2

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EFFECTS OF MINIATURE CRT LOCATION UPON PRIMARY AND SECONDARY TASK PERFORMANCES (U)

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
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Dual task performances were investigated as a function of the location of a peripherally-mounted miniature CRT which presented secondary task information. The miniature CRT's location was varied across three levels of elevation and four levels of azimuth. Primary task information was presented by means of a stationary, centrally-located CRT. The primary task required continuous monitoring of the primary display, while the secondary task required continuous tracking of an object on the secondary display. In general, the results indicated that performance decrements were not only a function of the absolute size of the viewing angle formed by the primary and secondary displays, but, in addition, by its direction. For example, 1) primary task performance decrements were generally greater when upward eye shifts were required to view the secondary display than when the corresponding downward eye shifts were required; 2) secondary task performance decrements were obtained only with upward eye shifts; and 3) lateral eye shifts produced smaller primary task decrements than comparable upward eye shifts. Another finding was that ratings of eye

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movement discomfort were generally predictive of primary and secondary performance decrements. Finally, performance decrements could not be accounted for solely on the basis of a reduction in eye shifts.

Implications of these findings for the design of peripherally located displays are discussed. Finally, there are suggestions for future studies which could more precisely delineate the applicability of the current findings.

Preface

This report was accomplished at the Crew Station Integration Branch, Human Engineering Division, of the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL), Wright-Patterson Air Force Base, Ohio. The studies conducted for this analysis were in accordance with the Work Unit 71842703, Advanced C^3 Workstation Concepts. At the time of the research, Dr. Ronald Katsuyama was on a National Research Council Associateship appointment at AAMRL. The research described in the report was supported by Systems Research Laboratories (SRL), Dayton, Ohio, under Contract Number F33615-85-C-0541.

The authors gratefully acknowledge the support from a number of individuals. Bill McGovern and TSgt. Bob Stewart served as experimenters; Brian Porter wrote major segments of the programs used to present the experimental tasks and other procedures; Greg Bothe and Don Hardage provided engineering support; Curt Mayrand provided general hardware and software consultation; Chuck Goodyear provided guidance in data management and statistical analyses; Carol Lacy constructed Figures 1 and 2; and Maj. Mel O'Neal provided opthamological references.

Table of Contents

Section *Page*

List of Illustrations

List of Tables

INTRODUCTION

The present investigation is part of the Command, Control and Communication Operator Performance Engineering (COPE) research program of the Human Engineering Division (HED), Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL). One of COPE's primary missions has been to examine display technologies that have potential merit for ground or airborne Command, Control, and Communication (C^3) environments. Among the categories of displays which have been studied are (1) computer monitors which are commonly used in traditional workstations and (2) large screen displays which permit simultaneous viewing of display information by a number of users. Much of COPE's previous research has involved various relatively permanent workstation designs using traditional monitors or large screen displays and has examined the relationship between design variations and decision-making either by individuals or by groups.

The recent advent of miniature cathode ray tube (CRT) technology, however, has expanded the possibilities for displays, permitting innovative applications that are impossible to achieve or are awkward using conventional monitors or large screens. For example, current miniature CRTs can serve the following functions: (1) the addition of supplementary displays of information used under temporary conditions or emergency situations; (2) restricted viewing of classified or proprietary information; and (3) body-mounted displays that permit viewing while engaged in a variety of activities, some of which might necessitate movement away from a primary work area. While a miniature CRT could be mounted on one's shoulder or arm, the present investigation addresses issues relevant to a head- or helmet-mounted display. Consideration of the possible advantages of alternative mounting arrangements is presented in the Discussion section of this report.

Traditionally, helmet-mounted displays (HMDs) have been designed as monocular systems using one of two approaches: (1) as a see-through system providing a monocular view of a secondary display while permitting binocular viewing of the background; or (2) as an occluded system providing a monocular view of a secondary display and an independent monocular view of the background. However, a major drawback to each of these systems is the potential for binocular rivalry. Horowitz (1949) discusses the possible consequences of such rivalry: (1) the superimposition of the two fields; (2) the partial fusion of the two fields wherein parts of each are seen simultaneously; and (3) the domination of one field over the other. In the case of superimposition of the two fields (which is inherent to the one-eye, see-through system), it may be difficult to selectively process information from one or the other field. In the case of partial fusion of information, the resulting percept might be different from that obtained from either eye alone.

(For example, Horowitz describes the perception of "luster" from the presentation of a black field to one eye and a white field to the other.) Finally, the domination of one field over the other results in a reduced probability that information from the suppressed field will be processed. At times, there may even be complete suppression of an entire retina (Treisman, 1962). In addition, the alternation of dominance between the two fields can further complicate the task of selectively attending to information contained in one of the two fields.

In general, the difficulty with which attention is switched back and forth from a secondary HMD to the background (or to a primary display) might be analogous to the problems encountered when one must selectively listen to one or the other source in a dichotic presentation. Just as it may be difficult to focus upon a particular component of a complex, multi-channel sound, there may be a similar difficulty in evaluating specific information from one or the other visual channel. Moreover, in contrast to the ability of individuals to identify the source of sound as coming from the left or right ear, it is much more difficult to identify the source of visual information in situations of binocular rivalry (Moray, 1970). Problems associated with binocular rivalry when using an HMD might be negligible if the occasions for its occurrence were entirely understood and, therefore, predictable. However, it appears that several factors inherent in the stimuli (e.g., relative brightness, contour, color, etc.) as well as subject expectancies (e.g., meaningfulness of stimuli) contribute in a complicated, interactive manner. (Hughes, Chason, and Schwank, 1973, provide a review of binocular, or retinal, rivalry and related problems in the use of HMDs, while Neisser, 1967, provides a general discussion of the role of stimulus meaningfulness.) In summary, the use of traditional HMDs to supplement information obtained from the central viewing area of a workstation is associated with major problems in information integration.

In contrast to the CRTs used in traditional HMDs discussed above, current miniature CRTs are both smaller and lighter. Consequently, they can be affixed in the periphery, leaving a relatively unobstructed central viewing area. However, a decision regarding the optimal placement and use of such a display requires consideration of several factors. On the one hand, a relatively large, unobstructed central viewing area might be judged necessary, thus requiring that the miniature CRT be mounted in the peripheral viewing area. However, this might necessitate a relatively large eye rotation to permit its viewing. On the other hand, large eye movements can be avoided by mounting the miniature CRT closer to the center of the viewing field, but only at the expense of obstructing potentially important information in this area. Hence, the actual placement of such a display must typically involve a compromise between two competing goals: (1) comfortable and efficient monitoring of a miniature CRT when it is mounted near the center of the viewing field, and (2) unobstructed viewing of central, primary information when the miniature CRT is mounted in the periphery.

Very little information is available in the human factors literature to assist in the design and placement of such miniature, secondary displays for use in C^3 environments. Although there are several studies which investigated the relative comfort involved in the viewing of traditional displays in various locations relative to some central fixation point, these were done without regard for task demands and the type of information presented. Therefore, the absence of a clear consensus across studies is not surprising. For example, a "normal line of sight" (i.e., estimation of the "preferred" viewing angle) was identified as being 10° below the horizontal (VanCott & Kincade, 1972). Using different procedures, however, a range of viewing angles constituting a "preferred viewing cone" was estimated to be centered 40° below the horizontal with a range of plus and minus 20° (Kroemer & Hill, 1986). In yet another study, a range of preferred viewing angles relative to an undefined "normal" line of sight was identified; an "optimal visual zone" was said to be plus or minus 15° vertical disparity with respect to this reference line (Department of Defense Military Standard 1472C, "Optimal Visual Zone", 1981). With respect to the appropriate lateral placement of a display, an "optimal visual zone" of 15° to the left or right of fixation was identified, as was a maximum tolerable horizontal disparity of 35° (Department of Defense Military Standard 1472C "Optimal Visual Zone", 1981). However, Farrell and Booth (1984) recommend a "comfort limit" of between 30° and 40° of horizontal displacement from center. Figure 1 summarizes the various findings described above.

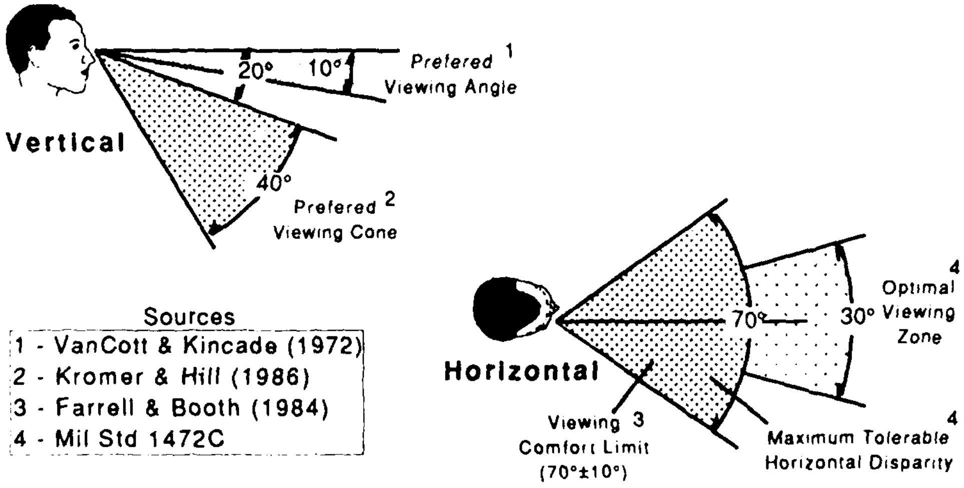

Figure 1. Viewing angles

Even if a consensus concerning the ideal placement of traditional monitors in the primary, central viewing area were available, such information would probably have little value in helping determine the appropriate placement of secondary monitors in the periphery. For example, when the user must rapidly alternate eye fixations between primary and secondary displays (such as between a centrally located traditional monitor and a peripherally located HMD), it is not clear from the existing human factors literature how perception of each display is influenced by the relative location of the peripheral, miniature CRT. Furthermore, the consequence of perceptual differences for performance on each task is also unknown. Consequently, although performance decrements can be expected when eye movements between the primary and secondary displays are required, the relationship between the extent and direction of required eye movements and primary and/or secondary task decrements remains unknown.

