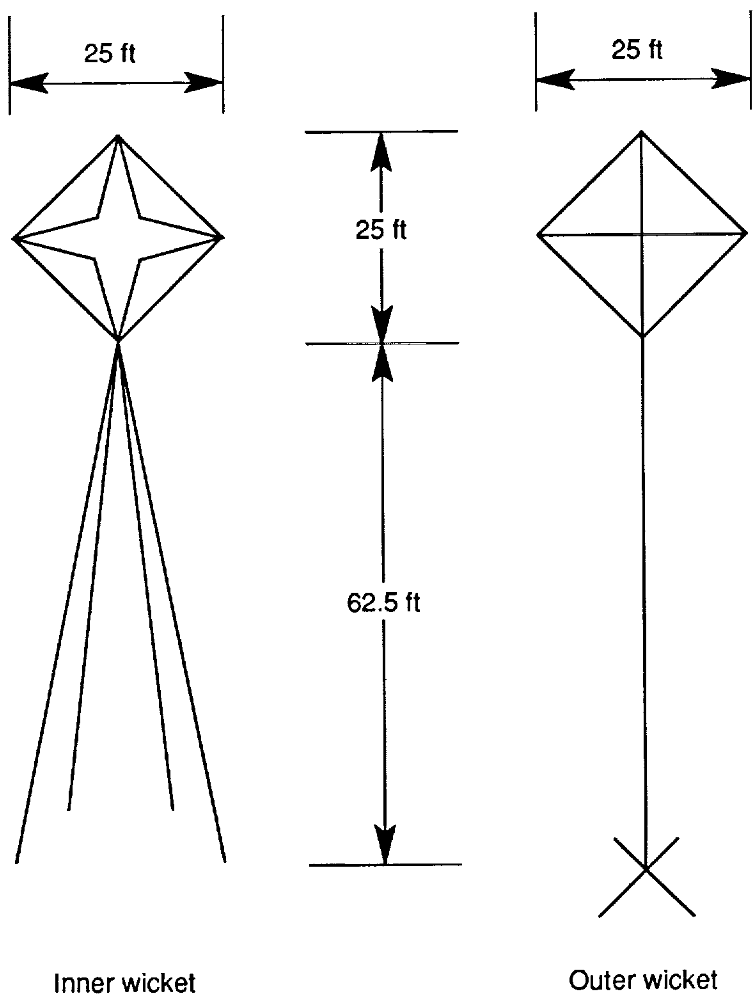



Figure 1. Diagram of inner and outer wickets.

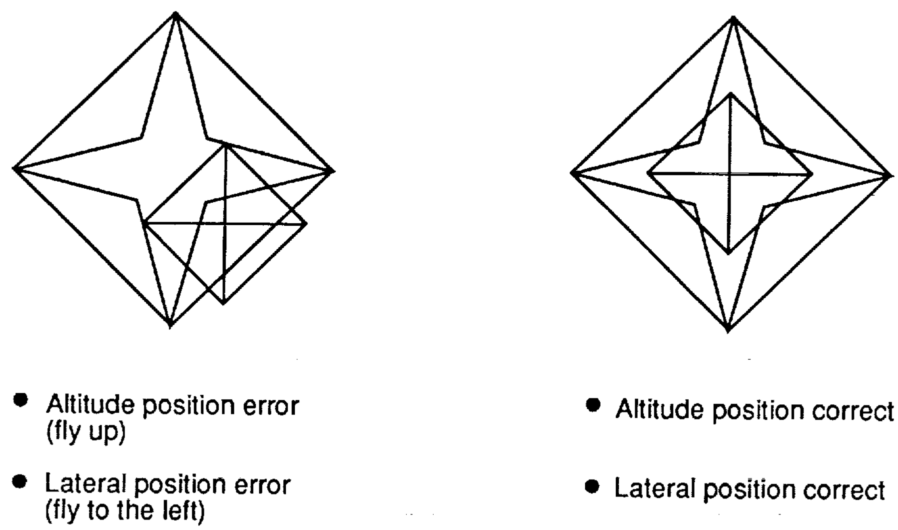



Figure 2. Single-wicket-pair alignments.

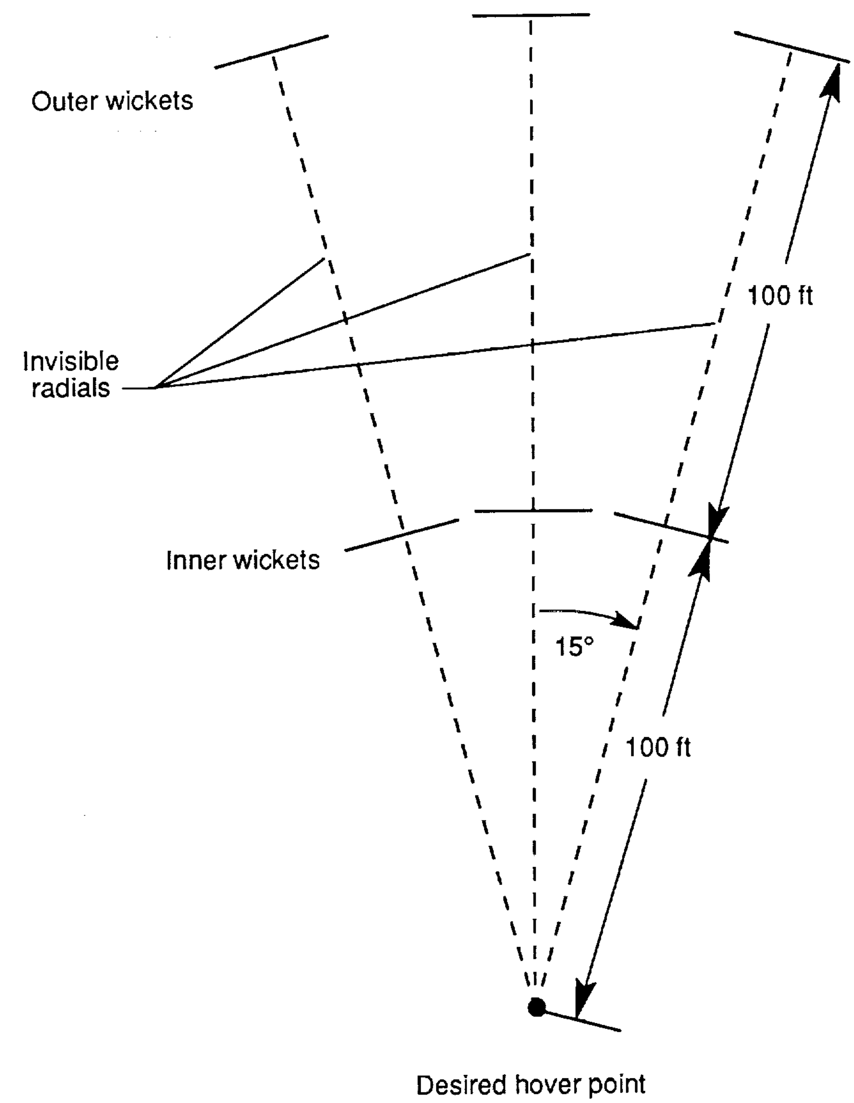



Figure 3. Top view of spatial relationships between wickets and desired hover point.

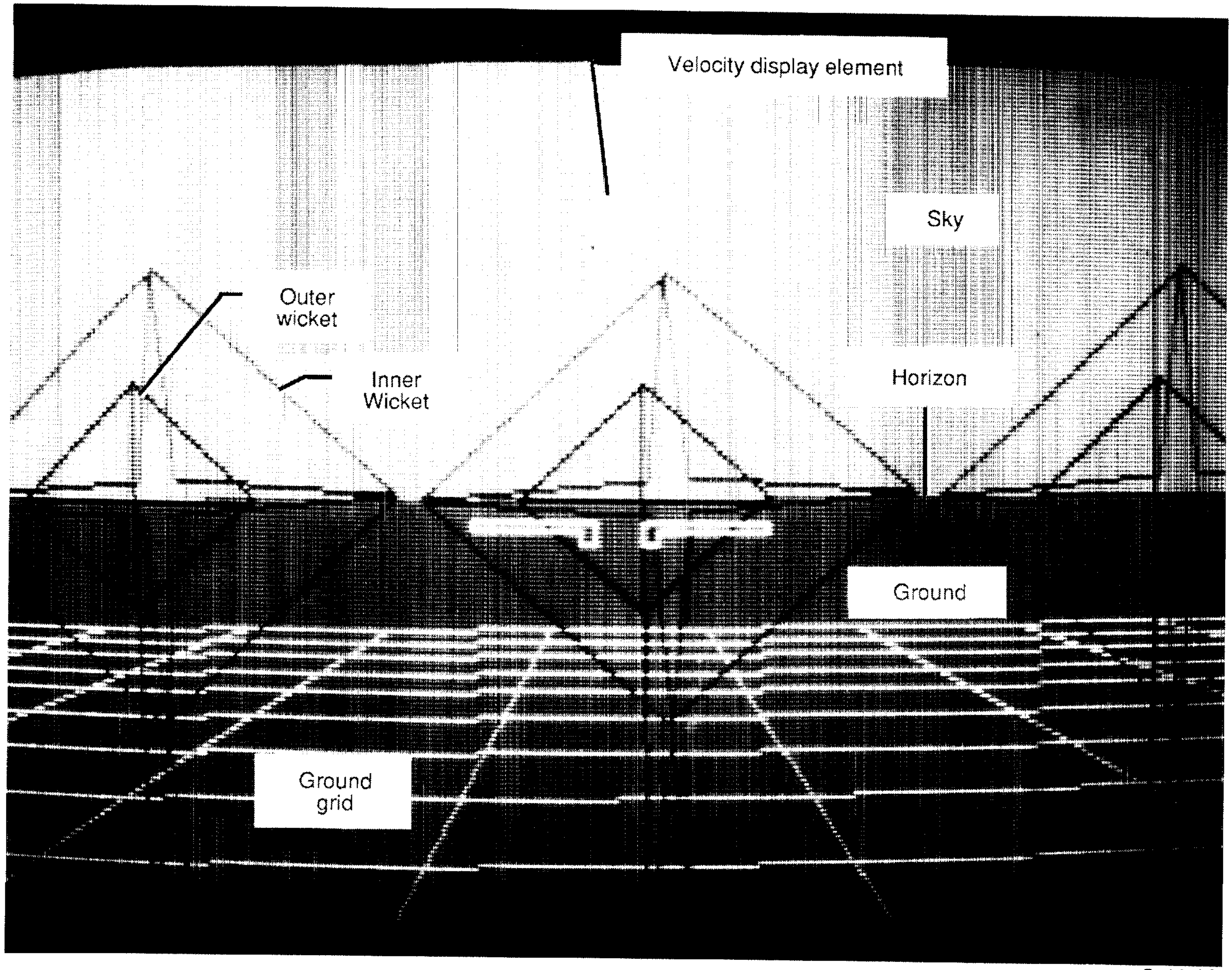



Figure 4. Pilot's view of "real-world" perspective display when vehicle is near desired hover point.

