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PERIPHERAL VISION DISPLAYS

by Leroy L. Vallerie

Prepared by
DUNLAP AND ASSOCIATES, INC.
Darien, Conn.
for Electronics Research Center

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ABSTRACT

A study was conducted to determine the effectiveness of peripheral vision displays for presenting dynamic tracking information during difficult control tasks such as landing high speed aircraft or rendezvousing spacecraft. Based on a review of the literature, it was hypothesized that peripheral displays could be successfully used to improve performance provided visual switching between information sources is normally an essential part of such tasks. Visual switching consists of eye movement, accommodation, and convergence. The hypothesis was tested in the laboratory by comparing operator performance on a two dimensional compensatory tracking task under conditions in which the requirements for visual switching and the provisions of peripheral displays were systematically varied and controlled. It was clearly demonstrated that tracking performance deteriorates as visual switching increases and that peripheral displays can be used to overcome its adverse effects.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

DISPLAYS FOR SEEING WITHOUT LOOKING

I. INTRODUCTION

Advances in our aerospacecraft capabilities have required man to perform an increasing number of complex, continuous control tasks based on visual information provided at the center of his field of view. A point is reached, however, in designing displays for such tasks where it becomes both impractical and inefficient to present all relevant information artificially on a single central display, or to supplement direct visual contact with superimposed symbolic data, such as is provided in certain aircraft projective systems, e.g., "heads-up" or weapon control displays. Majendie (1960) summarized the disadvantages of such projective systems in his rationale for peripheral vision displays, as follows:

- "Of little use during maneuvering or turbulent flight.
- Unusable when the pilot's line of sight is more than about 8° from the projective display, e.g., under transition conditions in the presence of lateral displacement or wind drift.
- Unusable when the pilot's attention is within the cockpit.
- Indications of malfunction not inherently available, except to an attentive pilot."

In a similar vein, Fish (1950) concluded that "heads-up" displays were of very limited use and might give rise to problems of double images.

Many centrally located visual displays are also so heavily cluttered with symbols that they are somewhat difficult to interpret. For these reasons and others, some designers have found it necessary to provide additional displays of redundant or supplementary information. Usually, these also have to be viewed foveally so that a man must shift his gaze rapidly between them and the primary information source. Time lost in making eye movements may seriously affect the rate of information transfer, especially in complex tracking tasks as, for example, in landing high performance vehicles, in operating airborne weapon control and detection systems while flying at supersonic speeds, or in maneuvering and rendezvousing spacecraft using multidimensional control systems.

The purpose of this research program is to investigate the capabilities of peripheral vision for improving information transfer to operators involved in complex control tasks. The ultimate goals are to determine under what conditions peripheral vision displays can be used to enhance performance, what information can best be presented peripherally, and in what form it should be displayed to the operator. To achieve these goals, it appeared logical to divide the research program into three phases. The purpose of Phase I is to determine the feasibility of using peripheral vision displays to improve performance in complex control tasks and to identify the underlying factors responsible for any such improvements. During Phase II, the objective is to develop optimum encoding techniques for the design of such displays giving due regard to the constraints and limitations of anticipated operational environments. The purpose of Phase III designs is to test and verify the relative merits of selected display designs in simulators and actual vehicles.

At the present time, Phase I is completed and is discussed in the following sections of this report. Phase II is also completed except for the portion dealing with the laboratory experimentation. The results of this effort are also contained in this report. Specific design requirements, however, cannot be developed before the Phase II experimentation is carried out. Once these requirements are finalized and actual displays fabricated, work can then begin on Phase III.

II. PHASE I--UTILITY OF PERIPHERAL VISION DISPLAYS

Before specific hypotheses can be developed concerning the utility of peripheral vision displays, it is necessary to examine the role that the operator plays in manual control systems and to identify the display characteristics which affect his performance. In a closed loop manual control system, the operator continuously attempts to minimize the error between a desired and an actual system output, i. e., he acts as an error corrector and may be compared, in this sense, to a servo-mechanism. As illustrated in Figure 1 (Ely, J. H., et al., 1956), the input to the system is presented on a display to the operator in the form of continuously changing information. The operator senses this information and performs a selected appropriate control movement. The control produces a change in the machine. The change in the machine is the system output. Information concerning system performance (output) is then fed back to the operator's display, closing the loop. The display, therefore, combines information about the system input and the system output. In such a closed loop system, both the characteristics of the operator and the characteristics of the display seriously affect the rate of information processing.

