TEMPORAL PERCEPTION VERSUS REALITY IN AN EYE-TRACKED DISPLAY: THE IMPACT OF LAG

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ABSTRACT

The development of a visual display system that takes advantage of the physiological process of vision requires a detailed knowledge of the parameters effected. During the development of the ESPRIT eye-tracked visual display, tests were run on allowable system lag, on the trade-off between the size of high resolution area and resolution, and on other parameters. The results indicated that some parameters could effect performance even though the viewer might not be aware of it. One of the parameters, eye-track lag, was found to have some unexpected results.

ABOUT THE AUTHORS

David Peters has been involved with visual systems for 33 years, 22 of them at Link. He is a senior member of the visual engineering staff. He has 18 patents, including the ESPRIT basic patent, and was the leader of the conceptual team that first developed the ESPRIT concept. He has been the author of several papers and taught a short course at UCLA on displays. He is a consultant throughout the CAE corporation of various visual projects.

James Turner has been involved with visual system development for 18 years at Link. He is a senior member of the visual engineering staff and holds several patents associated with eye-slave technologies. He is a key member of the eye-slave development team and is directly responsible for essential developments in servo systems, oculometer technology, area-of-interest blending, mapping, system throughput and software associated with ESPRIT. He developed several of the scenarios used in ESPRIT evaluations including those used to study the impact of lag.

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INTRODUCTION

The successful introduction of a visual system that uses the eye characteristics to reduce system complexity requires a knowledge of the parameters that control the eye/brain relationship so that the performance of the user is unaffected. The development of Link's Eye Slaved Projected Raster InseT (ESPRIT[1]) visual system that uses the resolution difference of the foveal and peripheral portions of the eye, coupled with the suppression that the eye/brain system normally introduces during saccades (pre-programmed rapid eye movements), to produce a very large field of view display system with very high resolution. In the pursuit of the program, one of the program phases was to study the various interrelationships involved.

The goal of the program was to produce a product that made use of the human visual system's characteristics to minimize equipment without any negative training results. During the course of this investigation, Link worked with personnel from the Ohio State University Foundation, led by Dr(s) Lawrence Wolpert and Dean H. Owen of the Department of Psychology, Aviation Psychology Lab.

EYE-TRACKED DISPLAY

CAE-Link's ESPRIT is the first simulator display system that has entered the training field that exploits the unique characteristics and capabilities of the human visual process by centering a high resolution image where the eye is looking and placing low resolution imagery throughout the remaining field of view. The display system has a very large field-of-view (FOV) with minimal (though sophisticated) hardware.

The ESPRIT system uses a "real-image" approach, and in the most economical configuration has only two channels from the computer image generator to cover a field of view of 240° horizontal by 140° vertical. One channel covers the entire field of view with a low resolution background. The other channel is servo driven to follow the eye using an Area-of-Interest (AOI) approach that blends and insets the small high-resolution AOI into the background and minimizes the difference between the AOI and the background to prevent the AOI from being highlighted. Figure 1 illustrates this configuration. Other configurations are possible including complete 360° field of view.

The exact requirements of a visual system are determined by analysis of the training that the visual system must support. A training analyst will consider many things during this process. He will look at the mission, the environment, the capabilities of the weapons platform, and the requirements for night vision devices and Head Up Displays (HUD). He also considers the aggressive nature of tactical flight and the need to use in-cockpit displays. After considering these and many other variables, the analyst will evolve specific visual system requirements to support an effective simulation of the aircraft and its mission.

ESPRIT Hardware

The ESPRIT hardware consists of several key components that have been integrated to form the operational display.

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The Display Surface. The ESPRIT display hardware includes a dome display surface finished to a high degree of accuracy, and painted with a high gain reflective material to increase the brightness. The dome may be mounted on a motion platform as shown in Figure 1 or be stationary.

Background Image Projector(s). The background or peripheral projector (since the eye can not directly look at this image, it can only be viewed in the peripheral part of the eye) in Figure 1 uses a single GE light valve to provide the field of view of more than 240° by 140°. An advanced lens design provides a projection output of more than 200° with a very large depth of field. By locating the lens above and to the rear of the student, the coverage from the design eye is increased to 240°.