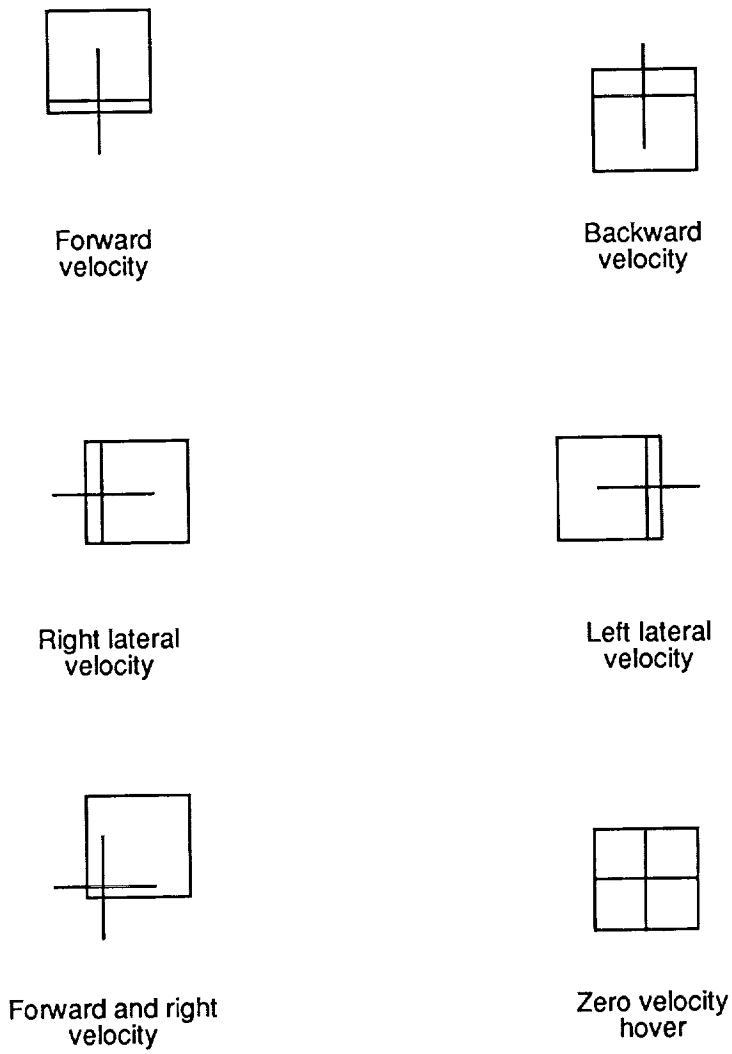
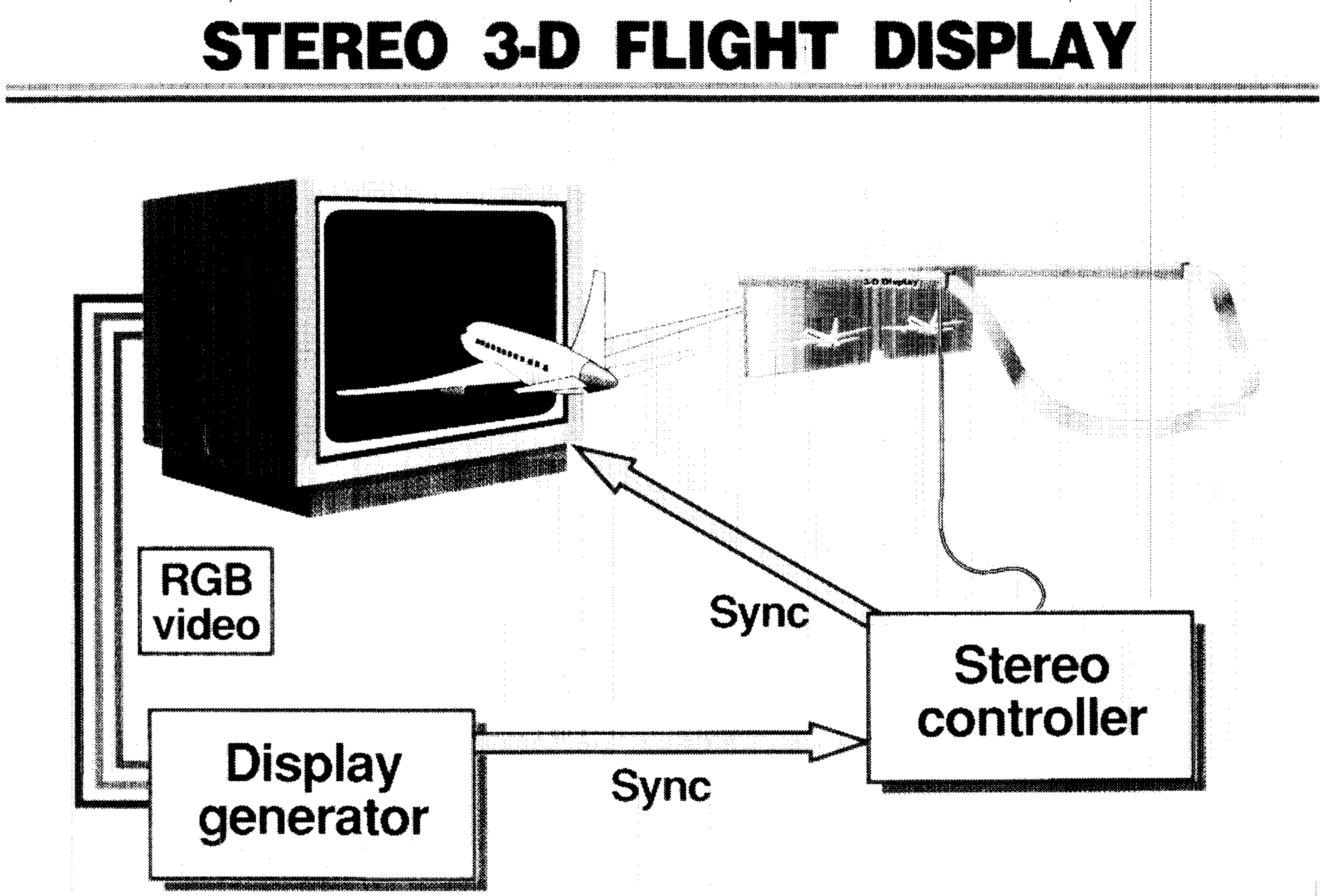



Figure 5. Velocity display element symbology.

L-90-23

Figure 6. Stereo-pair images produced by graphics generation system.




L-89-8776

Figure 7. Stereo 3-D flight display.

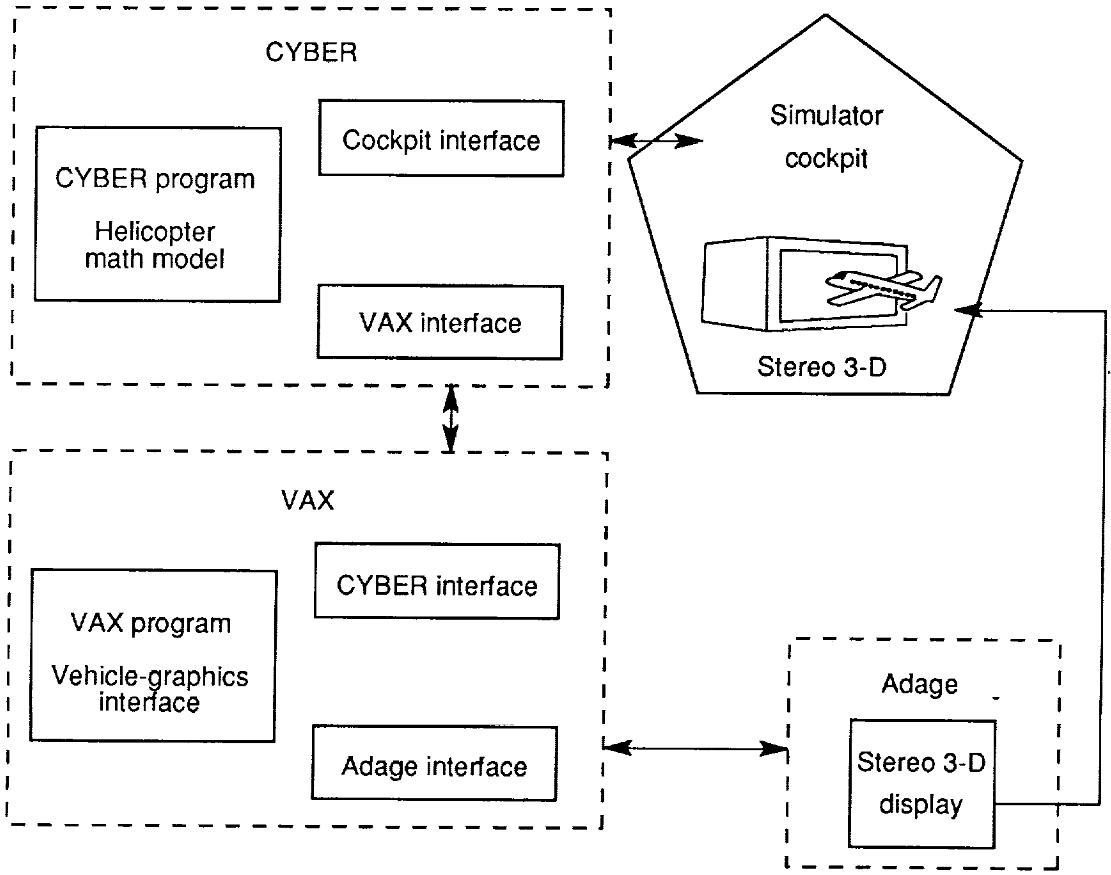



Figure 8. Three-stage computer pipeline used in study.