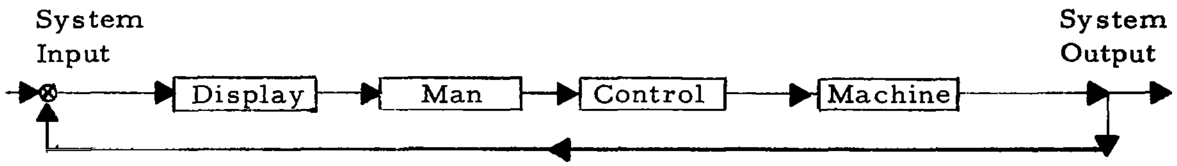

Figure 1. Closed Loop Manual Control System.

Other feedback loops are also present in a typical manned control system (e.g., from the control and from the machine) which are not shown in the illustration. Characteristics of controls of machines, therefore, also affect performance but are not pertinent to the present discussion.

A. Operator Characteristics Affecting the Rate of Information Processing

There are a number of human time lags which affect the rate of information processing in a manual tracking system. Among these are lags due to times for visual switching between information sources, attention switching, detection, decision, and response. They are not mutually exclusive, but interact with one another in a complex manner. For convenience, each time lag will be discussed as if it were independent.

Visual Switching

Visual switching time is the time required to shift the point of fixation from one location to another and to refocus. At high vehicular speeds, a significant distance will be covered during this time interval. Wulfeck, et al. (1958) in Vision in Military Aviation, have compiled data on the latencies associated with aircraft flying and have shown that the switching of fixation from outside an aircraft to the instrument panel and back again requires over two seconds. The authors concluded: "An instrument showing aircraft position at a glance will be as necessary as a compass is now." Time consumed by a glance may even be excessive in view of the speed and complexity of future aerospacecraft.

Travis (1948) pointed out the importance of accommodation and convergence as aspects of scanning in aircraft flying, especially during take-offs and landings. During these maneuvers, the pilot must make a number of quick glances between the runway and his cockpit instruments. The average time for accommodation and convergence alone in binocular refixation of near and far stimuli was measured to be on the order of 0.20 second, with quite large individual differences. In a task involving visual acuity, recognition of the stimulus, a verbal report, a manual movement of a lever as well as accommodation and convergence, average time for refixating near and far stimuli successively was 1.06 seconds. Lags due to visual switching including accommodation and convergence, therefore, can limit the time available for information transfer in any manual control task. Research by Conrad (1951, 1955),* Wiener (1964) and Olson (1963) provides direct evidence that presenting information on multiple displays does not enhance the rate of information transfer. Rather, in Olson's study, rate of transfer (bits/min.) was considerably lower with twelve displays than it was with six.

The location of displays in the field of view affects the rate at which a man can receive and use information (Olson, 1963; Senders, 1955). The speed and accuracy of response, as measured by them, was lower for peripherally located displays than for displays in the central field of view. In one case, this appears to depend directly on the differential sensitivity of the eye, i.e., on the progressive loss in resolution from the fovea to the periphery of the retina (Senders, 1955). In the other (Olson, 1963), it appears to depend on the saturation of a man's capacity to process information with additional information he is obtaining from the more central (and more easily discernible) displays, and from the interference of a simultaneous central tracking task.

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*A replot of Conrad's data (1951) in information theory terms is presented in Appendix A.

Attention Switching

In the strictest sense, man cannot attend to two things simultaneously; he must attend to them sequentially. Senders (1965) reviewed the literature dealing with attention and concluded, along with others, that attention is "unitary and capable of dealing with one demand at a time. The frequency with which it can alternate between various time series of events may be sufficiently high so that apparent simultaneity of processing will be observed. Whether apparent simultaneity will be observed is calculable on the basis of the physical characteristics of the time series involved. Looked at in this light, one may consider the attention of an observer to be a channel which processes in sequence, never simultaneously, information arriving from outside sources... the basis on which an information source demands attention from an observer, or, alternatively, the basis on which an observer decides to direct his attention to an information source... is one of uncertainty reduction."

Kristofferson (1965) also was concerned with the problem of attention and views it as a "selective control of information flow in the central nervous system." This "control or gating of information is accomplished... by a central-neural mechanism... which has the logical properties of a many-poled, highly-flexible switch which funnels messages into a single processing channel." In experiments carried out by Kristofferson (1965), he found support for the hypothesis that "the switching of attention is controlled by a periodic mechanism and that switching can occur only once every M msec..." Broadbent (1958, 1961) also supports the conclusion that some finite time is required to shift from one input source to another. Senders (1965) suggests that the mechanism which controls attentional shift could apply either to different sense modalities, to different sense organs in the same sense modality, or to different stimulus aspects in the same organ.