Eye-Track Projector. The eye-track or foveal projector provides a high-resolution picture (≈3 arc minutes/olp with an AOI of 24 degrees in a current application) in an "area of interest" (AOI) mode of operation using a GE light valve as display source. The scene is 'insetted' into the background by high speed servo operation that operates at a speed faster than the eye. Eye saccade velocities can reach 700 degrees per second, and have accelerations of up to 50,000 degrees per second. The static line of sight accuracy of the azimuth/elevation servos is better than 1 minute of arc, while the dynamic accuracy is better than 3 minutes of arc at an angular velocity of 700° per second – all the while having no noticeable jerks, hesitation, jumps, or overshoot. Figure 2 illustrates the projectors mounted in their relative positions. The use of a real-image display mounted away from the user's head relaxes the accuracy requirement of the eye measuring device. Since the servo system is highly accurate, the AOI information is always correct with respect to the peripheral image, and the image flow from the low resolution background image to the high resolution foveal image is continuous. Even if the eye measuring device is in error three degrees, the image is correctly located – but the eye is not perfectly centered in the inset. The tolerance of the user to measurement error is a function of the size of the inset.

Eye Line of Sight Measurement. The eye line of sight is determined by the helmet-mounted oculometer (HMOS) developed by Honeywell. The HMOS consists of two subsystems. The first is the head sensor that determines the 6 degrees of freedom of the helmet or head, and the second subsystem is the oculometer that determines the eye line of sight with respect to the helmet. This information is then combined to form the eye position and angular look angle. Since the display is a real image display system, the angular errors due to the head motion relative to the screen surface are removed to give the viewer a better sense of reality and three-dimensional space, using a head position correction algorithm. Figure 3 illustrates the HMOS system.

The value of the head position correction to the user has been under-appreciated. Head position correction permits the user to look around objects by moving his head. Pilot have given us unsolicited comments to the effect that when they first climbed into the cockpit they felt 'boxed-in', but after the correction was switched in "the world opened up". Another commented that "the vane is operating correctly (assuming we had a physical, mechanical image generator database, and the head position sensor permitted him to "look around" the vane as in the real aircraft). Head position correction allows a sense of reality to be present during aerial refueling, and in general removes the feeling of enclosure caused by the large screen surrounding the user.

The process of initially bringing a user into the eye tracked system takes about five minutes, with the data stored for each user. When the user re-enters the simulator, it requires about a one minute process to initialize.

The two key developments in the ESPRIT approach have been the development of a Helmet-Mounted Oculometer System (HMOS) and the development of very high speed and accurate servo systems that operate faster than the eye. The use of the Link MOD DIG image generator results in a closely coupled visual system that gives the trainee a field of view capability close to that of the aircraft at a resolution that approaches that of the viewer in the real world.

ESPRIT TEST BED

During the development of the ESPRIT, an engineering test bed was developed to evaluate both the eye-slaved display concept and most of the major ESPRIT components. The ESPRIT display components used in the valuation are depicted in the block diagram in Figure 4.

Table I compares the test bed and baseline system parameters; from the pilot's point of view the two systems differ only in field of view (74° by 67° versus 240° by 150°). From an engineering standpoint, the systems differ only in the characteristics of the display surface and the peripheral projection lens.