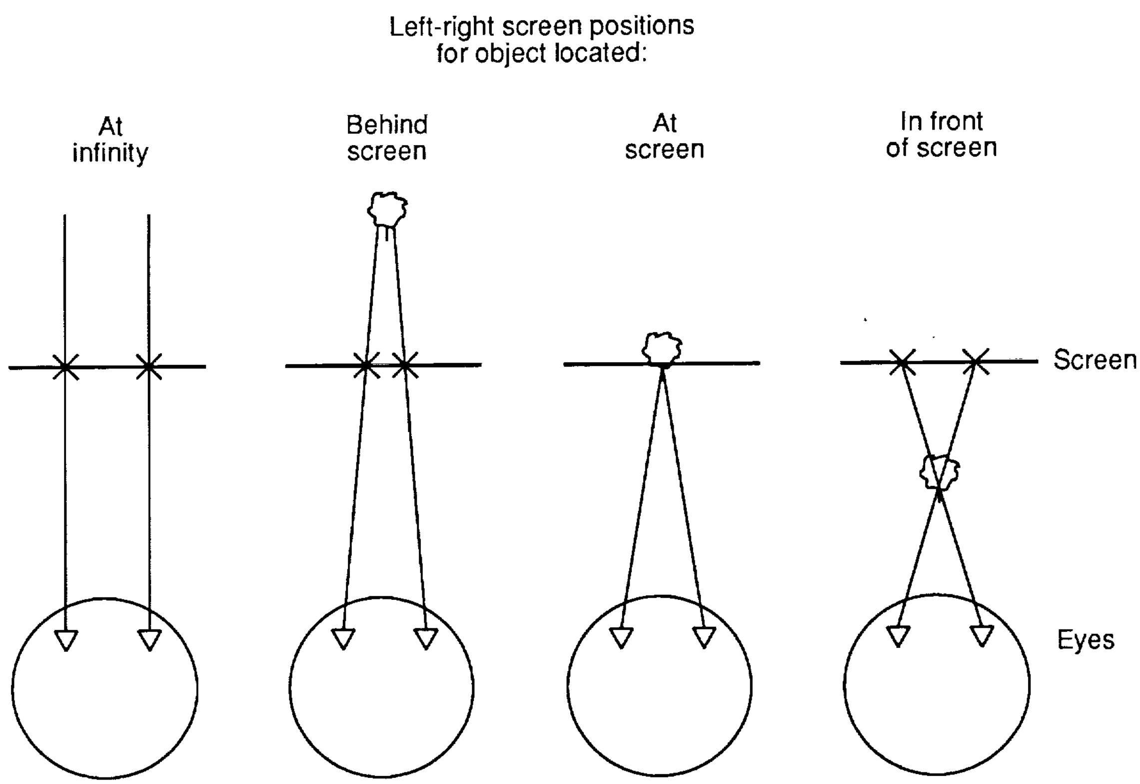
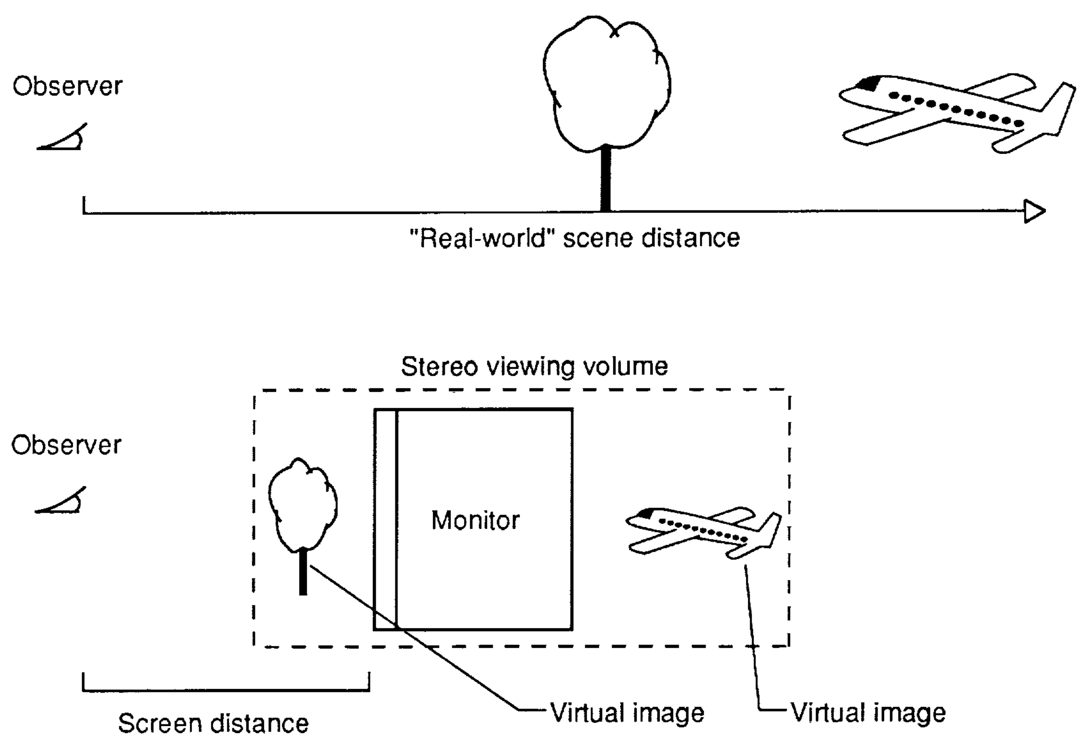
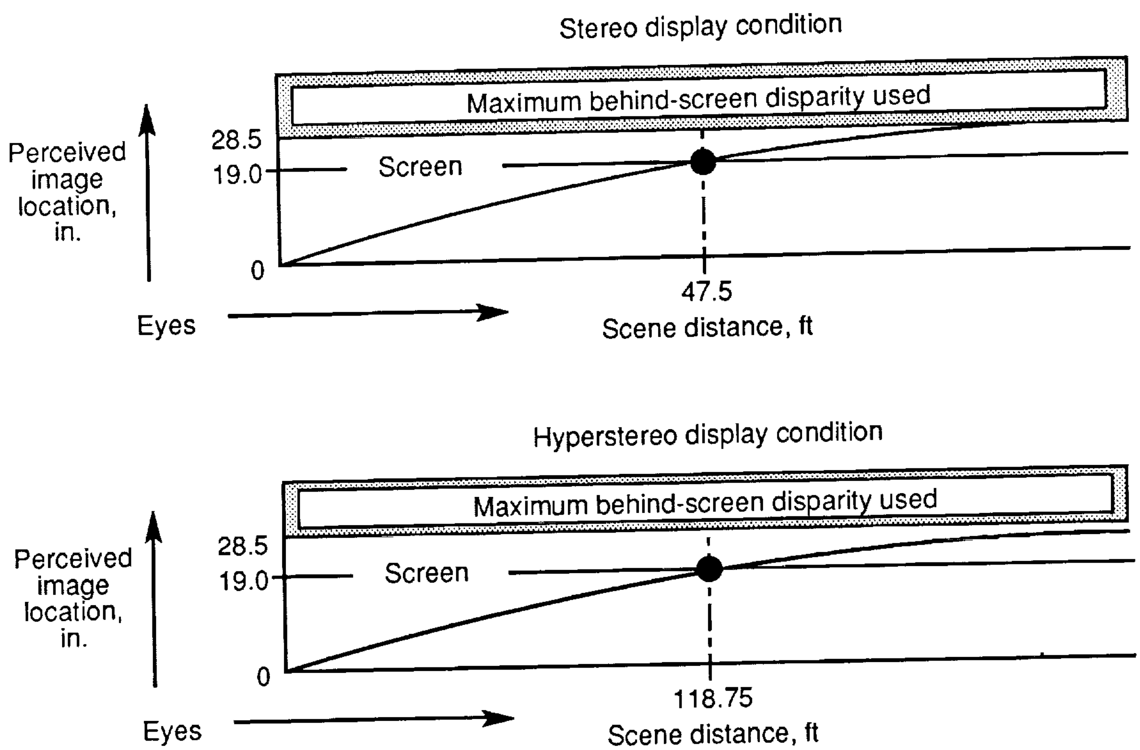



Figure 9. Top view of geometric principle for producing left- and right-eye views.




(a) Scene-to-screen mapping.

Figure 10. Visual scene mapping.




(b) Visual scene mapping into stereo 3-D viewing volume using asymptotic transformations.

Figure 10. Concluded.

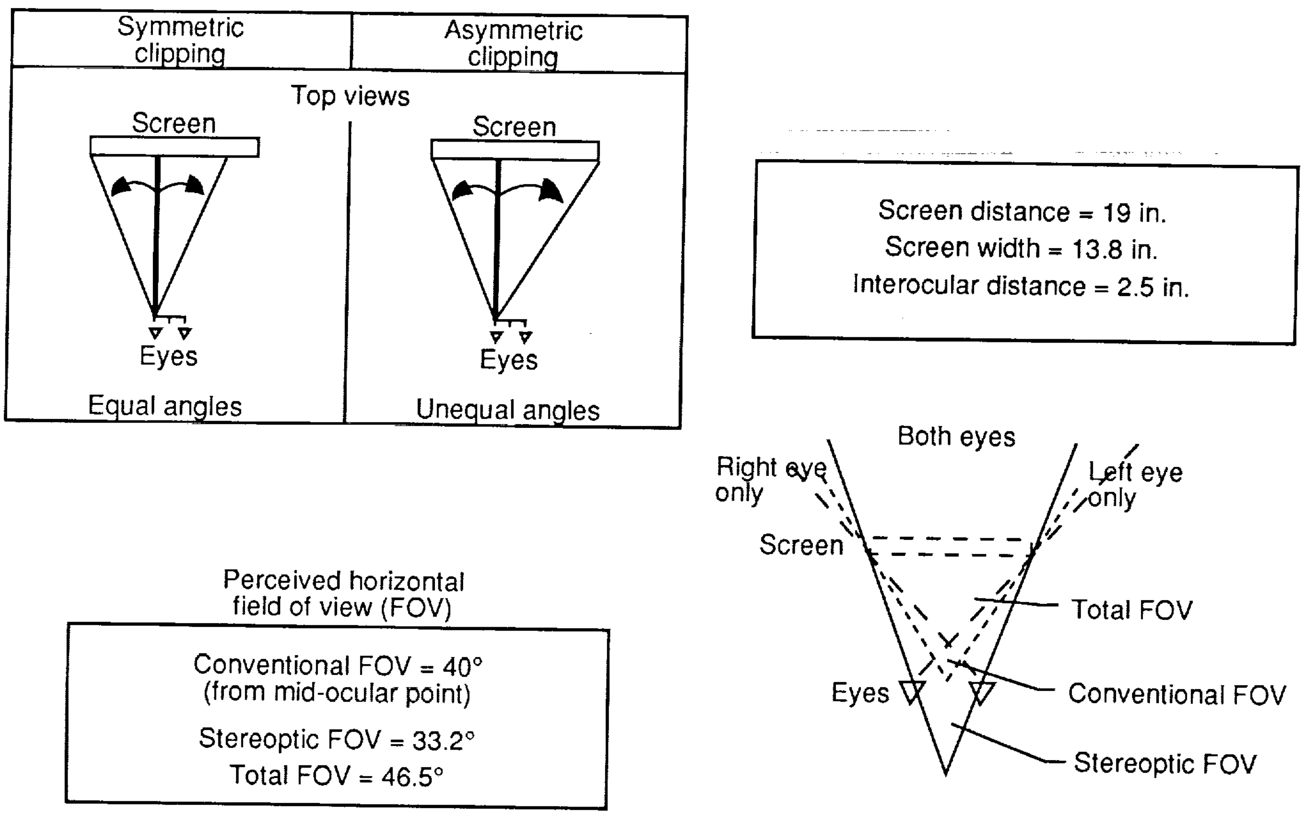



Figure 11. Comparison of symmetric and asymmetric clipping.

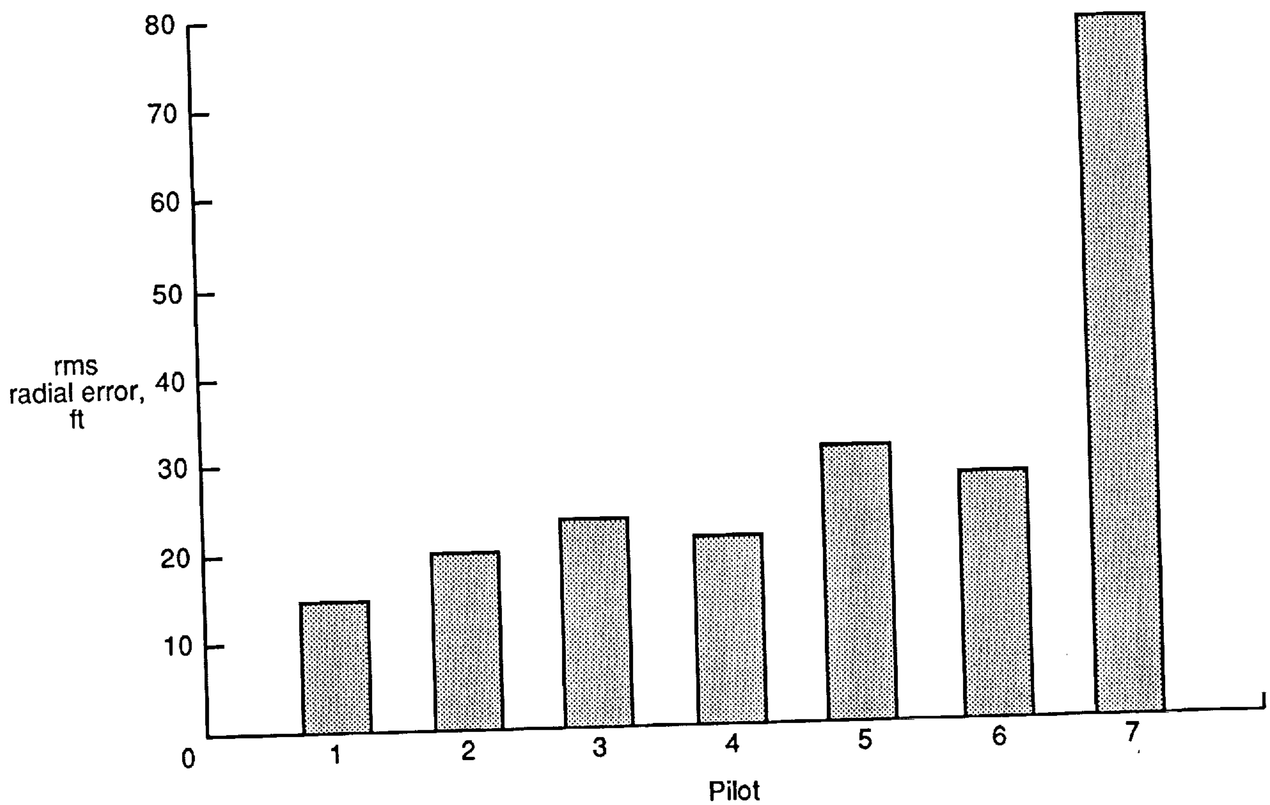



Figure 12. Mean rms radial error for each pilot.