In 1929, Meisenheimer, and in 1931, Grindley, concluded that attention has a significant effect on the perception of peripheral stimuli. In research carried out by Webster and Haslerud (1964), the problem of attention was attacked by determining what would happen to a peripheral visual task when attention also had to be directed "simultaneously" toward an auditory or foveal visual task. The results indicated that "both auditory and foveal counting tasks had equally significant detrimental effects on both the number of responses... and reaction... to peripheral lights." The counting tasks, however, were almost 100% correct. They suggest this technique as a "new" way to measure quantitatively the effects of attention and to determine the distribution of attention between two tasks. Since both foveal and auditory counting tasks had equal detrimental effects on peripheral visual perception, the adverse effect was attributable to the mental counting rather than the sense modality used. "Therefore, attention is a function of the integrated organism rather than only the orientation of a sense organ (to a stimulus) and if these results are further supported, attention will need redefinition." The authors proceed to conclude that it is "impossible to assume that an object located inside the peripheral limit is necessarily perceived by an individual involved in some other task." This research, therefore, also lends support to the concept of attention switching and to the idea that the periphery of the retina should be treated as an independent input channel for information. Assuming this were true, simultaneous attention to both central and peripheral channels of information would, in the strictest sense, be impossible.

Work performed by Bursill (1958) and Mackworth (1965) would also support the concept of attention switching. In general, their studies indicate that stress in the form of heat, visual noise and high load conditions, can cause "tunnel vision" or a "funnelling of peripheral awareness." Bursill used a peripheral visual task concurrently with a continuous foveal pursuitmeter task. He defined "funnelling" operationally as "the proportional increase in the number of peripheral signals missed as the eccentric angle of the peripheral stimulus increases relative to the point of fixation." Under low stimulus loads in the central task, the funnel effect did not occur. Hence, alternations in the central attentional processes were suggested to account for the effect rather than any physiological effect on the peripheral retina of the eye. This also suggests a central attention switching mechanism that is capable of scanning a limited number of information sources and is adversely affected by stress whether it is task-induced or due to external factors such as heat, noise, fatigue, sleep deprivation, etc.

The sequential nature of attention is also supported by the evidence on reaction times and the concept of the psychological refractory period. When one signal is presented shortly after another, the time taken to respond to the second signal is delayed longer than would normally be expected (Telford, 1931; Vince, 1948 and 1950; Broadbent, 1958; Welford, 1952 and 1959). According to Welford (1960), the best supported explanation of this phenomenon is that some part of the central mechanisms can deal with only one signal at a time. Welford (1960) states: "If, therefore, a signal appears during the reaction time to a previous signal, the second signal has, as it were, to queue up until the central mechanisms are free." The central mechanisms must also monitor actions as well so that "signals may have to queue up if they arrive during or shortly after the movement to a response to a previous signal as they may clash with kinaesthetic or other sensory 'feedback' from the movement. Monitoring of responses may in some cases be eliminated (Davis, 1956; Marill, 1957) by intensive practice."

Detection

Assuming an operator has fixated an information source and is attending to it, some finite amount of time is required to detect and recognize the signal of interest. Discriminability of input signals was found by Herman (1965) to limit information processing rate. In general, an easily discriminated signal is detected with greater speed and accuracy. Detection time, therefore, depends on the properties of the stimulus used, e.g., size, brightness, color, duration, contrast or signal-to-noise ratio, etc. Detection time, for easily discriminated signals under rather simple conditions, amounts to a few hundredths of a second.

Decision

Decision time varies depending on the complexity of the decision that must be made. In general, decision time is proportional to the logarithm of the number of alternative choices up to some limit that defines an operator's channel capacity. The central mechanisms, therefore, act as if they contained a single-channel decision mechanism of limited capacity that requires a finite time to process information and can deal only with a limited amount of information in a given time interval. The rate, even under favorable conditions, appears to be related to the operator's ability to perceive and encode the "instantaneous" sensory data into relatively few (seven or eight) items or sources of information (Miller, 1956; Quastler, 1956; Broadbent, 1957 and 1958; Welford, 1959 and 1960).