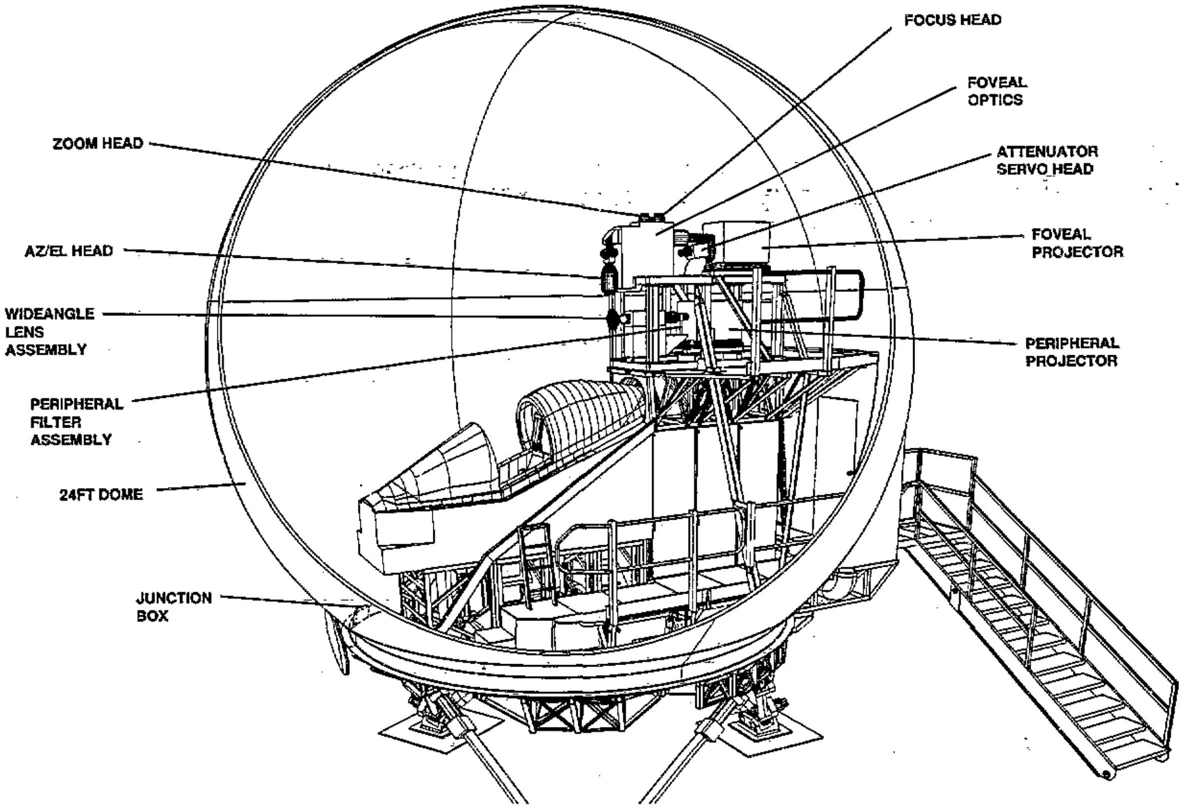

Figure 1 ESPRIT Display Layout

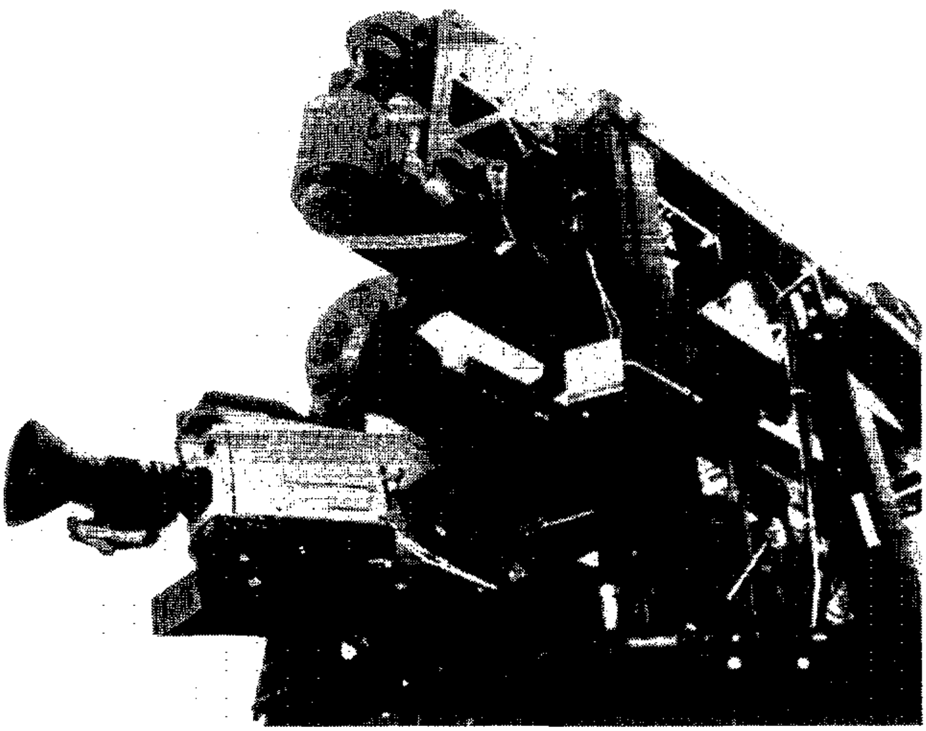

Figure 2 ESPRIT Projector Arrangement

Figure 3 Helmet-Mounted Oculometer (Courtesy of Honeywell, Inc.)

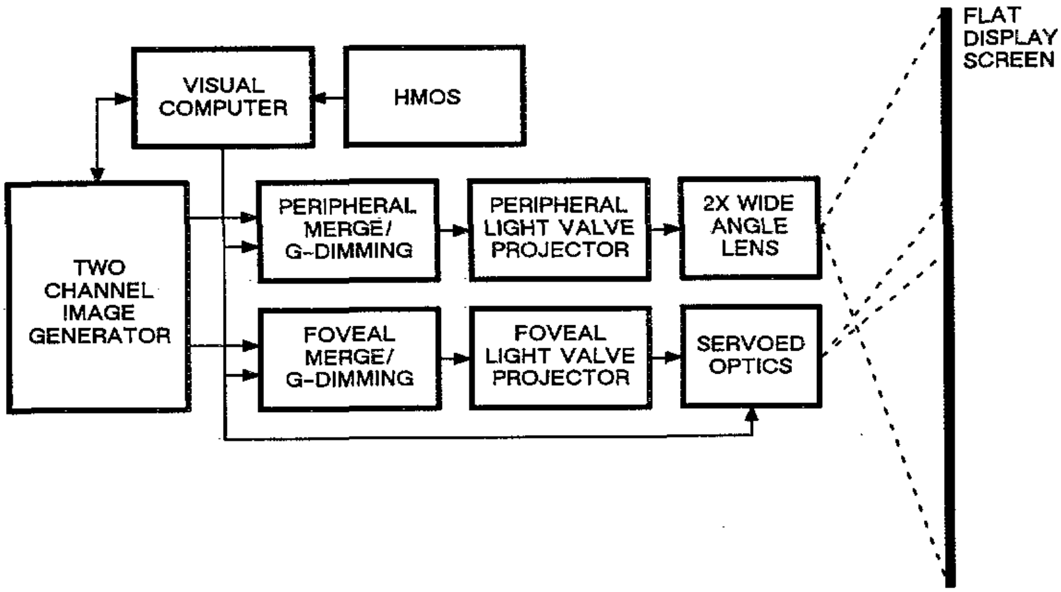

Figure 4 Test Bed Block Diagram ITSC_ITEC

Table I ESPRIT Baseline and Test Bed Comparison

Parameter	**ESPRIT Baseline**	**Test Bed**
Effective Resolution	3 Arm-min/line pair	3 Ar-min/line pair
Brightness	3 Footlamberts	2.5 Footlamberts
Display	12' Radius Dome	Flat Screen (12' View Distance)
Color	Full	Full
Head Motion Compensation	Yes	Yes

PSYCHOPHYSICAL EVALUATIONS

The ESPRIT test bed was initially used to demonstrate the technical feasibility of slaving an AOI inset to the extraordinarily rapid movements of the eye using ESPRIT technology. Once that hurdle was cleared, the emphasis switched from engineering to training applicability and impact. With the help of the Air Force Aeronautical Systems Division and NTSC on the Eye-slaved Display Integration and Test (EDIT) program, evaluations addressing eye-slave impact on performance and design tradeoffs were performed.