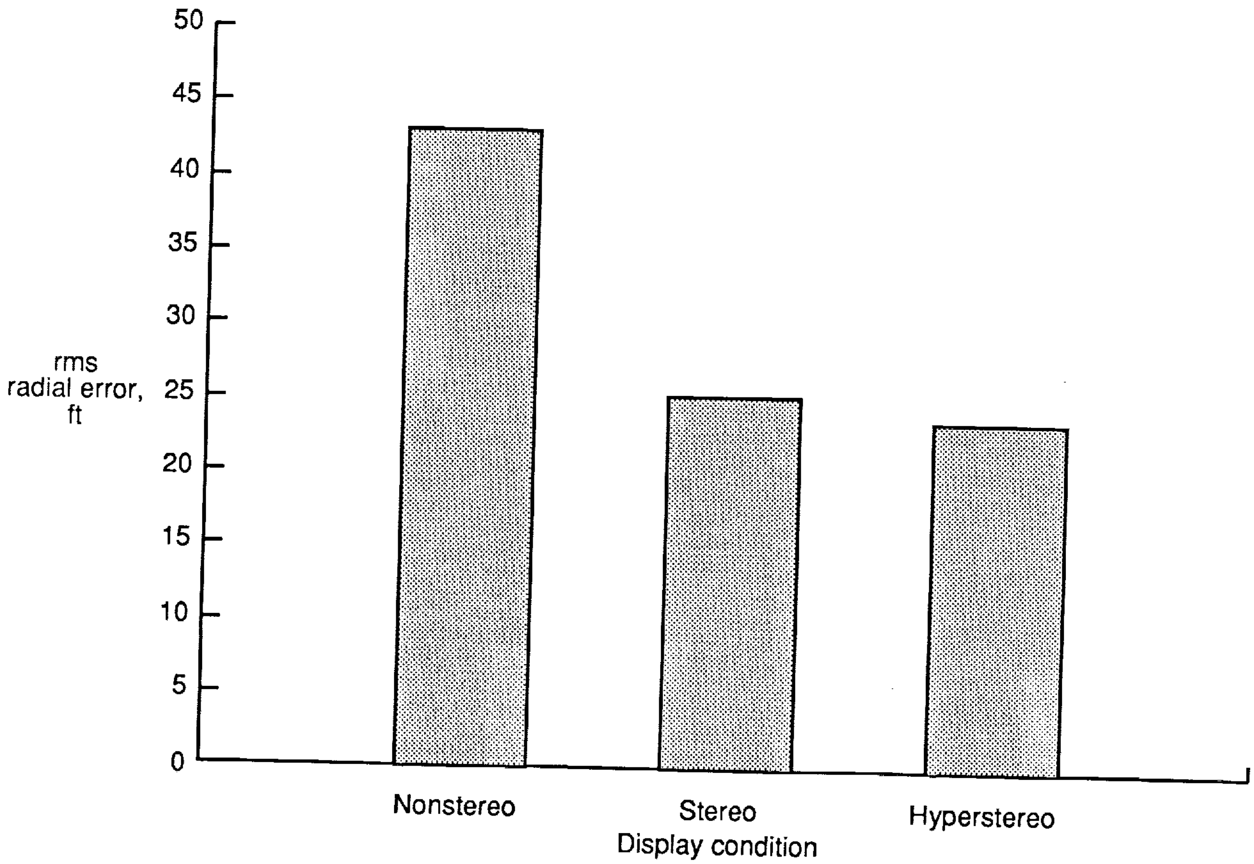



Figure 13. Mean rms radial error for each display condition (all pilots).

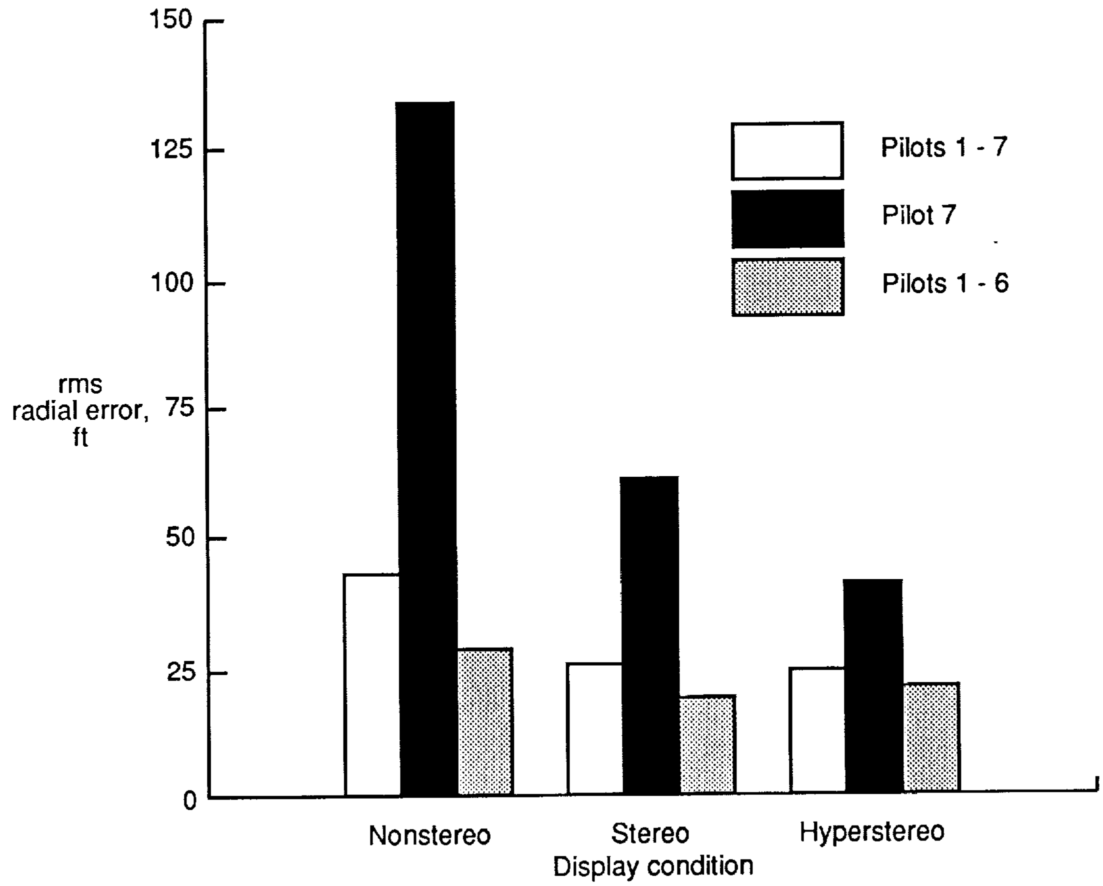



Figure 14. Mean rms radial error for each display condition with pilot 7 compared with average errors for other pilots.

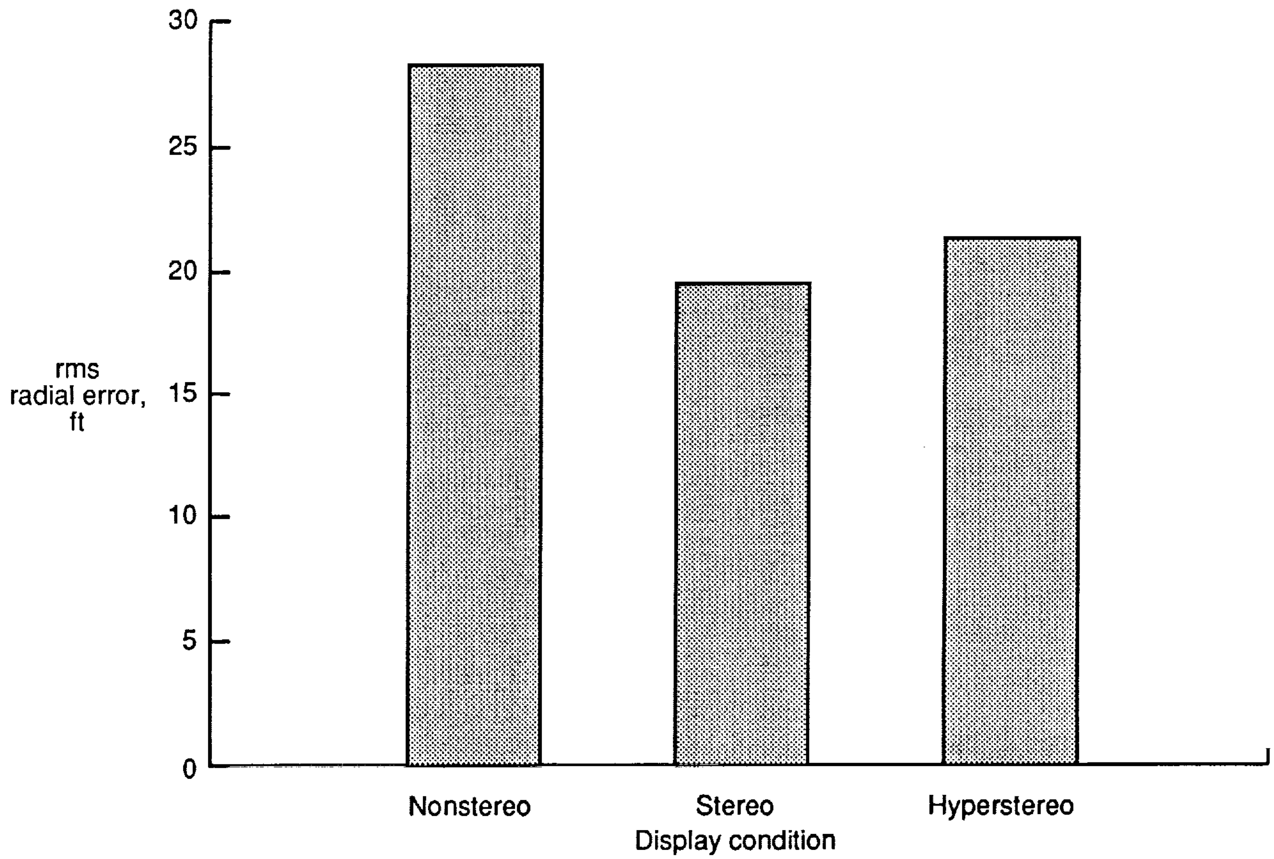



Figure 15. Mean rms radial error for each display condition (pilots 1 to 6).