Therefore, the present study was designed to provide guidelines for determining the optimal location for a secondary display when the user must rapidly alternate eye fixations between it and a centrally located primary display. More specifically, the present investigation attempted to determine the effect of a miniature CRT's location upon the performance of subjects on each of two tasks. The primary task (i.e., the one to which subjects were instructed to give priority) required close monitoring of information presented centrally on a traditional monitor, while the secondary task required attention to information contained on a miniature, peripheral CRT. If maximal performance is to be attained on both tasks, subjects must necessarily monitor both the primary and secondary displays, rapidly alternating eye fixations from one display to the other. In the present experiment, the location of the miniature CRT was factorially manipulated along three levels of elevation (+15°, 0°, and -15° along the Y-axis) and four levels of azimuth (0°, 20°, 35°, and 45° along the X-axis).

General Predictions

It was predicted that secondary task performances would decline as the viewing angle formed by the primary and secondary displays increased from 0° to 45° along the horizontal axis.

The nature of the relationship between subject discomfort and performance decrement was also of particular interest. Therefore, the relative level of discomfort associated with eye movements to each location of the secondary CRT was assessed. This permitted a comparison of the pattern of performance decrements with the pattern of comfort decrements across secondary CRT locations. Conceivably, subjects' perceived level of discomfort could be directly related to performance decrements to an extent that the latter completely predicts the former. This would be the case if subjects' perceived discomfort induces the occurrence of a mediating variable which, in turn, causes performance decrements. For example, a secondary task performance decrement might occur because subjects decrease the rate at which they alternate eye fixations between the primary and secondary displays. The hypothesized reduction in eye movements with increases in the viewing angle between displays might occur either by choice or because of a physical constraint. Regardless, if increased discomfort caused by extreme eye movements is related to a slower rate of successive fixations than is required for maintaining maximal performance levels on the secondary task, then there should be a strong negative relationship between the number of eye movements (i.e. the number of eye movements per trial) and the number of secondary task errors. Alternatively, the number of successive eye fixations might either be maintained across increasingly large eye rotations or it may decline only slightly, but not to the extent that would account for secondary task performance decrements. In this case, performance decrements would be attributed to a decline in the processing of task-relevant information. Perhaps there are more variable, less precise fixations when eye movements must span large viewing angles. Alternatively, an increase in the time required for such eye movements and a corresponding decrease in time available for evaluating one or both displays might produce performance decrements.

In order to clarify the relationship between discomfort and performance, the number of eye movements was assessed for each of the locations of the miniature CRT. Subsequently, the effects of miniature CRT location upon secondary task performance was examined with eye movements statistically controlled (i.e., partitioned out using an analyses of covariance). If subject discomfort is a variable that causes performance decrements by reducing eye movements, then any secondary task performance decrements associated with secondary CRT location would be fully predictable from eye movement data alone. In this case, the analyses of covariance would reveal no significant effects of secondary CRT location.

Secondary task performance decrements were also expected to be a function of the direction as well as the extent of the viewing angle formed by the two displays. For example, based upon the preferences summarized in Figure 1, movement in the downward direction was predicted to be easier and/or more efficient than movement in the upward direction. Also one might speculate that humans have more frequent occasion and greater need to shift their eyes downward, as when checking one's footing amidst uncertain terrain, than upward, as when checking for a potential falling object.

Findings of superior secondary task performances with the secondary display at -15° elevation than at +15° elevation might also be explained in terms of ocular muscle action. Starting at the baseline position, the eye is raised primarily by the contraction of the superior rectus muscle and is lowered primarily by the contraction of the inferior rectus muscle (Moses, 1970). These muscles are antagonistic in their action (i.e., one is inhibited for the other to act). However, the inferior rectus attaches to the sclera (the outermost covering of the globe of the eye) at a distance of 6.5 mm. from the cornea (the anterior, transparent covering), while the superior rectus attaches at a distance of 7.7 mm. from the cornea (Last, 1968). In addition, the superior rectus is attached to the levator palpebrae superioris which functions to open the upper eye lid. Thus when the superior rectus is fully contracted, it not only raises the eye ball, but also tends to open the upper eye lid. Consequently, the inferior rectus is likely to have greater power in directing downward eye movements compared to the upward movements directed by the superior rectus.

When starting at a position other than the baseline (i.e., at 20-, 35-, or 45-degrees azimuth), upward eye movements are caused primarily by contraction of the superior rectus muscle of the right eye and by contraction of the inferior oblique muscle of the left eye (Moses, 1970). These muscles are said to be yoked to one another. Similarly, downward movements are directed by the simultaneous contraction of the inferior rectus muscle of the right eye and the yoked superior oblique muscle of the left eye. In comparing the relative strength of each muscle pair, the superior oblique muscle may be more powerful than the inferior oblique muscle, thus combining with the advantage of the inferior rectus over the superior rectus. (Moses, 1970, reports that the superior oblique muscle, in contrast to the inferior oblique muscle, has no check ligament which limits its action). Furthermore, the superior oblique is longer (thereby more resistant to fatigue) and has a shorter arc of contact with the globe (which permits greater mechanical advantage) than the inferior oblique. Consequently, beginning at 0° elevation and 20° or more azimuth, the advantage of downward eye movements over upward eye movements might be even greater than the corresponding advantage of downward eye movements beginning at the baseline position. It is unknown, however, whether such expected differences in vertical eye movements are manifested in similar differences between upward oblique and downward oblique movements.

Independent of the issue concerning the relative efficiency of upward vesus downward eye movements is the comparison of secondary task performances following oblique movements with those following single axis (horizontal or vertical) movements. When the secondary display is located at

+15 or -15 degrees azimuth and 20° or more azimuth, oblique (i.e., diagonal) eye movements are expected to occur rather than separate, successive horizontal and vertical movements. These diagonal movements require the coordination of the lateral and medial recti (muscles controlling lateral and nasal movements, respectively). In addition, there must be a precise balance of innervation between members of the activated muscle pairs which direct upward or downward forces in order to prevent the eyes from rotating within a frontal plane (referred to as intorsion or extortion, depending upon the direction). Hence these additional adjustments could increase the difficulty with which the secondary display is perceived following diagonal eye movements, thereby resulting in interactive effects of elevation and azimuth upon secondary task performance.

METHOD

Subjects

Twelve right handed, right eye dominant male college students served as paid, volunteer subjects. Handedness was defined in terms of writing preference, while eye dominance was assessed using the two tasks described in Appendix A. Right eye dominance was judged to be advantageous for secondary task performance in the present procedure because of the monocular presentation of the secondary CRT to the right eye. In addition, constancy of handedness was maintained across subjects to reduce unwanted variability in the performance of the primary and secondary tasks, which required responding with the left and right hands, respectively.

Eight of the subjects had previously participated in a study using the Unstable Tracking (UT) task of the Criterion Task Set (CTS). (See Shingledecker, 1984, Acton & Crabtree, 1985, and Amell, Eggemeier, & Acton, 1986, for a detailed description of this task.) This previous experience was rather extensive, amounting to between 8 and 24 one-hour sessions in which the UT task was administered approximately 6 times per session. The remaining four subjects had no prior experience with the UT task.

Eleven of the subjects had 20/20 vision, with or without correction by contact lenses, while the remaining subject had 20/30 vision.

Apparatus

The apparatus consisted of the following: (1) an adjustable chin/head rest; (2) a response key connected to a Commodore 64 (C-64) computer system equipped with a 25 cm diagonal black and white CRT located 170 cm. from the chin-/headrest; (3) a rotary response knob connected to another C-64 system equipped with a 4 cm diagonal miniature, black and white CRT; (4) a chair which permitted continuous height adjustments for subjects; and (5) an adjustable stand with a clamp to hold the miniature CRT. Figure 2 illustrates the positioning of a subject relative to the experimental apparatus and depicts the primary and secondary task displays at the outset of the dual task procedure.

Experimental Tasks

The UT task from the CTS served as the secondary task. Briefly, this task required subjects to track a horizontally moving object with a rotary controller, keeping it between two vertical lines. The object accelerated toward the left or right as it moved away from either the center of the screen, which was an initial point of equilibrium, or from the point at which the object's velocity was changed by means of the controller. Immediately upon touching one of the vertical lines, the object was automatically returned to the center of the screen. This secondary task was presented by means of the miniature CRT, which was located in front of each subject's right eye. The housing of the miniature CRT prevented subjects from viewing the primary task monitor with the right eye.