Several aspects of the test bed were evaluated during this program. The first few evaluations placed emphasis on system acceptability and attempted to determine the impact certain system parameters had on performance. AOI size and AOI throughput were considered two of the more important system parameters evaluated.

AOI Size. The results of the AOI size evaluations were not at all surprising. Most subjects preferred larger AOI sizes in general but when given a task that could be performed better with a high resolution AOI, preference shifted toward smaller AOIs. On the other end of the scale, the smallest AOI sizes were slightly distracting even though they provided the highest resolution. Results from an evaluation that required target recognition showed a lower performance level for both the smallest (12°) and largest (28°) AOI sizes with best performance occurring with a size of approximately 20° including a 3° effective blending ring (14° clear).

Subjectively, once subjects were task loaded, the awareness of AOI presence diminished to a background level for all but the smallest AOI sizes. This is consistent with comments made by pilots currently flying ESPRIT equipped simulators. "The AOI is there but not disturbing during missions" was an unsolicited comment from a user.

AOI Throughput. The results of the AOI initial throughput evaluations came as quite a surprise both subjectively and quantitatively. A significant amount of additional lag had to be introduced in the oculometer to AOI transport chain before subjects started reporting anything noticeable (total throughput in the range of 180 to 230 msec). The metrics of the initial evaluation revealed no statistically significant effects at 180 msec level but did at the 230 msec level thus agreeing with the subjective results.

Test bed throughput was verified using a set of EKG (electrocardiogram) sensors attached to the area around the right eye. The sensors measured the start/end of eye movement and was compared to the AOI servo position feedback driven normally in response to oculometer outputs. Additional lags were introduced by delaying the oculometer outputs in increments of one computational frame time (16.66 msec) up to a total of 20 frames. All times quoted are averages of several runs with the EKG sensors; therefore, to get to worst case time, an additional 8.33 msec must be added to account for the asynchronism of eye movement with respect to ESPRIT. The AOI servo throughput was previously adjusted (delayed) to match the IG output such that the projected image center was positioned correctly under dynamic conditions.

AOI Throughput "Under the Microscope"

The results of the initial throughput evaluation, although quite satisfying from subjective responses, still left questions unanswered concerning performance impacts that might be present below 'subjective' thresholds. Believing that the initial evaluation metrics may not have been sensitive enough at these lower levels of lag, a second experiment/evaluation was developed that hopefully would yield statistically significant results where the first had not.

Apparatus. Four small targets were placed as the corners of a square and viewed from a distance of 12 feet. Each target included a circle with three short radial arms pointing toward the other three targets (see Figure 5). Only one radial arm could be active at a time and it indicated the target to which the subject should saccade next. As the subject arrived near a new target (based upon non-delayed oculometer outputs) the other three targets' radial arms were randomly changed to indicate new paths for each. This way based upon information received visually, the subject was directed to saccade from one corner target to another. Since the pointing information was only changed upon arrival at a target and only for the other three, new pointing information was available even before the subject went to look for it.

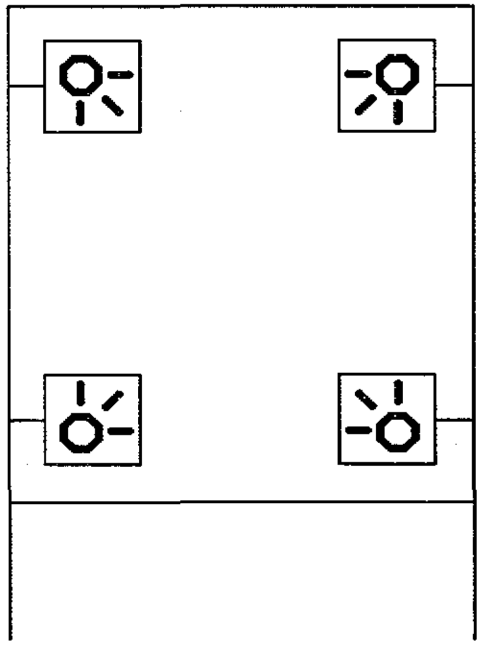

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Figure 5 Evaluation Fixture

The target information was depicted one of two ways:

1) From the ESPRIT test beds image generator (IG) and display, or
2) From a hardware frame using multiple LEDs that replicated the image generator's targets and actions

Three different target separations were used during the evaluations, each viewed from a distance of 144 inches. Table II contains those square sizes with the respective edge, diagonal and average angles encountered during the evaluations. The hardware frame only duplicated the middle separation distance.