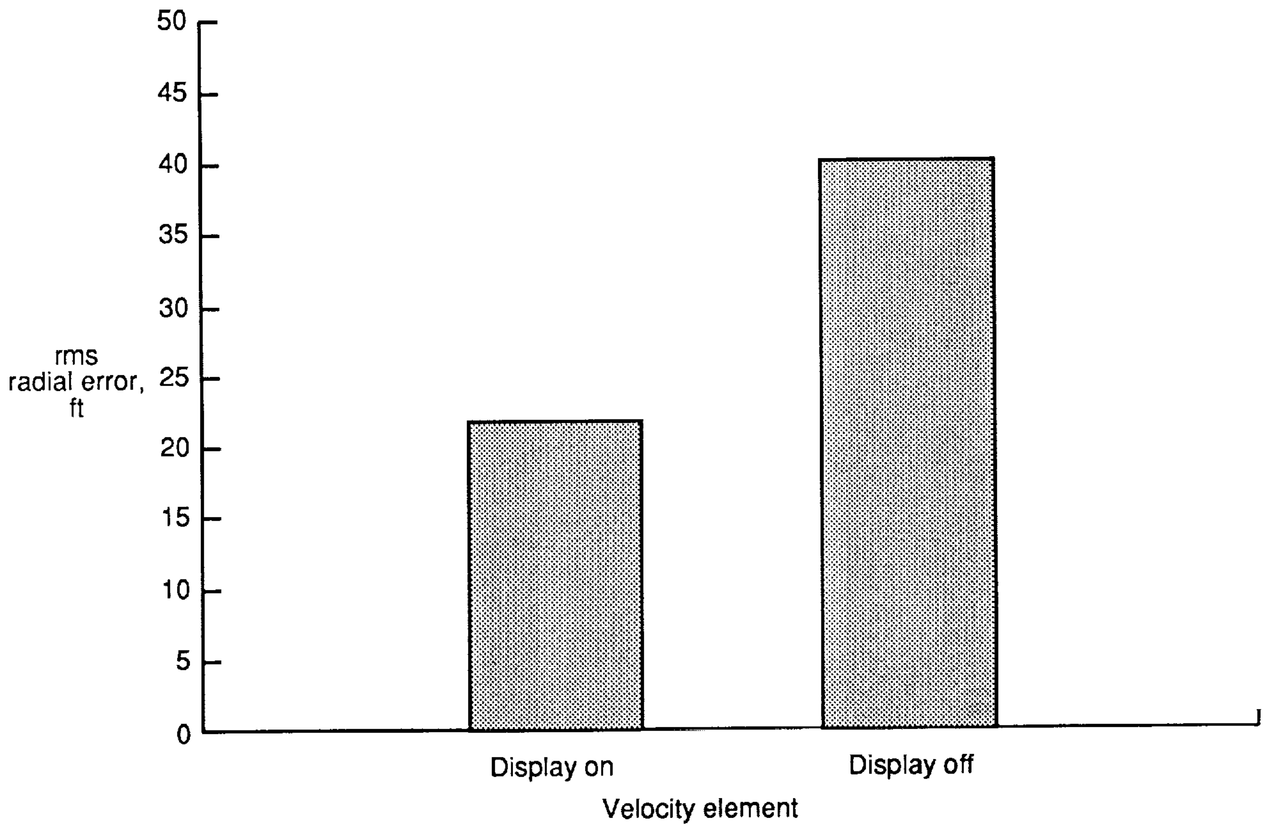



Figure 16. Mean rms radial error with velocity display element "on" and "off" (all pilots).

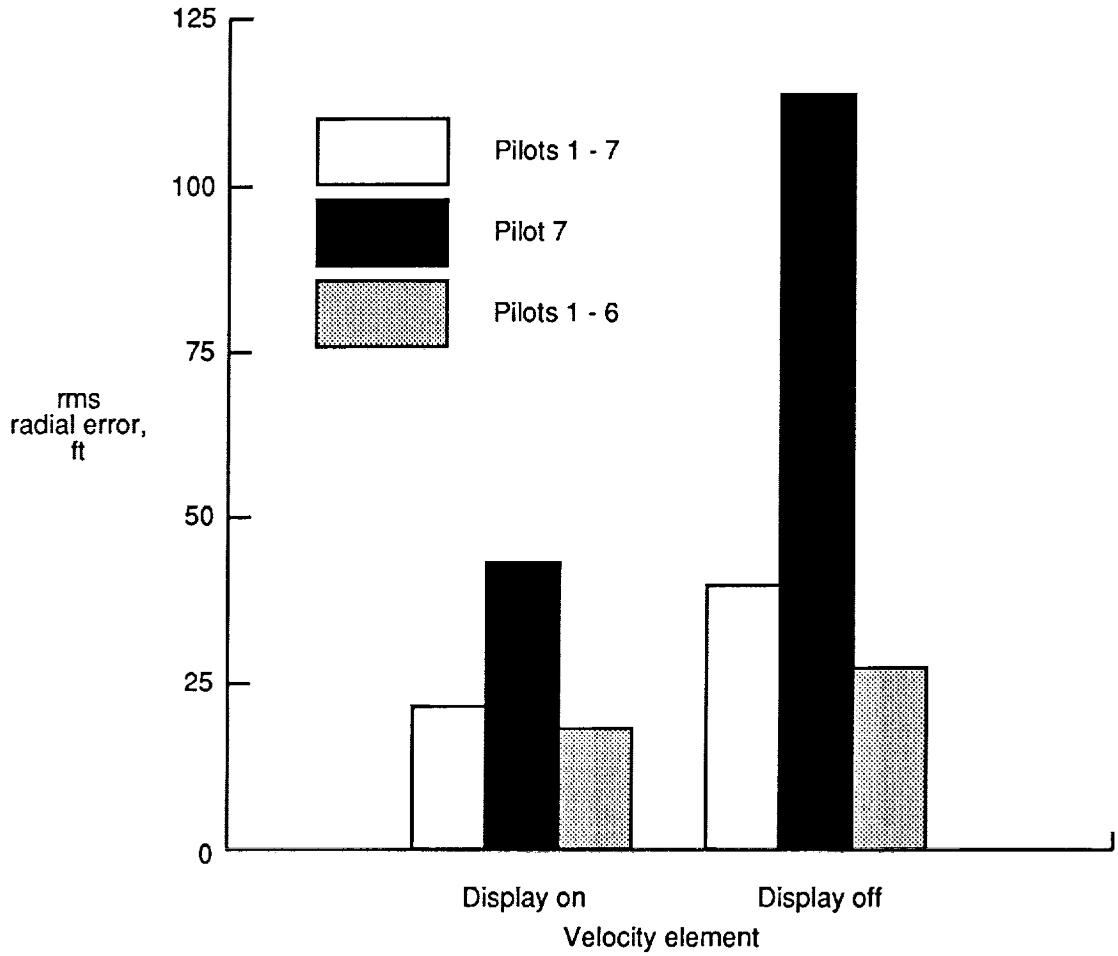



Figure 17. Mean rms radial error with velocity display element "on" or "off" for pilot 7 compared with average errors for other pilots.

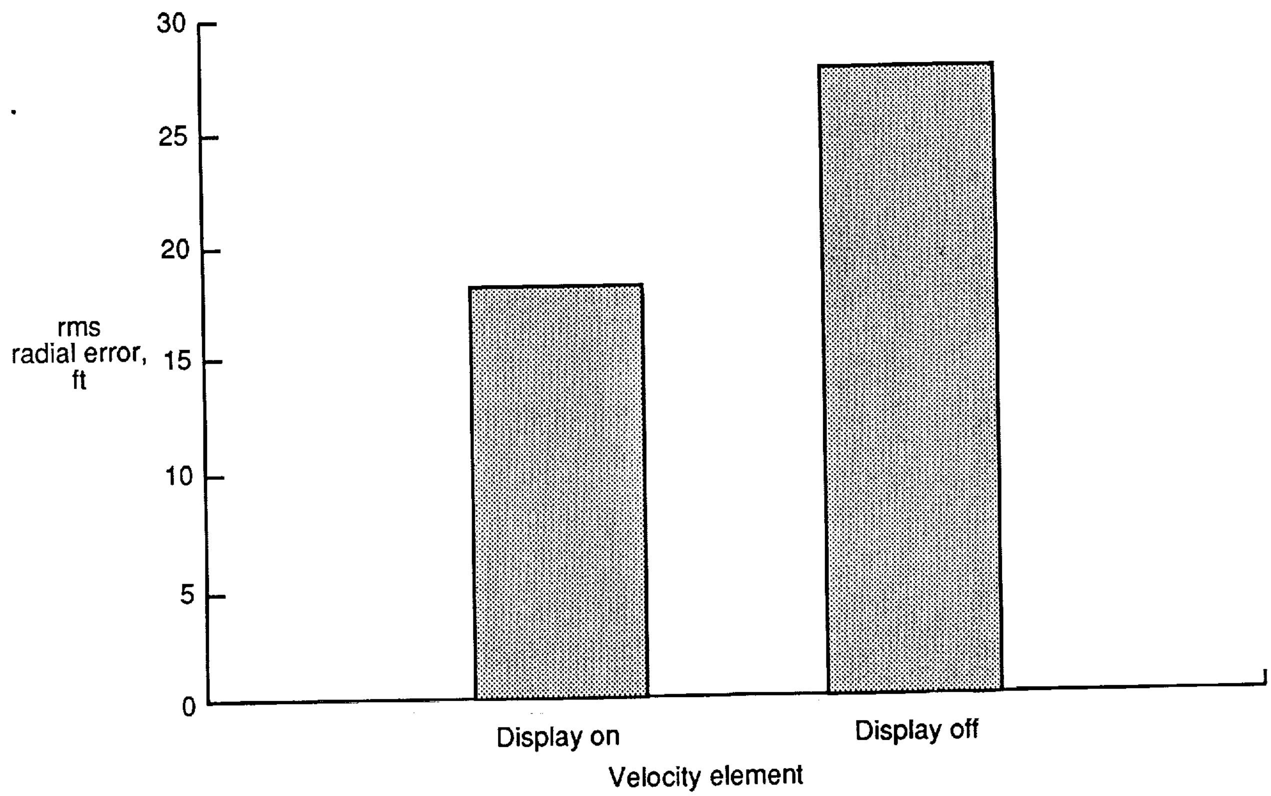



Figure 18. Mean rms radial error with velocity display element "on" and "off" (pilots 1 to 6).