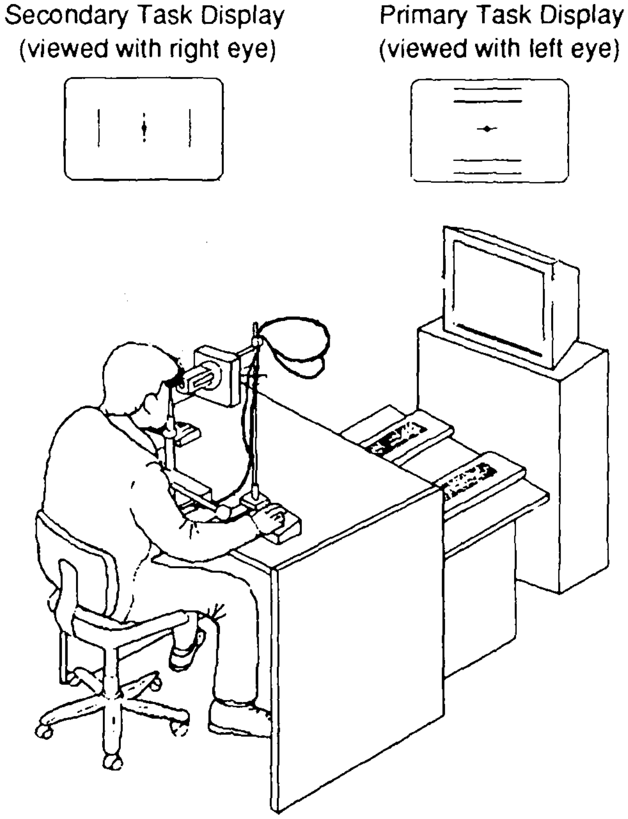

Figure 2. Experimental setup

The primary task, which will be referred to as the Unstable Event Monitoring (UEM) task, was developed by modifying the UT task described above. Starting at the center of the screen, the object accelerated upward or downward. Located near the top and near the bottom of the primary task CRT were pairs of horizontal lines which mark the "target" regions. A correct response was defined as a keypress which occurred while the object was within one of these two regions. A keypress either before the object entered a target region or after it left was an incorrect response. Failure to respond before the target disappeared from the screen was also defined as an error (an edge violation). Following each keypress or edge violation, the object was automatically returned to the center of the screen, at which time the following parameters, which determined the object's subsequent movement, were randomly selected: (1) the direction of movement; (2) the acceleration (selected from one of five predetermined values); and (3) the time that the object was to remain fixed in the center of the screen (which varied between 0 and 0.5 s.). Feedback consisted of a tone which was presented immediately following each error. The primary, UEM task was presented by means of a traditional monitor which was located at the subject's eye level. This primary monitor could only be viewed with the left eye.

Design

The viewing angle of the miniature, secondary CRT relative to the primary monitor was manipulated across 12 treatment conditions obtained by combining three levels of elevation, +15°, 0°, and -15°, and four levels of azimuth, 0° (i.e, to the immediate right of the primary monitor), 20°, 35°, and 45°. Hence, the study used a 3 (Elevation) x 4 (Azimuth) factorial design with repeated measures (within subjects) for each treatment.

Procedure

Each subject participated in a total of seven daily sessions. Session 1 involved training with the primary and secondary tasks administered separately as well as together (i.e., as a dual task). Each of the remaining sessions involved the administration of experimental, dual tasks in which the secondary task CRT was positioned at each of the azimuth locations within a given elevation. During the first three experimental sessions (Sessions 2-4) subjects were administered trials involving secondary task CRT locations at each of the elevation and azimuth locations. This first experimental series (Series 1) was repeated in Sessions 5-7 (Series 2). Each of two subjects received one of the six possible orderings of the three elevations. All training trials as well as experimental trials lasted three minutes.

Prior to the beginning of each session, the chin-/headrest and the location of the primary CRT were adjusted for each subject to insure that the primary and secondary displays were perceived as being adjacent to one another and centered at 99 cm above the floor and directly in front of the subject. This was accomplished as follows: First, the secondary CRT was fixed in a baseline position defined as 0° elevation and 0° azimuth at a height of 99 cm above the floor. Using the chin-/headrest to keep the subject's head stationary in a standard position, the location of the primary task CRT was adjusted so that when simultaneously viewing the primary CRT with the left eye and the secondary CRT with the right eye, the subject perceived that the center of the primary CRT and a vertical reference line near the left edge of the secondary CRT were superimposed and at the same height of 99 cm above the floor.

Prior to the beginning of each trial, the miniature, secondary task CRT was adjusted by the experimenter in the following manner: While positioned in the chin-/headrest at the standard height and facing the primary task monitor, the experimenter fixated upon the appropriate, predetermined target point on a wall. With the target point viewed by his left eye and the miniature CRT viewed with his right eye, the experimenter adjusted the miniature CRT so that the target appeared centered upon it.

Training trials. The first two trials of the training session involved administration of the primary task alone. (See Appendix B for the complete instructions associated with each task.) Subjects were required to make left handed keypress responses to the primary task throughout the study. For each trial the number of errors (i.e., the sum of edge violations, early responses, and late responses) was divided by the total number of object deflections and multiplied by 100 to obtain the percentage of responses in error. This value was automatically recorded and reported to subjects.

The next two training trials involved only the secondary task with the secondary CRT positioned in the baseline location. Throughout the study each subject was required to rotate the controller knob with his right hand in attempting to keep the secondary display's moving object between the two vertical lines. The number of edge violation errors (i.e., the number of times that the object was allowed to pass beyond either vertical boundary line) was automatically recorded and reported to subjects.

The next eight training trials involved simultaneous performance of both the primary and secondary tasks. The secondary CRT remained in the baseline location throughout this training. On these dual task trials subjects were instructed to try to attain maximal performance on the primary task, thereby maintaining the level attained on the single task trials. As was the case for single task performance measures, dual task performance measures (i.e., the percentage of primary task errors and the number of secondary task edge violations) were also automatically recorded and reported to subjects.

Experimental trials. Each experimental session involved a particular sequence of dual task trials. On the first and last trial of each session, the secondary CRT was located at the baseline position. In between these trials, the secondary CRT was positioned at a given elevation but with the azimuth varied from one trial run to another. At elevations +15° and -15°, the sequence of trials consisted of successively increasing azimuth locations (0°, 20°, 35°, and 45°) followed by a sequence of successively decreasing azimuth locations (45°, 35°, 20°, and 0°). Hence, during sessions involving +15° or -15° elevation treatments, there were 10 trials in all. In addition to the two trials with the secondary CRT at the baseline location, subjects were tested twice under each azimuth location. At the 0° elevation there were only 8 trials with the secondary CRT azimuth location varied according to the following sequence: 0°, 20°, 35°, 45°, 45°, 35°, 20°, and 0°.

During each three-minute experimental trial, the experimenter counted the number of eye movements, each of which presumably represented an eye fixation upon the secondary display.

Following each trial subjects rated the discomfort associated with making eye shifts to the miniature CRT by selecting one of the following adjectives: "none", "slight", "moderate", or "severe". Ratings of perceived discomfort in making eye shifts to the miniature CRT were also obtained following each session. These post session ratings involved a scale of 0-9 where "0" represented "none", "3" represented "slight", "6" represented "moderate", and "9" represented "severe". The same 0-9 scale was also used to obtain ratings of perceived discomfort involved in making eye shifts following Series 1 (Session 4) and, again, following Series 2 (Session 7).

RESULTS

Primary Task Errors

Table 1 presents the mean percentage of primary task errors according to series, elevation, and azimuth.

Table 1
Mean Percentage of Primary Task Errors

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	11.82	13.96	15.04	16.68	14.38
	0°	6.98	9.58	11.96	15.45	10.99
	-15°	11.91	12.01	12.79	16.30	13.25
2	+15°	6.70	8.85	9.24	9.93	8.68
	0°	4.87	6.08	6.95	8.99	6.72
	-15°	7.08	6.92	7.83	8.88	7.68
Means		8.23	9.57	10.64	12.70	

A

A 2 (Series -- 1 and 2) x 3 (Elevation -- +15°, 0°, and -15°) x 4 (Azimuth -- 0°, 20°, 35°, and 45°) analysis of variance was performed upon the percentage of primary task errors. Figure 3 shows the mean percentage of primary task errors according to elevation and azimuth. As illustrated by the generally, positive slopes in this figure, the percentage of errors varied directly with azimuth $F(3,33) = 11.42$, $p < .001$.

Furthermore, relative to performance under the 0° elevation conditions (M= 8.86% errors), performance declined under conditions of -15° elevation (M = 10.47% errors) and, to an even greater extent, under conditions of +15° elevation (M = 11.53% errors), $F(2,22) = 9.29$, $p < .01$. Performances at +15° elevation and -15° elevation were not significantly different, $p > .05$.

In addition, performance improved from Series 1 (M = 12.87% errors) to Series 2 (M = 7.69% errors), $F(1,11) = 52.00$, $p < .001$. Finally, the significant Series x Azimuth interaction, $F(3,33) = 3.65$, $p < .05$, reflected the greater simple effect of azimuth upon errors during Series 1 (Ms = 10.24%, 11.85%, 13.26%, 16.14% for the 0°, 20°, 35°, and 45° locations, respectively) compared to Series 2 (corresponding Ms = 6.22%, 7.28%, 8.01%, and 9.27%).

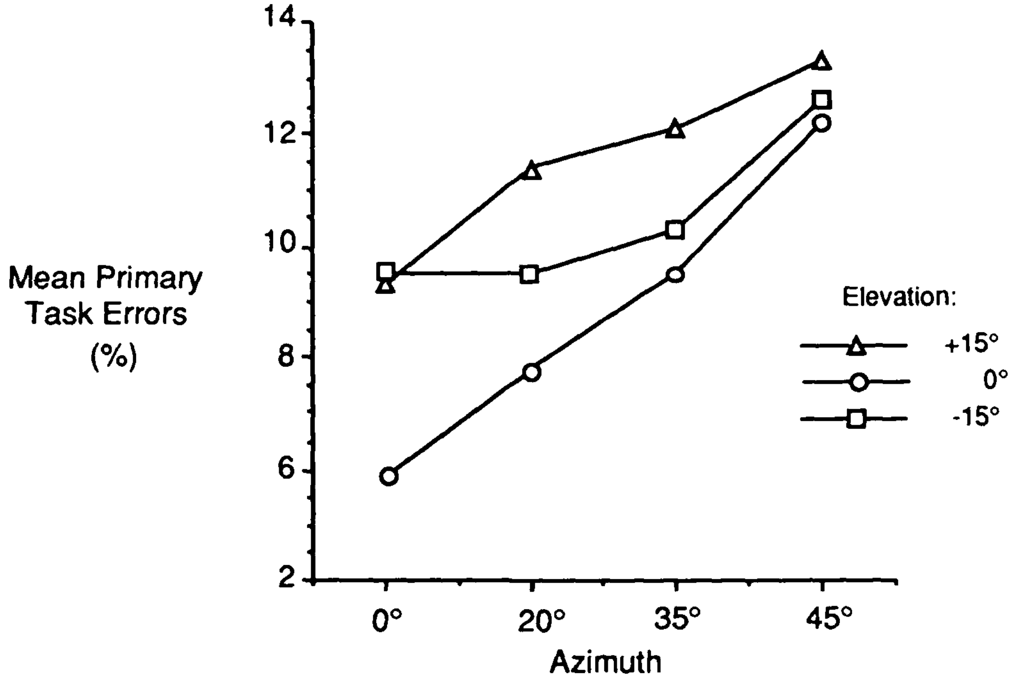

Figure 3. Mean percentage primary task errors according to elevation and azimuth

Secondary Task Errors

Table 2 presents the mean numbers of secondary task errors according to series, elevation, and azimuth.