In addition to the various square sizes, several other factors were varied with the IG presentation including:

1) background texture (flat blue or a coarse checkerboard)
2) AOI (with or without)
3) simulated hardware frame (with or without), and
4) AOI additional delay (0, 1, 2 or 3 fields)

Table II Available Target Separations

		Angle Between Targets		
Square Size	Source	On Side	Diagonal	Average
37.8" x 37.8"	IG Only	14.8°	21.0°	16.9°
50.1" x 50.1"	IG & Frame	19.5°	27.7°	22.2°
65.1" x 65.1"	IG Only	24.9°	35.5°	28.4°

With the above combinations, twenty-three variations (trials) were presented to each subject in a random order. In addition, to get a baseline that could be used to measure learning and fatigue, a test using the hardware frame against the textured background was inserted at trials 1, 7, 14, 21 and 28.

Procedure. The task was to look at the upper right target, squeeze the trigger when ready and quickly scan from target to target guided by the presence of one of three radial arms at each successive target. In the event of an error, the subject was instructed to continue on the new path without returning to the last corrected one.

At the end of approximately 15 seconds, the display was extinguished. After a rest period of about five seconds, the next trial was presented and once again was initiated by the subject when ready. The entire procedure took about 20 minutes.

Subjects. Twenty-six subjects participated in this evaluation. All had 20/30 uncorrected or corrected vision.

Metrics. Four dependent variables were used to analyze the results of this evaluation:

1) the amount of time taken to view the target (look or fixation time),

2) the time taken to saccade to the target (travel time),

3) the number of error responses (moving to an incorrect target), and

4) the number of targets acquired in each trial.

Results. As was hoped, this evaluation generated statistically significant correlations between some of the metrics listed above and AOI throughput as shown in Table III.

An obvious question is how does the AOI with its inherent lag compare to the Hardware frame with zero lag. Table IV contains evaluation data for the test bed at 80 msec AOI throughput (hardware frame size only) and the data for Trials 7, 14 and 21 (excludes first and last) using the hardware frame.

Table III Effects of AOI Throughput

		AOI Throughput		
Metric	80 msec	97 msec	113 msec	130 msec
Look Time	500 msec	510 msec	520 msec	530 msec
Travel Time	N/C	N/C	N/C	N/C
Error Responses	N/C	N/C	N/C	N/C
# Targets Acquired	28.4	28.0	27.6	27.3

N/C = No Correlation

Table IV Zero Log Hardware Frame Vs 80 msec AOI

	Image Source (Hardware Size Only)	
Metric	Hardware Frame	IG @ 80 msec AOI
Look Time	510 msec	500 msec
Travel Time	N/C	N/C
Error Responses	N/C	N/C
# Targets Acquired	28.0	28.6

N/C = No Correlation

Another area of this evaluation that was found to have a statistically significant correlation with the metrics was square size. It is mentioned here not because of the metrics that did correlate, but because of the one metric that did not (Look Time) as shown in Table V.

Discussion. It is apparent from the above data (Table III) that there is a slight impact on task performance as AOI throughput increases from the 80 msec level. For this highly intensive visual task, the impact of each additional 16.66 msec in throughput only added 10 msec to the amount of the time the subjects spent looking at each target (for a throughput of up to 130 msec). On a much more important scale, the number of acquired targets only decreased by less than 1.5% with each additional field of delay!