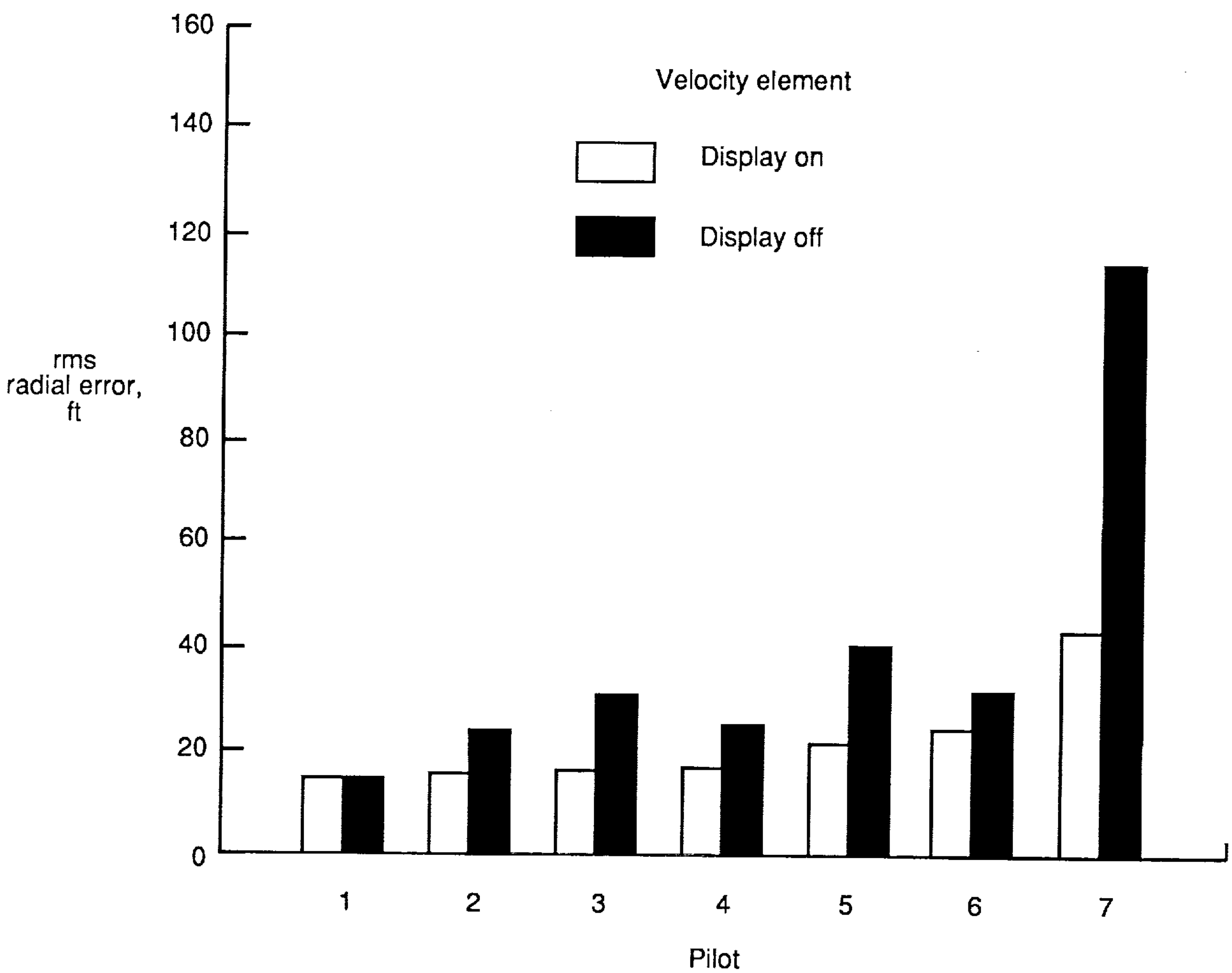



Figure 19. Mean rms radial error for each pilot with velocity display element "on" and "off."

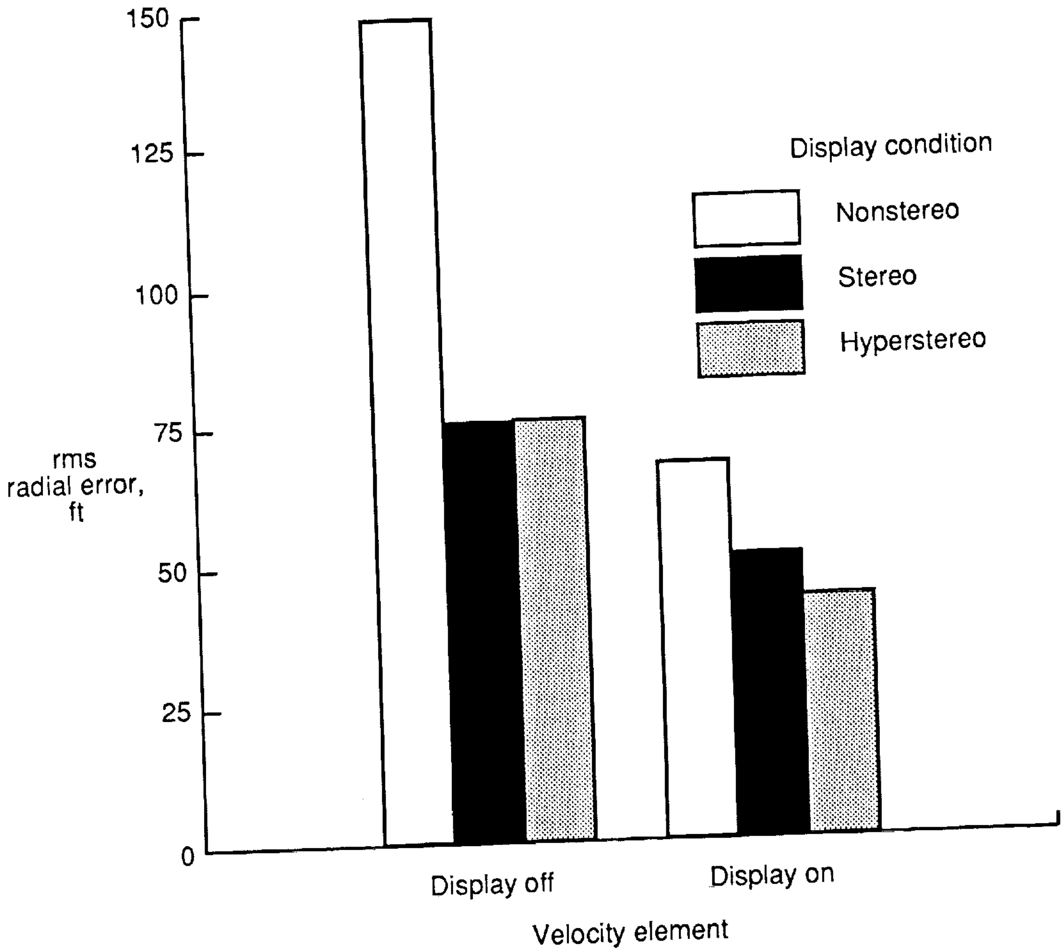



Figure 20. Mean rms radial error for each display condition with velocity display element "on" and "off."

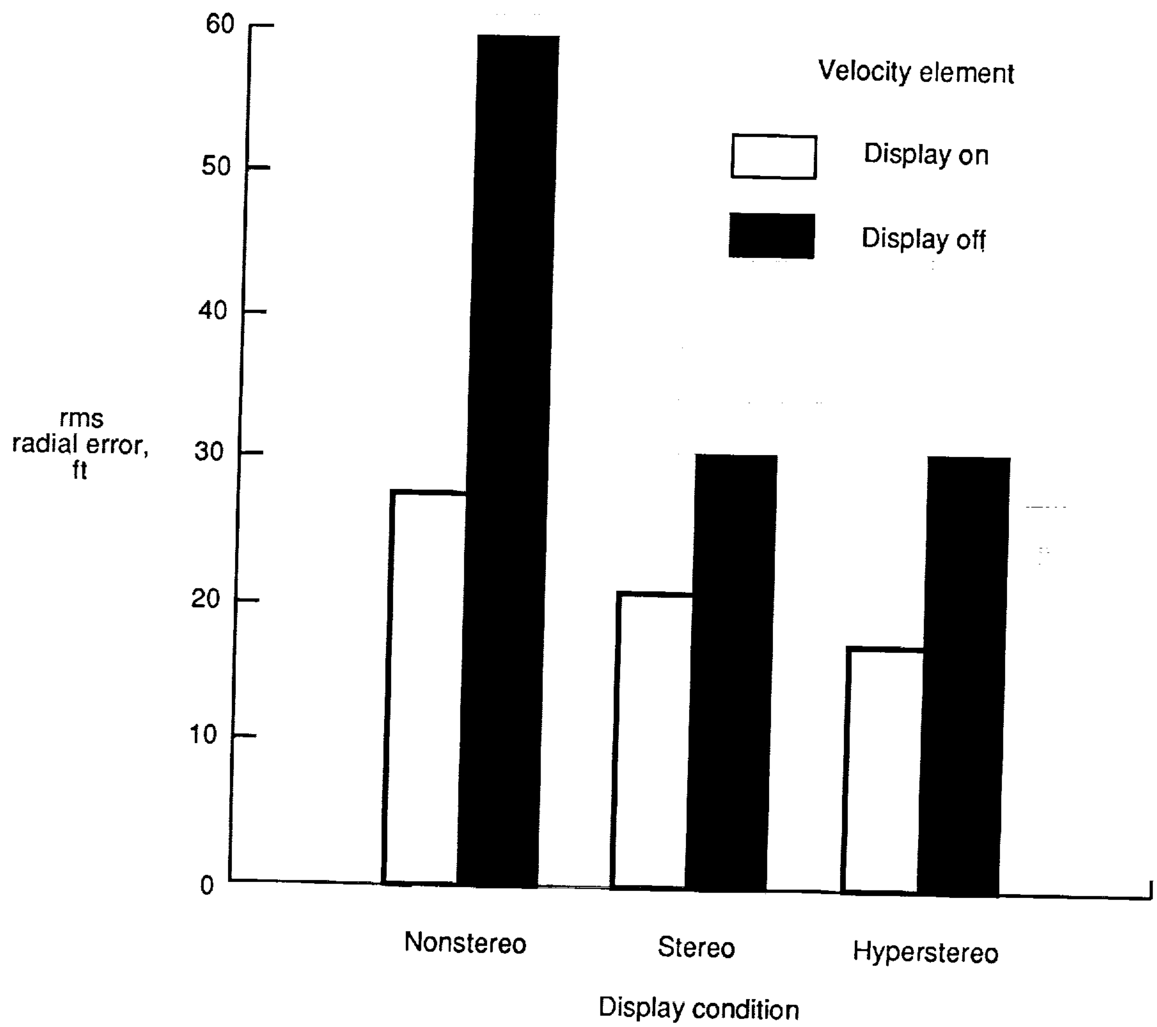



Figure 21. Mean rms radial error for each display condition with velocity display element "on" and "off."

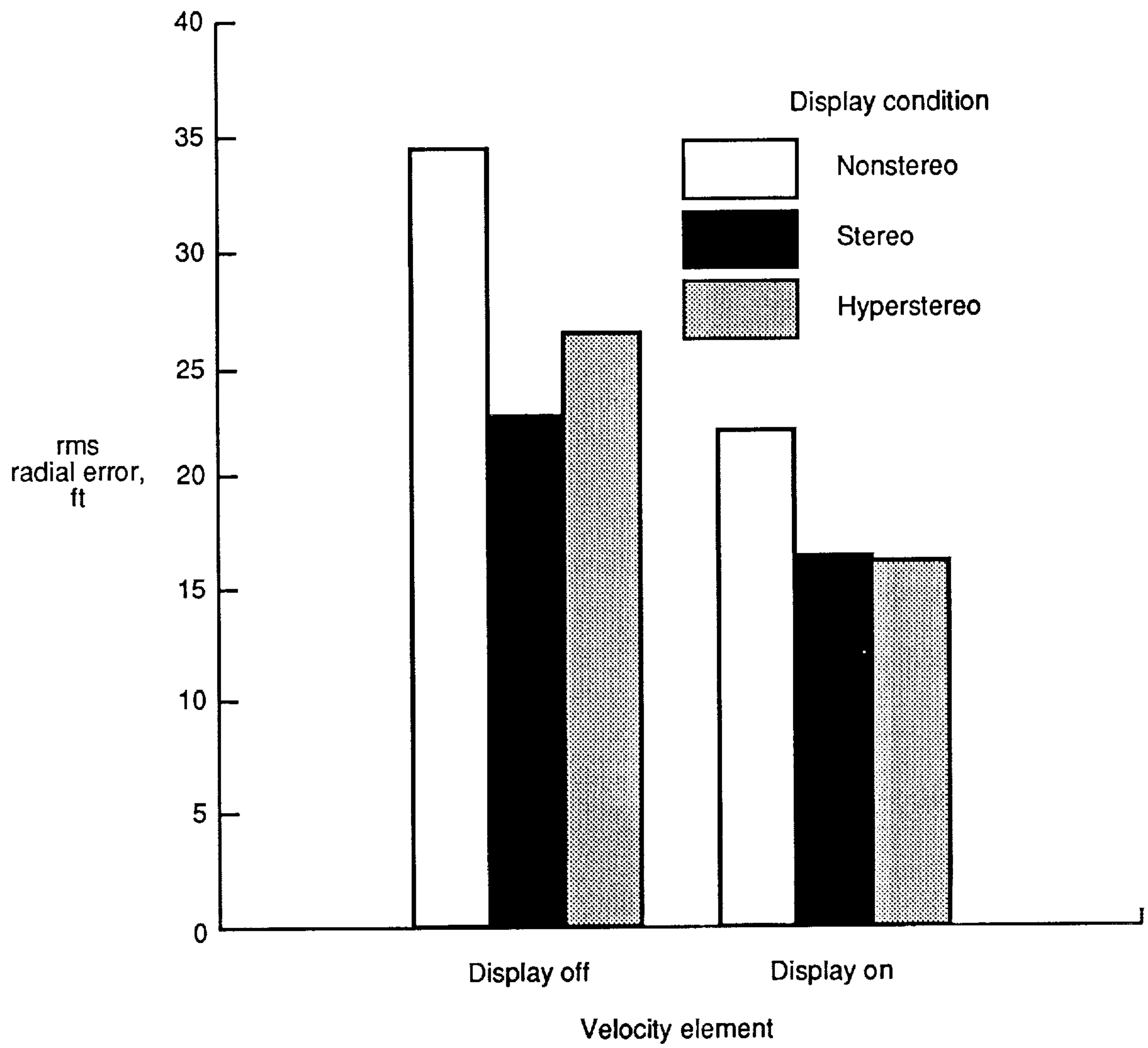



Figure 22. Mean rms radial error for each display condition with velocity display element “on” and “off” (only pilots 1 to 6).