Table 2.
Mean Number of Secondary Task Errors

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	7.33	16.08	27.62	32.62	20.92
	0°	1.04	9.88	18.00	26.12	13.76
	-15°	1.21	5.08	16.04	26.79	12.28
2	+15°	2.33	9.71	18.50	28.08	14.66
	0°	0.12	2.83	9.71	17.00	7.42
	-15°	0.38	2.79	14.12	20.00	9.32
Means		2.07	7.73	17.33	25.10	

A 2 (Series) x 3 (Elevation) x 4 (Azimuth) analysis of variance was performed upon secondary task errors. Figure 4 illustrates the mean secondary task errors according to elevation and azimuth. As this figure clearly illustrates, errors generally increased with increasing azimuth $F(3,33) = 12.47$, $p < .001$.

Errors were also influenced by elevation, $F(2,22) = 8.15$, $p < .05$. Mean errors under the +15° conditions (17.79) were greater than under the 0° conditions (10.59) or the -15° conditions (10.80), which did not differ from one another. The absence of a significant Elevation x Azimuth interaction is illustrated in Figure 4 by the virtually parallel functions.

Finally, errors declined from Series 1 ($M = 15.65$) to Series 2 ($M = 10.47$), $F(1,11) = 16.40$, $p < .01$.

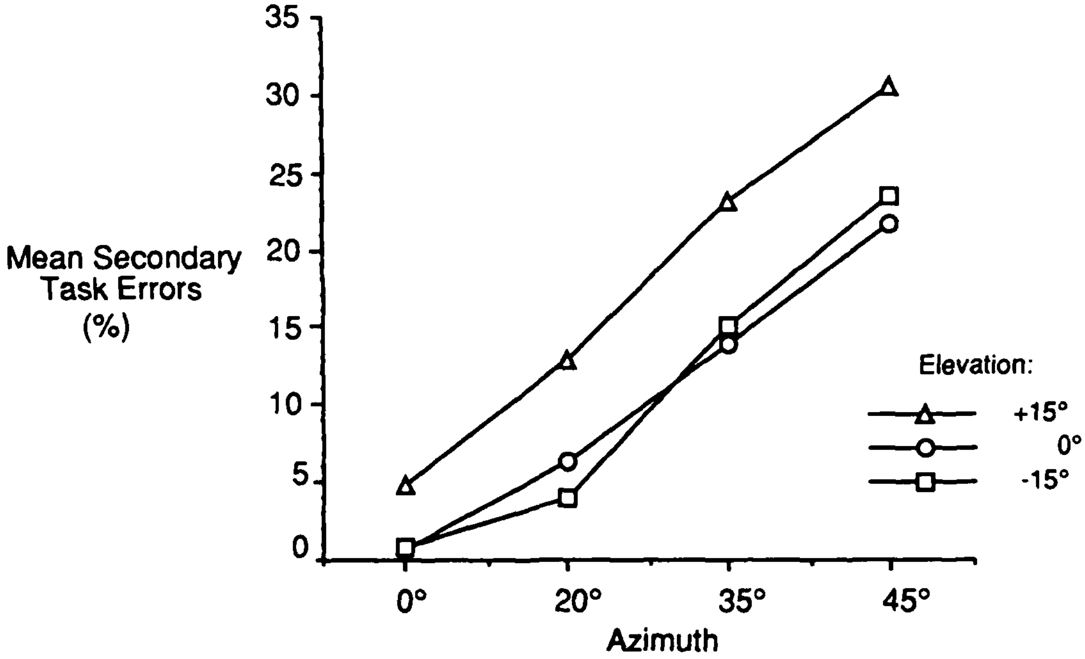

Figure 4. Mean percentage secondary task errors according to elevation and azimuth

Discomfort Ratings

Table 3 (a, b & c) presents the mean discomfort ratings according to series, elevation, and azimuth for post-series, post-session, and post-trial ratings, respectively. Separate 2 (Series) x 3 (Elevation) x 4 (Azimuth) analyses of variance were performed for each measure.

Table 3a

Mean Discomfort Ratings (Post Series Ratings))

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	0.83	2.17	3.83	5.67	3.12
	0°	0.08	1.17	2.50	4.42	2.04
	-15°	1.08	2.08	4.00	5.75	3.23
2	+15°	1.25	2.25	4.33	6.33	3.54
	0°	0.17	1.00	2.83	5.00	2.25
	-15°	1.25	2.08	4.17	5.92	3.35
Means		0.78	1.79	3.61	5.51	

Note: Subjects used a scale of 0 to 9

Table 3b

Mean Discomfort Ratings (Post Session Ratings)

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	1.50	3.00	4.75	6.42	3.92
	0°	0.42	1.75	3.17	4.58	2.48
	-15°	1.33	2.50	3.83	5.42	3.27
2	+15°	0.67	2.17	4.00	5.58	3.10
	0°	0.17	1.08	2.58	4.25	2.02
	-15°	0.75	1.75	3.25	4.83	2.65
Means		0.81	2.04	3.60	5.18	

Note: Subjects used a scale of 0 to 9

Table 3c

Mean Discomfort Ratings (Post Trial Ratings)

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	0.62	1.04	1.67	2.21	1.39
	0°	0.12	0.42	1.00	1.50	0.76
	-15°	0.50	0.75	1.08	1.79	1.03
2	+15°	0.50	0.79	1.42	2.00	1.18
	0°	0.12	0.38	0.79	1.33	0.66
	-15°	0.25	0.58	0.79	1.46	0.77
Means		0.35	0.66	1.12	1.72	

Note: Subjects used a scale of 0 to 3

Figure 5(a) shows the mean post series discomfort ratings according to elevation and azimuth. As can be seen from inspection of this figure, discomfort generally increased as azimuth increased, $F\,(3,33) = 34.29$, $p < .001$. Also apparent from inspection of Figure 5(a) are the similar discomfort ratings obtained under the +15° and -15° elevation conditions. Discomfort ratings obtained at +15° elevation ($M = 3.33$) did not differ from those obtained at -15° elevation ($M = 3.29$), but each were greater than those obtained at 0° elevation ($M = 2.15$), $F\,(2,22) = 10.49$, $p < .001$.

Three significant findings were obtained from analysis of post-session ratings. Figure 5(b) shows the mean post-session discomfort ratings according to elevation and azimuth. As occurred for post-series ratings, post session discomfort ratings increased as azimuth increased, $F(3,33) = 29.45$, $p < .001$. Also in common with post-series discomfort ratings, post-session discomfort ratings varied according to elevation, $F(2,22) = 6.28$, $p < .01$. However, discomfort was higher for +15° eye shifts ($M = 3.51$) than for 0° eye shifts ($M = 2.25$), $p < .05$. Neither of these means differed from the mean discomfort associated with -15° eye shifts ($M = 2.96$). Finally, discomfort was higher in Series 1 ($M = 3.22$) than Series 2 ($M = 2.59$), $F(1,11) = 5.43$, $p < .05$.

Analysis of post-trial ratings indicated similar findings to those obtained from post-session ratings. Figure 5(c) shows the mean post-trial discomfort ratings according to elevation and azimuth. First of all, discomfort increased as azimuth increased, $F(3,33) = 26.49$. $p < .001$. Secondly, discomfort varied according to elevation, $F(2,22) = 15.07$, $p < .001$. In contrast to post-session ratings, however, discomfort associated with +15° eye shifts ($M = 1.28$) was higher than that associated with eye shifts at 0° ($M = 0.90$) and -15° ($M = 0.71$), $p < .05$. The latter means were not significantly different. Finally, discomfort was higher in Series 1 ($M = 1.06$) than in Series 2 ($M = 0.87$), $F(1,11) = 6.85$, $p < .05$.

No other results approached statistical significance.