Table V Effects of Square Size

	Square Size		
Metric	**Small**	**Medium**	**Large**
Look Time	N/C	N/C	N/C
Travel Time	20 msec	32 msec	58 msec
Error Responses	12%	10%	13%
# Targets Acquired	28.2	27.8	26.0

N/C = No Correlation

Interestingly enough, a comparison of the subjects' performance using the test bed at 80 msec AOI throughput versus using the actual hardware frame (zero effective lag) actually favors the test bed by 2% (Table IV)! The authors believe that this can be explained by the differences between the LED targets and the IG targets. Although the brightness of the two images was made identical, the actual shapes were slightly different. Both the pointing arms and 'circle' generated by the IG were solid polygons whereas the targets for the hardware frame were composed of multiple LEDs as shown by Figure 6. The small perturbations caused by this slight shape difference may have been the cause of this unexpected result. If this is the case, it certainly puts a new perspective on the impact of lag in the 80 msec to 130 msec range.

Although not unexpected, it appears that for the saccade sizes evaluated, there is no correlation between the Look Time at the end of a large saccade as compared to a smaller one (Table V). There is, of course, a strong correlation to saccade size and respective Travel Time.

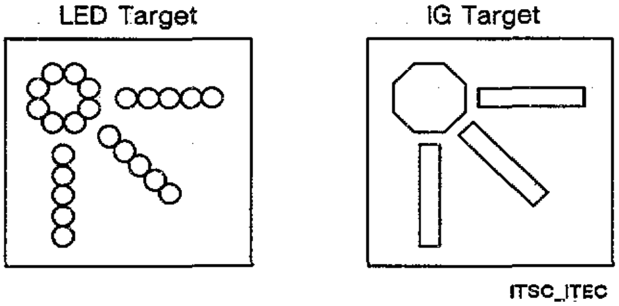

Figure 6 IG Versus LED Target

Conclusions. The experimental design for this evaluation provided the sensitivity required to gather data that could be used to measure the impact of additional eye-to-AOI lag on performance when using eye-slave visual systems similar to ESPRIT. The finding that the impact of lag is much less than one-to-one (more like 60%) in the throughput range of 80 to 130 msec may give future eye-slave system designers a little more flexibility during their initial cost/performance tradeoff analysis. The design and requirements for oculometers, for iteration rates, for displays and/or for image generators should be items on their list.

It is somewhat disappointing that the evaluations did not provide data that could be used to quantitatively compare the AOI system to a zero lag system. Qualitatively though, one might get a feel for the small magnitude of this impact by realizing that the zero lag hardware frame yielded the same performance as the 97 msec AOI system, most likely due to the very slight difference in target appearance. It would be very interesting to run the evaluation with a more modern IG, one that would more closely match the target appearance in the hardware frame.

It is of interest to note the lack of correlation between saccade size and look time. If the evaluation had found otherwise, it might have been possible for system designers to take advantage of such a correlation.

SUMMARY

The detailed experiments resulted in many insights that effected the program goals. Even though the user did not detect additional log until approximately 200 ms delay or higher, there was still a small effect on the response time of the user for delays less than 150 ms.

Accuracy of image placement with respect to an object of interest in the periphery is paramount. The user sees an object of interest in his peripheral view and the brain makes note of the angular position. The brain then programs the saccadic mechanism of the eye to land at that angle very accurately. If the image were to land in the wrong place, the saccade would not be at the desired position relative to the object of interest. Correction would require a secondary saccade, extending the time before recognition intolerably. Conversely, accuracy of angular measurement of the eye is not critical. Angular error in eye measurement results in the eye not centered in the foveal image, but as long as the projected image is in the expected location on the screen, the user will detect nothing amiss.

These experiments and results are only valid for systems that are similar to ESPRIT, where the peripheral image is stationary relative to the static worlds, including the cockpit. Those approaches that slew the entire image including the peripheral will have different requirements. It is our opinion that since the peripheral is very sensitive to motion, and the eye recovers recognition from the lowest resolution to the highest, the time allowed from end of saccade to image placement will be much reduced before obvious discomfort is felt or performance is effected.

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