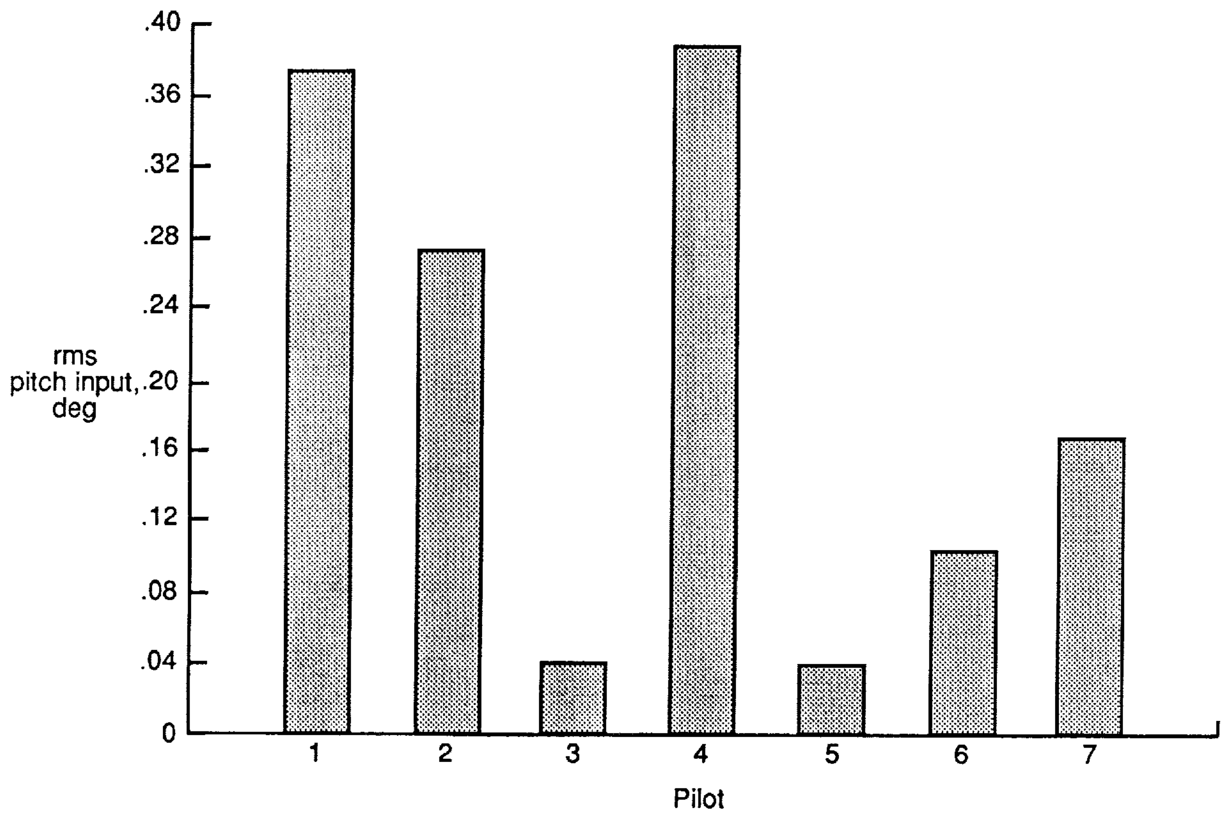



Figure 23. Mean rms pitch input for each pilot.

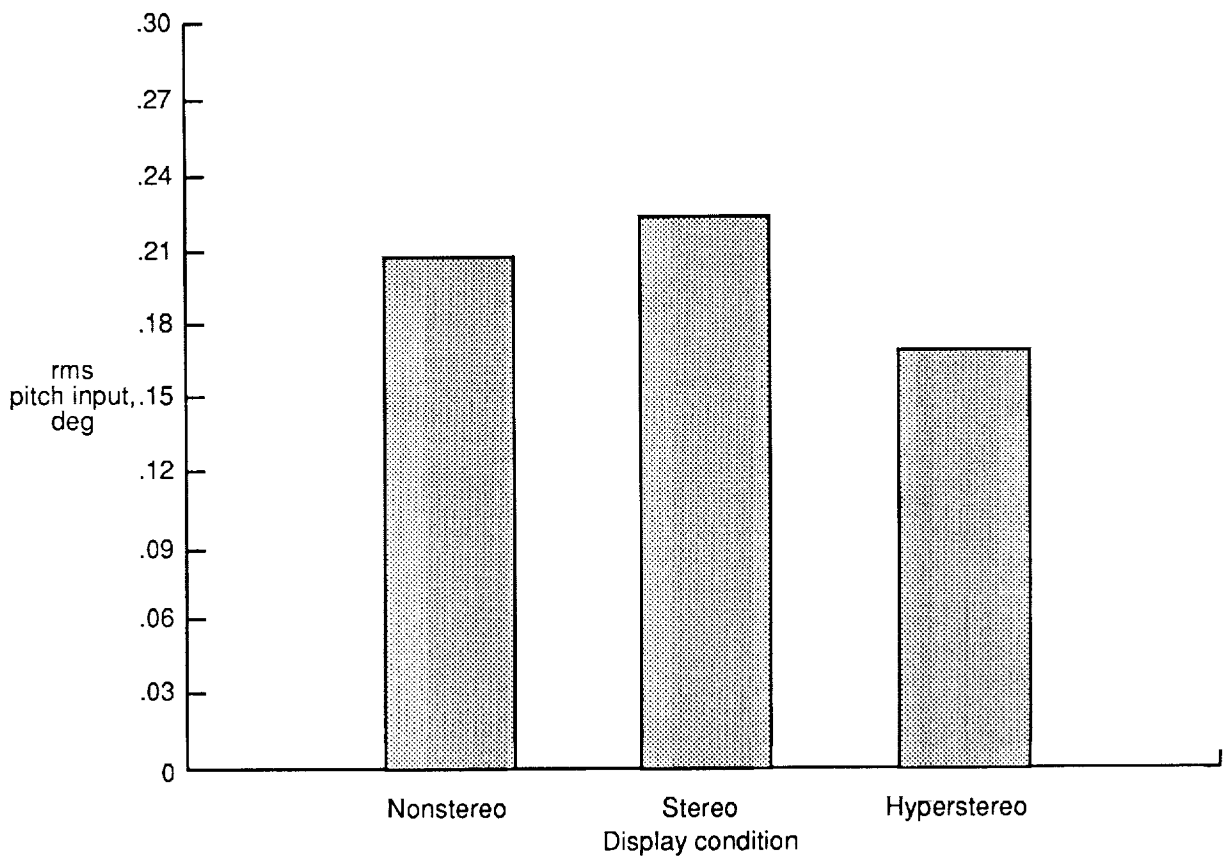



Figure 24. Mean rms pitch input for each display condition.

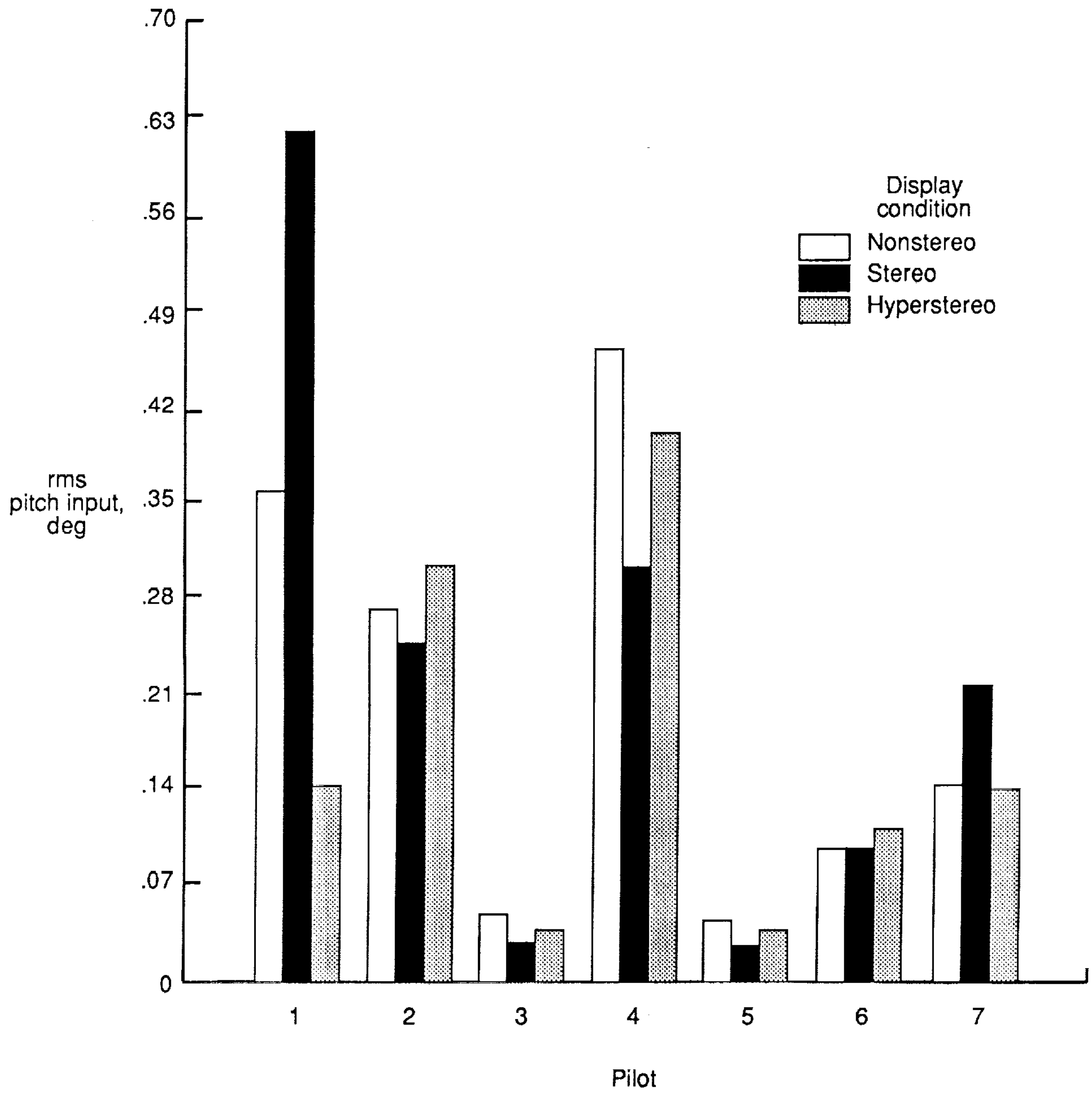



Figure 25. Mean rms pitch input for each pilot across display conditions.