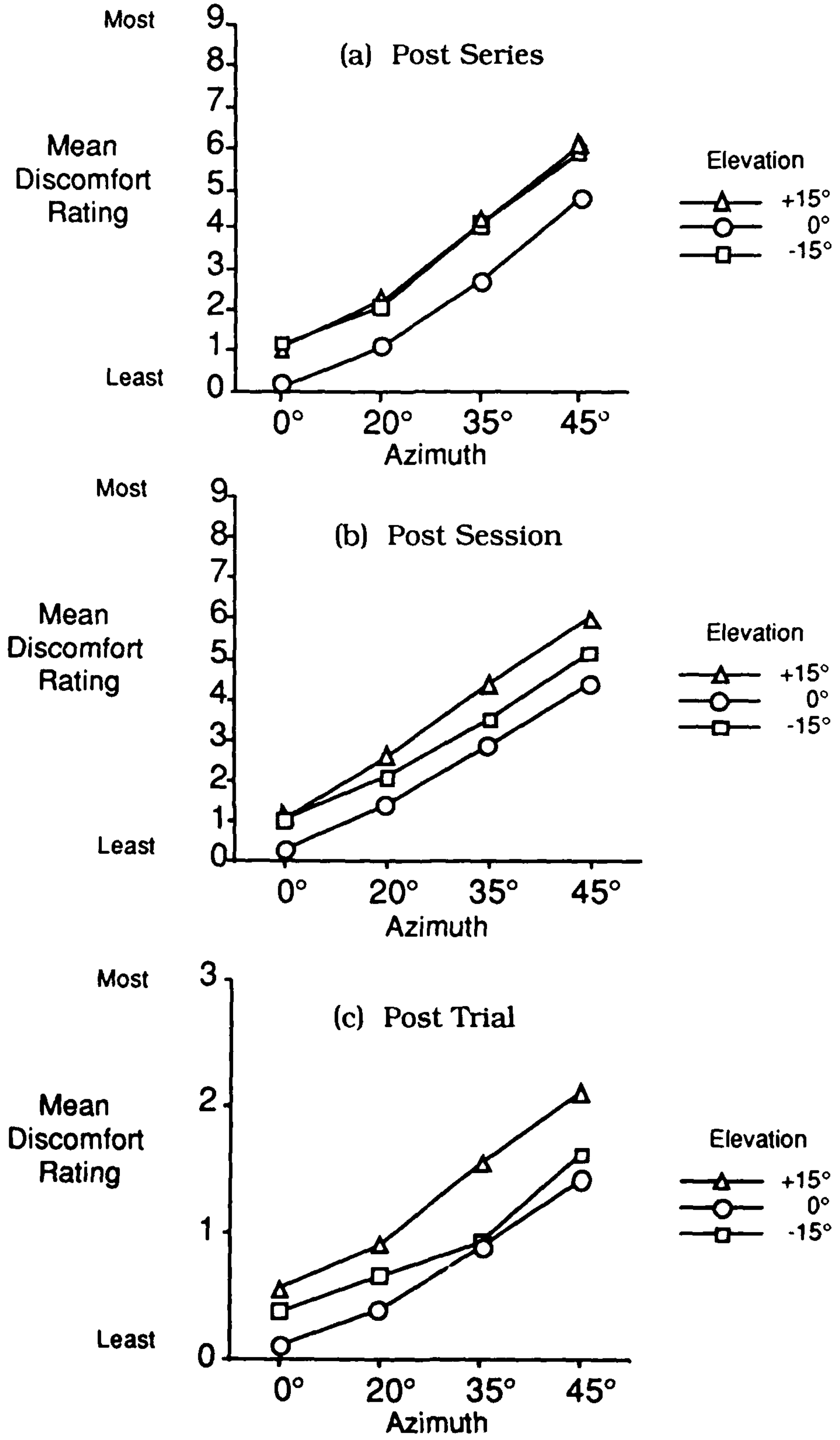

Figure 5. Mean discomfort ratings according to elevation and azimuth

Number of Eye Shifts

Subjects' sustained viewing of the primary display was interrupted by periodic, brief eye shifts toward the secondary display. Table 4 presents the mean number of such eye shifts according to series, elevation, and azimuth, with the exclusion of values for the baseline treatment (0° elevation and 0° azimuth). Eye shifts occurring at this location were extremely difficult to detect and such observations were, therefore, deemed unreliable. Consequently, two separate analyses were performed upon the number of eye shifts obtained when the secondary CRT was at other locations. Figure 6 illustrates the mean number of eye shifts according to elevation and azimuth.

Table 4
Mean Number of Eye Shifts

Series	Elevation	Azimuth				Means
		0°	20°	35°	45°	
1	+15°	63.21	68.46	68.50	66.50	66.67
	0°	-	72.83	72.54	61.42	68.93
	-15°	59.29	73.42	72.00	63.62	67.08
2	+15°	75.21	74.08	70.33	62.21	70.46
	0°	-	91.75	74.29	65.83	77.29
	-15°	73.50	85.21	79.88	73.83	78.10
Means		67.80	77.62	72.92	65.57	

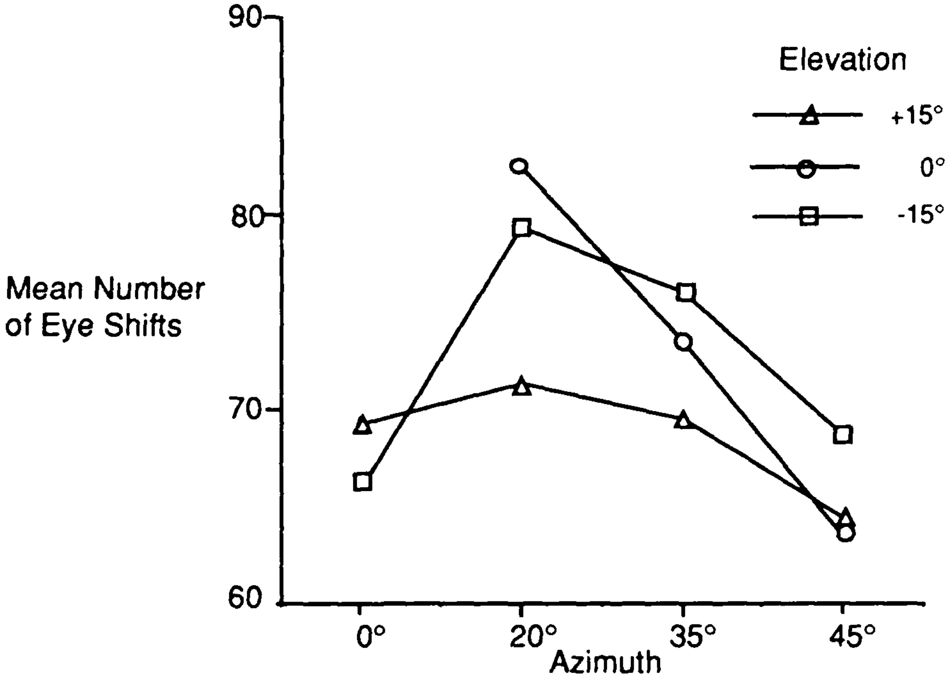

Figure 6. Mean number of eye shifts according to elevation and azimuth.

A 2 (Series) x 3 (Elevation) x 3 (Azimuth) analysis of variance performed upon the number of eye shifts indicated that the numbers declined with increasing levels of azimuth, $F\,(2,22) = 17.17$, $p < .001$. In addition, a significant Series x Azimuth interaction, $F\,(2,22) = 10.54$, $p < .001$, reflected the greater increase in eye shift frequencies from Series 1 to Series 2 under the 20° conditions (*M*s = 71.6 and 83.7) than under the 35° conditions (*M*s = 71.0 and 74.8) or under the 45° conditions (*M*s = 63.8 and 67.3). The overall increase in eye shifts from Series 1 ($M = 68.8$) to Series 2 ($M = 75.3$) approached, but did not attain, significance, $F\,(1,11) = 3.57$, $p = .085$.

A 2 (Series) x 2 (Elevation) x 4 (Azimuth) analysis of variance indicated a significant Series x Azimuth interaction, $F\,(3,33) = 4.69$, $p < .01$. As illustrated in Figure 7, the increase in eye shifts from Series 1 to Series 2 decreased as azimuth increased. In contrast to the previous analysis, the main effect of azimuth approached, but did not attain, significance, $F\,(3,33) = 2.84$, $p = .053$.

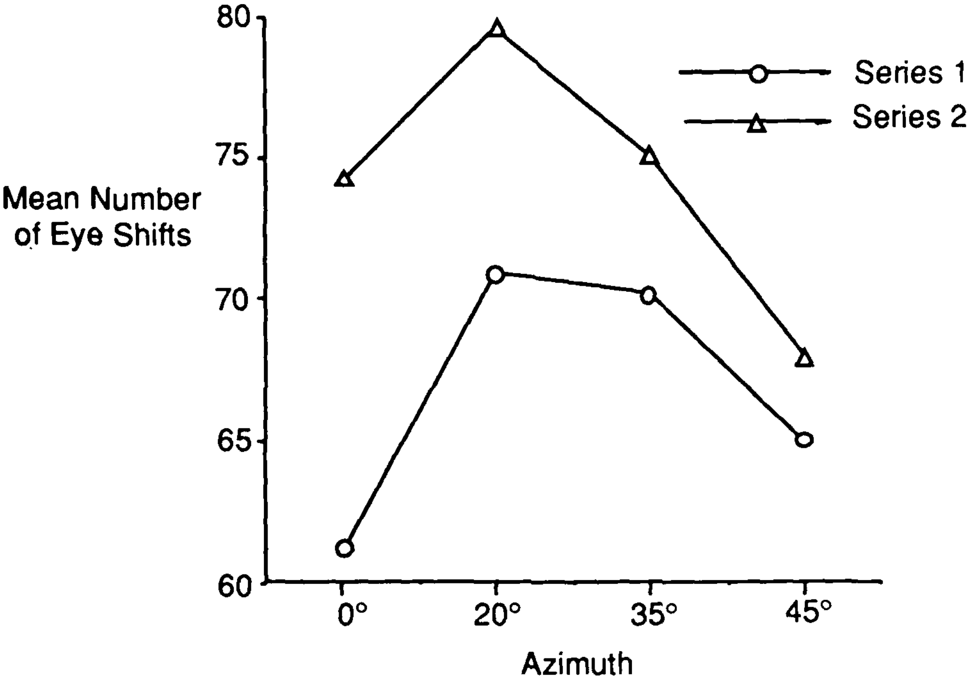

Figure 7. Mean number of eye shifts according to azimuth and series

Primary Task Errors with Effects of Eye Shifts Partitioned Out

A 3 (Elevation) x 3 (Azimuth) analysis of covariance performed upon percentages of primary task errors, using eye shifts as the covariate, revealed significant main effects of elevation, F (2,22) = 7.07, p < .01 and azimuth, F(2,22) = 5.06, p < .05.

The number of eye movements was positively correlated with the percentage of primary task errors when data were summed across subjects at each of the nine combinations of elevation and azimuth, r(9) = 0.93, p < .001. Individual differences in primary task performance could not be predicted on the basis of eye movements, given the absence of a significant correlation between the total number of eye movements and the total percentage of primary task errors, collapsed across treatments, r (12) = 0.37, p > .05.

Secondary Task Errors with Effects of Eye Shifts Partitioned Out

A 3 (Elevation) x 3 (Azimuth) analysis of covariance performed upon secondary task errors using eye shifts as the covariate revealed a significant main effect of azimuth, F (2,22) = 5.05, p < .05, and a main effect of elevation which approached significance, F (2,22) = 3.08, p = .066.

The number of eye shifts was negatively correlated with the mean secondary task errors when the data were summed across subjects at each of the nine combinations of elevation and azimuth, $r(9) = -0.89$, $p < .05$. Individual differences in secondary task performance could be predicted on the basis of eye movements given the significant positive correlation between the total number of eye movements and the total number of secondary task errors, $r(12) = -0.70$, $p < .05$.

Table 5 summarizes all results that attain significance, $ps < .05$, as well as results which approach, but do not attain, significance, $.05 < p < .10$.

Appendix C contains all analyses of variance summary tables.

Table 5
Summary of Significant Effects

Variable Analyzed	Analysis[a]	Effect			
		Series	Elevation	Azimuth	Series x Azimuth
Mean Percentage of Primary Task Errors	2x3x4 ANOVA	<.001	<.01	<.001	<.05
	3x3 ANCOVA		<.01	<.05	
Mean Number of Secondary Task Errors	2x3x4 ANOVA	<.01	<.05	<.001	
	3x3 ANCOVA		<.10	<.05	
Mean Discomfort Ratings	2x3x4 ANOVA				
	Post Series		<.001	<.001	
	Post Session	<.05	<.01	<.001	
	Post Trial	<.05	<.001	<.001	<.001
Mean Number of Eye Shifts	2x3x3 ANOVA	<.10		<.001	<.01
	2x2x4 ANOVA			<.10	

[a] Each is a Series x Elevation x Azimuth analysis of variance (ANOVA) except for the 3 x 3 (Elevation x Azimuth) analysis of covariance (ANCOVA) using the mean number of eye shifts as the covariate.

DISCUSSION

Under conditions which require frequent eye shifts between a primary display and a secondary display, the location of the latter can have important consequences for the processing of both sources of information. In the present study, as the secondary task display was moved further into the periphery not only was there a secondary task performance decrement but, in addition, primary task performance also declined. The implications of this finding are especially important in certain emergency C^3 operations wherein operators are expected to rapidly process information from a peripheral display while continuing to process information from a primary, central display. The ideal situation is, of course, one in which performances on both primary and secondary tasks are maintained despite the separation of respective displays containing crucial information. However, when decrements resulting from the separation of such displays are predicted, the design engineer can attempt to eliminate or attenuate them by making one or both of the following adjustments: (1) changing the viewing angle separating the primary and secondary displays; and/or (2) permitting head movements along with eye movements in directing visual attention from one display to the other. Considerations of each of these possibilities will be discussed below.

Changing the Primary and Secondary Display Viewing Angle

There are five general conclusions drawn from the findings obtained in the present experiment that can have important implications for the design of secondary displays for workstations: (1) Secondary task displays located 15° below a primary viewing area are better perceived than identical displays located 15° above the primary viewing area; (2) Lateral eye movements are more efficient than vertical eye movements; (3) Primary and secondary task performance decrements associated with diagonal eye shifts are predictable from performances under conditions of vertical and horizontal shifts alone; (4) The degree to which subjects' ratings of discomfort predicts their primary and secondary task performances depends upon when those ratings are obtained; and (5) Neither primary nor secondary task performance decrements can be accounted for solely on the basis of changes in the number of eye shifts. Each of these will be discussed below.

Vertical location of the secondary display. When there is a choice between locating a secondary display 15° above a primary viewing area versus 15° below that region, the present results indicate a clear advantage for the latter. If the present results generalize to the processing of information contained in head- and helmet-mounted displays, then both primary- and secondary-task performances would be superior when eye movements are restricted to those occurring below zero degree elevation than corresponding eye movements occurring above that level.

It is possible, of course, that more extensive practice involving eye movements above the horizon can reduce or eliminate an initial disadvantage, thus resulting in acceptable performance across a wide range of eye movements including those investigated in the present study. An absence of performance differences as a function of viewing angle could also be obtained when relatively simple tasks are involved. However, if primary and secondary tasks are no less difficult than those used in the present study, then it appears unlikely that more extensive practice would eliminate the superior performance associated with below-horizontal eye movements compared with above-horizontal eye movements. In the present experiment, for example, although there was general improvement in both primary- and secondary-task performance from Series 1, which involved a total of 28 three-minute trials, to Series 2 this effect was independent of elevation. Hence, below-horizontal eye movements remained associated with superior performance following a total of 114 minutes of dual task experience spread across four days (i.e., one practice and three experimental sessions). Interestingly, the only conditions under which no improvement appeared to occur involved the primary task with the secondary task display at 45° azimuth. Hence, this provides evidence that the physical limits of human performance might have been approached by requiring eye movements of this magnitude.

Rear view mirrors in automobiles are typically mounted above the operator's line of sight. Based upon the current findings, one might be tempted to suggest a mounting at a lower location, even below the driver's line of view, to the extent that such engineering is possible and that such a location does not hinder necessary physical operations. Also based upon the current findings one might conclude that a rear view mirror of a motorcycle, which is mounted on the handlebars and below the operator's typical line of sight, offers advantages for the processing of both primary and secondary information over an automobile rear view mirror, which is mounted above the driver's line of sight. However, such conclusions would be premature, as the present findings concerning the processing of both primary- and secondary-task information were obtained under conditions of head restrain which, at times, necessitated relatively large eye movements. These results might not generalize to conditions in which the secondary display is mounted independent of the head. For example, either a shoulder-mounted CRT or one mounted independent of body orientation might permit the use of crucial attention mechanisms associated with head movements which facilitate the processing of both primary- and secondary-task displays. This issue will be discussed later.

Advantage of lateral eye movements. Primary task performance under conditions of 35° azimuth/0° elevation (M = 9.45% errors) were similar to those under conditions of 0° azimuth/+15° elevation (M = 9.26% errors) and 0° azimuth/-15° elevation (M = 9.49% errors). This is another indication that performance decrements were not determined solely by the absolute size of the viewing angle formed by the primary- and secondary-displays but, in addition, by its direction. The finding that lateral eye movements up to 35° produced no greater primary task performance decrements than vertical eye movements of ±15° can be explained in terms of both eye musculature as well as everyday experiences. Lateral movements of the right eye toward the secondary display occur as a result of contraction of the lateral rectus and inhibition of the medial rectus. The opposite pattern occurs in the left eye (i.e., contraction of the medial rectus, the largest and strongest of the extraoccular muscles, and inhibition of the lateral rectus). All other muscles are said to maintain their normal muscle tone (Moses, 1970). However, as the right eye increasingly turns temporally (i.e., toward the right), the superior and inferior oblique muscles also increase their temporal force. In addition, when the right eye is turned more than 21° outward, the superior and inferior rectus muscles also contribute additional force toward this direction. In opposite fashion, movement of the left eye nasally (i.e., toward the right) is first directed by contraction of the medial rectus and inhibition of the lateral rectus. However, as the left eye increasingly turns toward the right, the superior and inferior recti proportionately increase the strength with which they reinforce this inward turning. In contrast to the large lateral movements described above, vertical movements from the baseline position are largely the result of a single muscle contraction in each eye. (For upward movements, the superior rectus provides the major force with minor reinforcement by the inferior oblique, while the inferior rectus provides the major downward force with reinforcement by the superior oblique.) Hence, large horizontal eye movements are likely to occur with greater force than corresponding vertical eye movements. In addition to anatomical considerations, experiential factors might also account for the above findings. For example, more eye movements occur laterally than vertically.

Predicting decrements associated with diagonal eye movements. The absence of interactive effects of elevation and azimuth in the analysis of primary- and secondary-task performances (see Figures 3 and 4, respectively) suggests that primary- and secondary-task performance decrements associated with eye shifts containing both vertical and horizontal components can be predicted on the basis of performances under conditions of vertical and horizontal shifts, alone.

However, it is possible that the results would have been different if tasks involving more complex displays had been selected, especially in the case of the secondary task, on which errors were virtually absent in the 0° elevation/0° azimuth and 0° elevation/-15° elevation treatments. For example, the "floor effect" obtained on the secondary task in the latter treatments might have masked differential effects of elevation across these conditions. Conceivably, performance under the 0° elevation/0° azimuth condition might have been superior to that under the 0° elevation/-15° azimuth condition. This would, of course, have contributed to an interaction effect between elevation and azimuth in the present experiment. Along these lines, a more difficult primary task might also have produced a significant Elevation x Azimuth interaction that, in the present study, only approached significance, $p = .11$. Hence, the assumption of independent (i.e., additive) effects of vertical and horizontal eye shifts upon task difficulty must remain tenuous pending additional verification.

Observer discomfort ratings - performance relationships. There were similar effects of azimuth upon all sets of discomfort ratings (post trial, post session, and post series), as well as upon both primary and secondary task performances. That is, as azimuth increased, discomfort ratings, primary task errors, and secondary task errors all increased. However, with respect to the effects of elevation, a similar correspondence between performance and discomfort ratings was not consistently obtained throughout the experiment. For example, secondary task performances could be better predicted by post-trial ratings than by post-series ratings. Secondary task errors were greatest with +15° elevation, with no difference between the 0° and -15° elevations, a pattern of results which corresponds to the post-trial discomfort ratings but not to the post-series ratings. In contrast, on the primary task, the percentage of errors was greater with +15° and -15° elevations than with a 0° elevation. Although this finding corresponded to the post-series pattern of discomfort ratings, it was not reflected in the post-trial ratings. On the post-trial ratings, subjects rated discomfort at the +15° elevation the highest with no differences between the 0° and -15° elevations. Hence, primary task performances could be better predicted by post-series ratings than by post-trial ratings. In the case of both primary task and secondary task performances, the pattern of post session ratings were midway between those of the post-trial and post-series ratings.