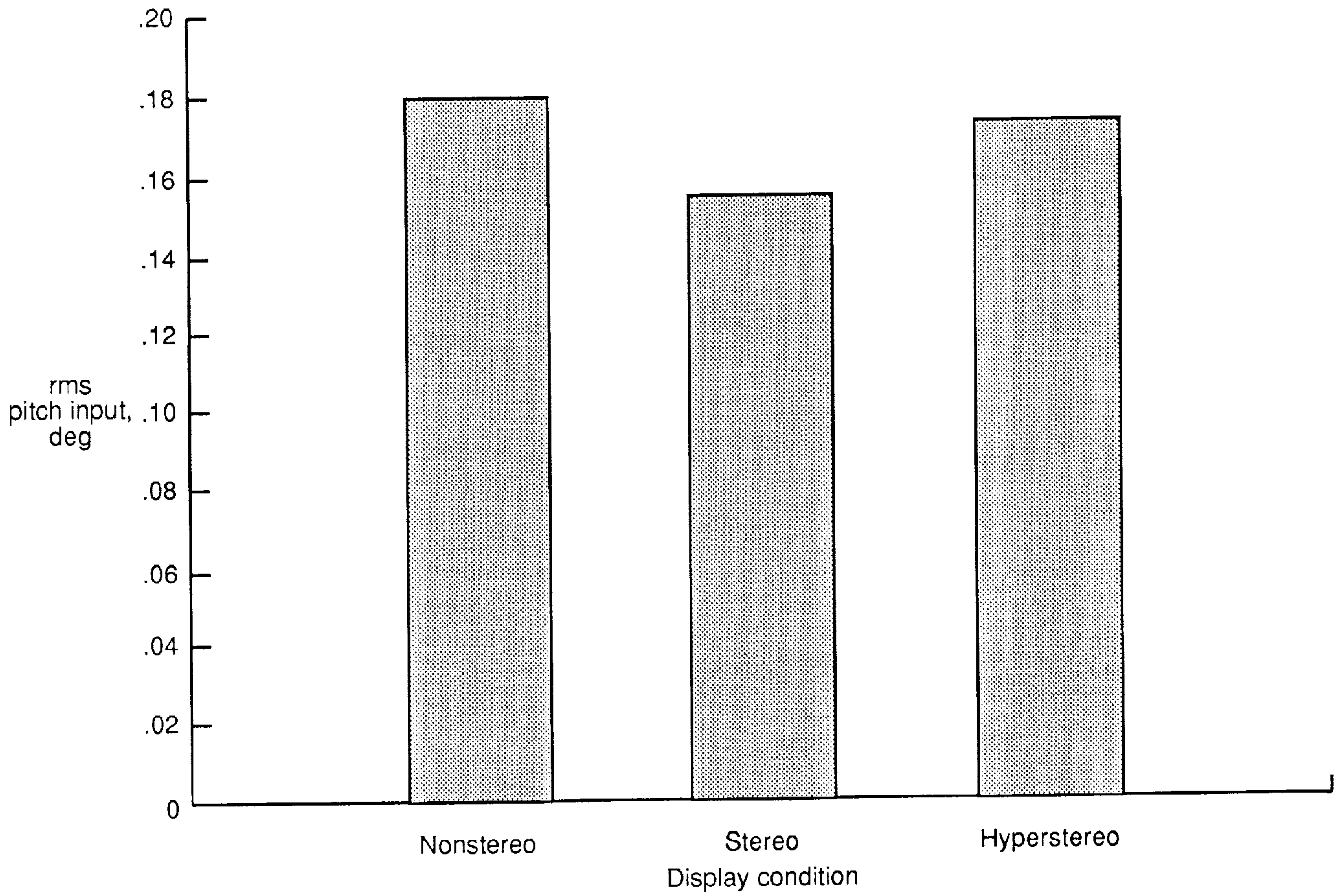



Figure 26. Mean rms pitch input for each display condition (pilots 2 to 7).

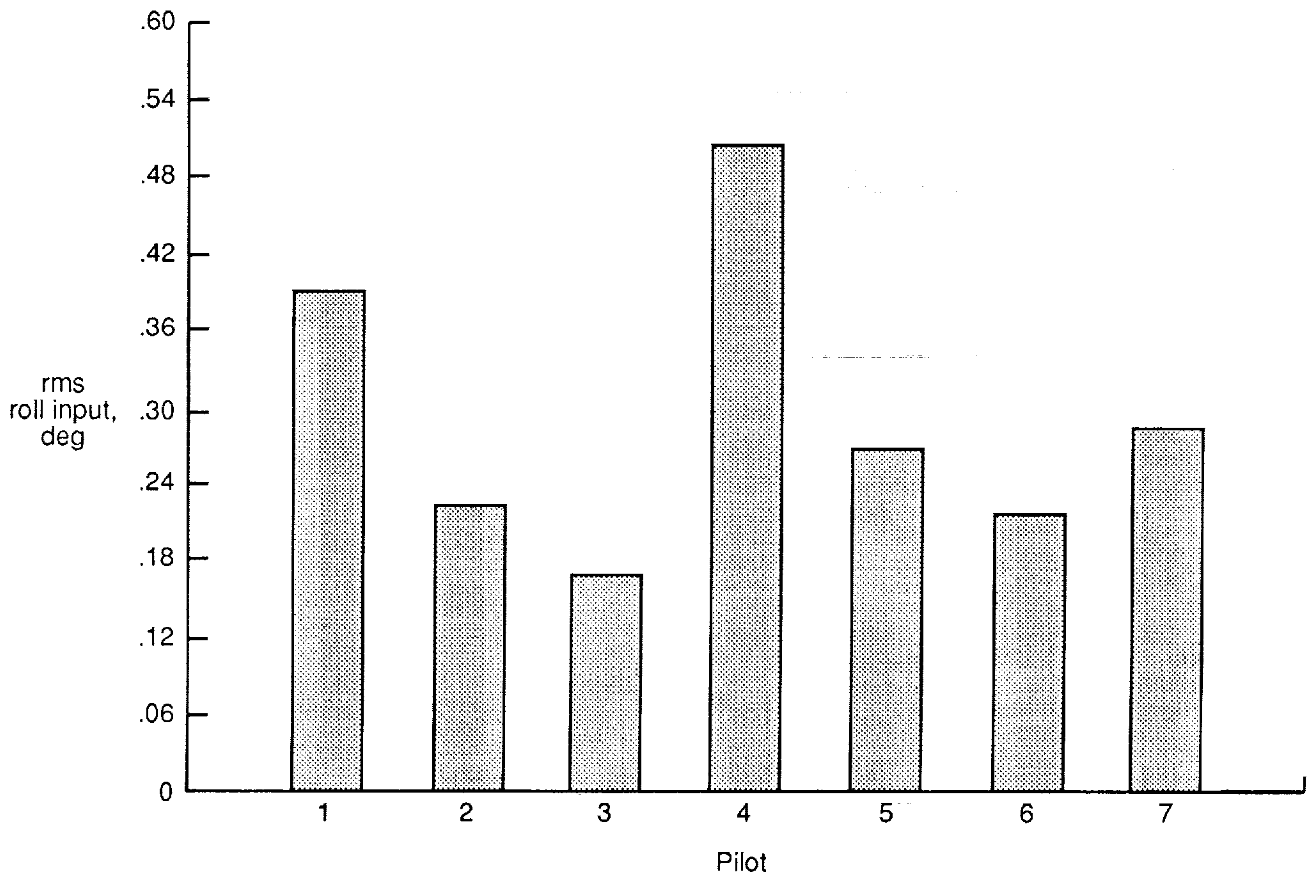



Figure 27. Mean rms roll input for each pilot.

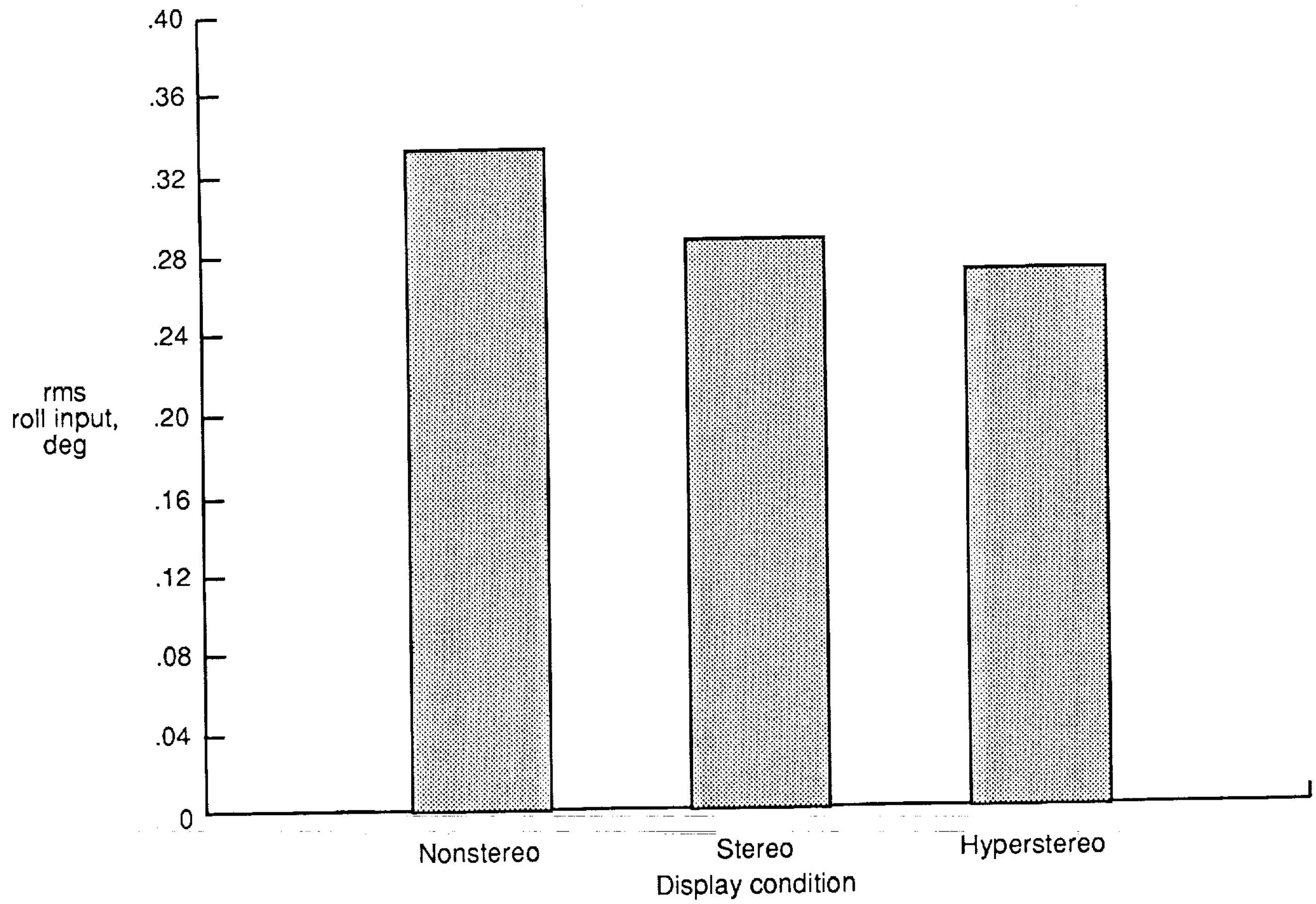



Figure 28. Mean rms roll input for each display condition.