In summary, subject ratings appear useful in predicting both primary task and secondary task performance decrements associated with increasing horizontal eye shifts. However, the prediction of performance decrements associated with vertical eye shifts may depend upon the type of task and the time at which ratings are obtained. Ratings obtained immediately following the task appear to better predict secondary task performance, while ratings obtained later better predict primary task performance. Regardless of when ratings were obtained, however, discomfort was higher when eye movements in the upward direction were involved than when corresponding eye movements without a vertical component were involved. Nevertheless, given certain differences between the effect of vertical eye movements upon subjective reports of discomfort, on the one hand, and task performances, on the other, the process of designing secondary displays which require vertical eye movements should incorporate behavioral indicators of effective viewing. Clearly, the design process should not rely totally upon brief, introspective reports concerning observer comfort.

The eye shift - performance relationship. The number of eye shifts was positively correlated with primary task errors and negatively correlated with secondary task errors. Nevertheless, the effects of azimuth upon both primary and secondary task errors and the effect of elevation upon primary task errors remained significant in the respective analyses of errors with the contribution of the number of eye shifts partitioned out of the variances. (The effect of elevation upon secondary task errors with the contribution of number of eye shifts partitioned out was marginally significant, $.05 < p < .10$, with the resulting pattern of means comparable to that obtained in the analysis of variance reported earlier.) Hence, the obtained primary- and secondary-task performance decrements attributed to azimuth and/or elevation cannot be accounted for solely on the basis of a change in the number of eye shifts made.

In fact, although a larger number of eye shifts is associated with better secondary task performance, increasing the viewing angle formed by primary- and secondary-displays can, under certain conditions (e.g., between 0° and 20° azimuth), induce more frequent eye shifts *and* more errors. Although eye shifts declined with increasing azimuth from 20° to 45°, the number of eye shifts increased between 0° and 20°. In contrast, primary- and secondary-task performance decrements increased monotonically with increasing azimuth. The major implication of this finding is that under some conditions which prompt a large number of eye shifts between two displays, the eye movements themselves can contribute to performance decrements. Perhaps the time required to successively fixate upon the two displays reduces the time available for the processing of each display's information. The actual time required to fixate upon a newly-attended display in a manner that provides task-relevant information might include the time required to make an initial, large eye movement in the direction of that display followed by a period of time required for a fine adjustment. The latter would provide the requisite information that could not be obtained immediately following the initial, imprecise fixation. Alternatively, the consequence of some refractory/recovery period following each eye shift might be less processing of each display. The actual source of these performance decrements can only be ascertained from future research that measures performance as a function of the number of eye shifts and the time required for such shifts.

Using Head Movements to Aid the Switching of Visual Attention

The previous strategies aimed at facilitating the use of primary- and secondary-display information assumed the use of either a head- or helmet-mounted secondary CRT. However, another approach that could prove superior to either of the above strategies involves the mounting of the secondary display in a manner that allows it to move independently of head movements. For example, a shoulder-mounted display would remain in a constant location relative to one's body orientation, rather than to one's head orientation.

The potential advantage of permitting head movements in monitoring information across two displays separated by a relatively large viewing angle is probably related to several factors that can best be integrated within a framework such as that offered by Sanders (1967). Sanders distinguishes between three visual regions: (1) the "stationary field" is the region that can be sampled by the eye when it is in a fixed orientation; (2) the "eyefield" is the region that can be sampled by means of eye movements while the head remains in a fixed orientation; and (3) the "headfield" is the region that can be sampled by means of a combination of both head and eye movements. In a series of experiments, Sanders (1967) reported that the relationship between the visual angle and the accuracy with which subjects were able to recognize a pattern of lights briefly presented in each of two lateral displays was not a linear one. Instead, a discontinuity (plateau) occurred at about 25°-40° and another at about 80°. He attributes the former to a shift in processing from a stationary field to an eyefield and the latter to a shift from eyefield to headfield processing. Additional studies reported by Sanders (1970) suggest that the location of the shifts depends upon both the nature of the task and the amount of information in the displays.

Although it is not clear how head movements might enhance the performance attained with eye movements, alone, there are several interesting possibilities that could be investigated in future studies. First of all, at relatively large viewing angles, head movements followed by compensatory eye movements for under- or over-shoots by the head might be advantageous due to greater speed and/or accuracy of such coordinated adjustments (i.e., head-plus eye-movements) compared to the use of eye movements alone. Alternatively, slight head movements might be made simultaneously with relatively large eye movements, the latter being "guided" by the former.

Hence, the majority of the viewing angle could be spanned by eye movements, rather than by head movements. Still another possibility is that head movements might serve as an "energizing" force in a manner similar to "pointing" when one is counting an array of objects. The functional use of head movements for this purpose would also involve only slight displacements of the head, with the majority of viewing angle spanned by eye movements.

The relative contributions of head- and eye-movements toward bridging the viewing angle between displays may vary with the type of information needed from each display. For example, if necessary information contained in either the primary or secondary display can be obtained without a precise fixation at a specific location because of the usefulness of peripheral vision, then the ratio representing the extent of head movements relative to eye movements might be quite small.

In the present experiment, the finding of a relatively low number of eye shifts toward the secondary display located at +15° elevation and 0° azimuth or at -15° elevation and 0° azimuth locations combined with the relatively low error rate in comparison to other locations associated with higher numbers of eye shifts might be attributable to the use of peripheral vision to obtain some useful information. Although very little peripheral information is generally obtained beyond about 25°, the amount of useful information within those boundaries is, of course, dependent upon the nature of the task and complexity of the stimuli, among other factors. Although it is unlikely that much useful information concerning the primary- or secondary-displays used in the current study was obtainable through peripheral vision beyond 15°, within that limit, there could be considerable information obtained through peripheral vision without the need to fixate at a specific location such as the center of either display. Therefore, it seems reasonable to speculate that to the extent head movements facilitate the switching of visual attention from one display to the other, then attenuation or even elimination of the obtained performance decrement functions would result by permitting head movements in addition to eye movements.

An example of a situation in which relatively small head movements, relative to larger eye movements, might facilitate the rapid shifting of visual attention to a secondary display occurs when one makes a rapid glance toward the rear view mirror in the midst of driving through heavy traffic. Most drivers appear to make distinct head movements; however, the extent of movement appears relatively small, the majority of the viewing angle being bridged by eye movements. The reason for this is probably attributable to several factors. First of all, the eye need not fixate at a precise location when obtaining critical information such as the retinal size of the auto immediately behind. Secondly, once fixation on the secondary display (i.e., rear-view mirror) is achieved, there is no need to further scan that display, thus making further compensatory or contingent fixations unnecessary. This would be especially true if one need obtain only information concerning the presence or absence of an approaching vehicle or its relative size at a given instant. Finally, the "pointing" function of a head movement might also contribute to this phenomenon of a very slight head movement relative to eye movement. That is, in contrast to the type of visual scanning that might occur solely within the eyefield, selective visual attention to objects or patterns within the headfield might be facilitated by use of slight head movements as can be observed when one is counting objects within an array.

However, the head/eye movement ratio describing visual orientation toward a secondary display might be expected to be much different for other secondary tasks. In the case of tasks such as reading, wherein the eyes must scan the display, fixating at particular, precise locations which are determined in a sequential manner conditional upon what is currently processed, the observer might be expected to orient the head rather completely toward the secondary display, thus producing a relatively large head/eye movement ratio. In this case, one would also predict that performance decrement functions associated with increasing viewing angles between a primary task display and a secondary task display containing text would be much more extreme than those obtained in the present study, but that attenuation of those decrements under conditions of unrestricted head movements would also be large. If this line of reasoning is correct, then the advantage of unrestricted head movements (i.e., in the headfield) compared to those involving eye movements alone (i.e., in the eyefield) would be greater for the reading of text on the secondary display than it would be for the processing of non-textual, visual-spatial information.

RECOMMENDATIONS

The availability of high quality miniature CRTs permits the development of relatively light, comfortable head- or helmet-mounted displays. Such devices can be constructed in a manner that permits adjustment of the CRT so that it can be positioned at the most desirable location. The current study provides guidelines for such placement in attempts to minimize performance decrements on both primary- and secondary-tasks. These guidelines, however, assume a head- or helmet-mounting of the CRT.

However, it has yet to be determined whether the current results generalize to situations in which the viewing angle defined by the separation of the primary and secondary task displays can be spanned by a combination of head- and eye-movements, as would occur when one's head is free to move relative to the secondary display. Therefore, future research should be directed at investigating the extent of primary- and secondary-task decrements under conditions of unconstrained as well as constrained head movements. The former condition would simulate a head- or helmet-mounted secondary CRT, while the latter condition would simulate a shoulder-mounted CRT or one with a fixed location relative to the primary display.

A second issue which future research should address concerns the generality of the performance decrements across tasks involving different types of visual information. In particular, it is expected that in situations involving head- or helmet-mounted secondary displays containing text, performance decrements would be even larger than those obtained in the present experiment. However, unconstrained head movement relative to the secondary task display might attenuate these decrements involving text processing to a greater extent than would occur with other types of visual information processing.

APPENDIX A

Eye Dominance Tests

Tube Test

Each subject stood 14 ft (4.27 m) from a wall upon which a target spot was marked at about eye level. The subject was instructed to hold a short tube with both hands; then, while keeping his arms straight, he was asked to point the tube at the spot so that he could see it through the tube. The experimenter observed which eye was used to align the tube by looking through it from the opposite direction. This test was repeated, thus producing two responses. If a different eye was used on each of the first two tests, a third administration was used to break the tie. Hence, eye dominance was defined in terms of two responses with a given eye.

Cone Test

As for the tube test each subject stood 14 ft (4.27 m) from a target. While holding a cone with both hands, the subject was instructed to bring the wide end of the cone up to his face and look out the small end, aiming it so that the spot could be seen. The experimenter, then, observed which eye was used to align the cone by looking through it from the opposite direction. The cone test was repeated and, as in the tube test, eye dominance was defined in terms of two responses with a given eye.

APPENDIX B

Instructions to Subjects

Primary Task Training

Today you will receive practice on each of two visual monitoring tasks. The first task will be presented on the screen directly in front of you. It is called the primary task, because you will be expected to maintain a high performance level on this task throughout the experiment. The second task will be presented on the small CRT located in front of your right eye. It is called the secondary task because we are interested in how well you can perform this task while maintaining your performance on the primary task.

We will begin with training on the primary task alone. When I start each 3 minute trial, you will see a display such as this. (Hand the subject the schematic showing the primary task display.) The object located at the center of the screen will soon begin to move either upward or downward according to a randomly determined sequence. As it moves away from the center, it will accelerate at a relatively slow or relatively fast rate according to a randomly determined sequence. Your task is to press the key with your left hand when the object is in the target region defined by the two horizontal lines at the top or by the two lines at the bottom of the display. As soon as you make a keypress response, the object will return to the center. If you make an incorrect response such as pressing the key before the object enters the target region or after it leaves, you will hear a tone which indicates an error was made. An error tone will also occur if you fail to make a keypress before the object disappears from the screen. After each keypress or after leaving the screen, the target will return to the center and a new trial will begin. The task will automatically end after 3 minutes. Do you have any questions?

Secondary Task Training

You will now receive practice on the secondary task alone. When I start each 3 minute trial, you will see a display on the small CRT that looks like this. (The subject is shown a schematic of the secondary task display.) In this task, the object will move along a horizontal rather than a vertical path. Your task is to keep the object within the target region defined by the two vertical lines. As the object begins to move, it will gradually accelerate toward the right or the left. However, by turning the knob in one direction or the other, you can correct for any displacements that occur.

If the object should leave the target region, there will be no error tone; however, it will count as an error and the object will, then, return to the center to begin a new trial. The task will automatically end after 3 minutes. Do you have any questions?

Dual Task Training

You will now receive practice in performing the two tasks simultaneously. You should try to attain maximal performance on the primary task, despite the added difficulty resulting from dividing your attention between the two tasks. However, as you become more skilled, you might be able to reduce the errors you make on the secondary task while avoiding errors on the primary task altogether. The task will automatically end after 3 minutes. Do you have any questions?

Experimental (Dual Task) Trials

The purpose of yesterday's training was to give you practice in performing two tasks simultaneously. The primary task was presented on the large monitor directly in front of you. Recall that you attempted to avoid errors and achieve as many correct responses as possible by making key presses at the appropriate time. The secondary task was presented on the small CRT to the side. You attempted to keep the moving object within the region defined by two lines.

Your performance yesterday on the last few practice trials was ____ percent correct key press responses. (The average of the subject's final three practice trials on the primary task are reported.) Your performance on the secondary task was also acceptable because you made few errors in keeping the moving object between the two lines.

Beginning today, however, the experimental trials might become more difficult as we change the location of the small CRT which presents the secondary task. Regardless of the location of the small CRT, however, it is important that you maintain a high level of performance on the primary task presented on the screen directly in front of you. You should try to maintain primary task performance at or above the level that you achieved during yesterday's baseline trials. Do you have any questions?

Remember to keep your chin and forehead as far forward as possible and to keep your head as motionless as possible. That is, although your eyes might shift between the large, primary monitor and the small, secondary CRT, your head should not move at all.

When you are ready, you may begin the trials by rotating the knob.

APPENDIX C

Analysis of Variance Summary Tables

2 x 3 x 4 ANOVA upon Mean Percentage of Primary Task Errors

Source	*df*	*SS*	*F*	*p*
Series	1	19318033	52.00	.0001
Subject x Series	11	4086687		
Elevation	2	3475488	9.29	.0012***
Subject x Elevation	22	4115545		
Azimuth	3	7725449	11.42	.0001**
Subject x Azimuth	33	7444046		
Series x Elevation	2	300536	1.02	.3780
Subject x Series x Elevation	22	3250105		
Series x Azimuth	3	828906	3.65	.0224
Subject x Series x Azimuth	33	2500084		
Elevation x Azimuth	6	1027697	1.83	.1072
Subject x Elevation x Azimuth	66	6186274		
Series x Elevation x Azimuth	6	187544	.36	.8987
Subject x Series x Elevation x Azimuth	66	5655909		
Subject	11	90634670		
Total	287	156736971		

2 x 3 x 4 ANOVA upon Mean Number of Secondary Task Errors

Source	*df*	*SS*	*F*	*p*
Series	1	1937.5	16.40	.0019
Subject x Series	11	1299.9		
Elevation	2	3220.4	8.15	.0022*
Subject x Elevation	22	4345.0		
Azimuth	3	22502.4	12.47	.0001**
Subject x Azimuth	33	19855.7		
Series x Elevation	2	179.0	0.70	.5092
Subject x Series x Elevation	22	2828.5		
Series x Azimuth	3	231.7	1.53	.2239
Subject x Series x Azimuth	33	1661.4		
Elevation x Azimuth	6	318.6	1.10	.3692
Subject x Elevation x Azimuth	66	3172.5		
Series x Elevation x Azimuth	6	218.1	1.08	.3831
Subject x Series x Elevation x Azimuth	66	2219.6		
Subject	11	50435.6		
Total	287	114426.0		

Note: * With the variance attributable to eye movements partitioned out, $p = .07$
** With the variance attributable to eye movements partitioned out, $p < .05$
*** With the variance attributable to eye movements partitioned out, $p < .01$

2 x 3 x 4 ANOVA upon Mean Post Series Discomfort Ratings

Source	*df*	*SS*	*F*	*p*
Series	1	4.500	0.42	.5295
Subject x Series	11	117.417		
Elevation	2	87.194	10.49	.0006
Subject x Elevation	22	91.472		
Azimuth	3	940.903	34.29	.0001
Subject x Azimuth	33	301.847		
Series x Elevation	2	1.083	0.90	.4213
Subject x Series x Elevation	22	13.250		
Series x Azimuth	3	2.417	0.59	.6254
Subject x Series x Azimuth	33	45.000		
Elevation x Azimuth	6	2.389	0.68	.6658
Subject x Elevation x Azimuth	66	38.611		
Series x Elevation x Azimuth	6	0.667	0.39	.8811
Subject x Series x Elevation x Azimuth	66	18.667		
Subject	11	692.903		
Total	287	2358.319		

2 x 3 x 4 ANOVA upon Mean Post Session Discomfort Ratings

Source	*df*	*SS*	*F*	*p*
Series	1	28.753	5.43	.0398
Subject x Series	11	58.205		
Elevation	2	76.646	6.28	.0069
Subject x Elevation	22	134.188		
Azimuth	3	778.344	29.45	.0001
Subject x Azimuth	33	290.698		
Series x Elevation	2	1.507	0.29	.7529
Subject x Series x Elevation	22	57.660		
Series x Azimuth	3	0.399	0.09	.9647
Subject x Series x Azimuth	33	48.476		
Elevation x Azimuth	6	6.771	1.46	.2062
Subject x Elevation x Azimuth	66	51.062		
Series x Elevation x Azimuth	6	0.465	0.12	.9938
Subject x Series x Elevation x Azimuth	66	43.035		
Subject	11	918.260		
Total	287	2494.469		

2 x 3 x 4 ANOVA upon Mean Post Trial Discomfort Ratings

Source	*df*	*SS*	*F*	*p*
Series	1	2.626	6.85	.0240
Subject x Series	11	4.218		
Elevation	2	16.318	15.07	.0001
Subject x Elevation	22	11.911		
Azimuth	3	75.947	26.49	.0001
Subject x Azimuth	33	31.543		
Series x Elevation	2	0.304	0.61	.5540
Subject x Series x Elevation	22	5.509		
Series x Azimuth	3	0.204	0.40	.7564
Subject x Series x Azimuth	33	5.661		
Elevation x Azimuth	6	1.488	1.62	.1561
Subject x Elevation x Azimuth	66	10.116		
Series x Elevation x Azimuth	6	0.127	0.19	.9778
Subject x Series x Elevation x Azimuth	66	7.227		
Subject	11	105.169		
Total	287	278.367		

2 x 3 x 3 ANOVA upon Number of Eye Shift

Source	*df*	*SS*	*F*	*p*
Series	1	2252.34	3.57	.0854
Subject x Series	11	6938.53		
Elevation	2	1558.57	1.56	.2328
Subject x Elevation	22	11000.79		
Azimuth	2	5316.56	17.17	.0001
Subject x Azimuth	22	3405.97		
Series x Elevation	2	811.09	0.96	.4001
Subject x Series x Elevation	22	9340.66		
Series x Azimuth	2	864.02	10.54	.0006
Subject x Series x Azimuth	22	901.56		
Elevation x Azimuth	4	886.25	2.07	.1015
Subject x Elevation x Azimuth	44	4717.47		
Series x Elevation x Azimuth	4	507.14	1.63	.1825
Subject x Series x Elevation x Azimuth	44	3412.53		
Subject	11	259585.43		
Total	215	311498.92		

2 x 2 x 4 ANOVA upon Number of Eye Shifts

Source	*df*	*SS*	*F*	*p*
Series	1	2632.9	1.68	.2217
Subject x Series	11	17255.3		
Elevation	1	780.0	2.87	.1185
Subject x Elevation	11	2991.9		
Azimuth	3	2429.9	2.84	.0531
Subject x Azimuth	33	9425.5		
Series x Elevation	1	627.1	1.85	.2009
Subject x Series x Elevation	11	3727.5		
Series x Azimuth	3	725.5	4.69	.0078
Subject x Series x Azimuth	33	1702.3		
Elevation x Azimuth	3	830.8	1.60	.2089
Subject x Elevation x Azimuth	33	5725.2		
Series x Elevation x Azimuth	3	241.8	0.69	.5637
Subject x Series x Elevation x Azimuth	33	3846.5		
Subject	11	228260.5		
Total	191	280402.7		

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