Fitts (1964) also cites evidence, in supporting the concept of discontinuity in perceptual motor tasks, that information is handled as a limited number of discrete chunks and that the upper limit of information processing rate is similar for continuous, serial and discrete tasks. Research dealing with human transmission rates also indicates that the use of additional channels of information does not improve the rate of information processed by an operator (in Senders, 1965).

Further evidence to support the idea of a central decision channel of limited capacity is found in studies involving two tasks which are performed simultaneously either to provide a stressful environment for a primary task or to measure a man's spare channel capacity when he performs the primary task at some criterion level (Poulton, 1958; Brown and Poulton, 1961; Knowles, 1963; Webster and Haslerud, 1964). Generally, the secondary task has involved different sense modalities from the primary task, or at least different forms of response in order to minimize interference between common response mechanisms. However, this procedure appears successful only when the responses involve no choices among alternatives and little or no monitoring of the response movements (Kalsbeek, 1964), and depend on the "interleaving" of the two tasks so as to provide for rapid alternation of attention between them. Other research (Broadbent and Gregory, 1961) demonstrates that a man has greater difficulty in organizing and recording information presented in rapid alternation in two sensory modes (visual-auditory) than in two input channels within one sensory mode, i. e., to the two ears alternately. With respect to central and peripheral visual channels, both an auditory and foveal visual task has equal adverse effects on a peripheral visual task (Webster and Haslerud, 1964). As pointed out above, this appears to indicate that the fovea and periphery of the eye operate as independent input channels of information and cannot be attended to simultaneously.

Response

The time required to respond to a signal, once detected, depends on the complexity of the response (e. g., type of control, force, displacement, and precision) as well as the body member used. Simple responses made with a pushbutton, for example, require much less time than those requiring precise manipulation of a control lever. In simple tasks, not involving lags due to scanning, attention switching, and complex decisions, reaction time varies between 0. 15 to 0. 20 second depending on the sense modality used. Such simple tasks involve primarily detection and response times only. Since response time and the design of controls are not of particular interest to this investigation, this limitation on the rate of information transfer in manual tracking systems will not be treated to any great extent in this report.

B. Stimulus Characteristics Affecting the Rate of Information Processing

The rate of information transfer in a manual tracking system depends on the kind of signal that is displayed and how it is displayed to the operator. This study is concerned primarily with the design and arrangement of displays, but some mention should be made about the effects that changes in the functions displayed to the operator have on the information transfer rate in complex control systems.

In many vehicular systems, the level of manual control is determined by the complexity of the system characteristics representing the physical interfaces between the vehicle and its environment. In general, complex systems in a fluid environment (e. g., a helicopter or submarine) are more difficult to control than less complex systems interacting with their environment in fewer dimensions. Control of the former systems requires multiple integrations of information inputs.

The general practice in displaying control information in such systems is to provide one display for raw output information and a number of additional displays of derivative information about the output. As a result, the operator's task involves constant attention to the various displays and complex transformations of data involving high order differentiations and integrations. To simplify the operator's task, the display technique known as "quickening" has been used successfully in higher order systems.

In general, "quickening consists of a single display which provides immediate knowledge of the computed results of an operator's own control actions on the system before they would become available by sensing the system's actual output." (Chapanis, in Morgan, et al., 1963) The display indicates the sum of the machine output and its derivations. This information is derived by placing feedback loops between each of the derivatives of the machine output and the display. In a quickened system, the display indicates directly where the operator should position his control device and eliminates the requirement for making complex mental calculations, i.e., the machine makes the calculations instead of the operator. Hence, the limited channel capacity of an operator is not taken up with data transformation, thus permitting an improvement in the effective rate of information transfer by the overall system. The operator's capacity for information processing remains unchanged; the calculation function has simply been allocated to the machine which can accomplish it with greater speed and accuracy.

One of the major disadvantages of a quickened display is that the operator is not provided with information concerning the actual state of the system. To alleviate this problem, a second display is usually provided to supply positional or status information. A particularly attractive idea is to provide a positional display in the center of the field of view showing error and a quickened display(s) in the periphery showing a combination of error and error rate (or higher derivatives depending on the dynamics of the system controlled). The peripheral command indicator developed by Collins Radio Company (Fenwick, 1963) displays quickened flight direction signals.

How information is presented to the operator also affects the rate of information processing in a tracking system. Here, the concern is with such factors as the stimulus dimensions used as well as the type, size, location, and arrangement of displays. These factors primarily influence the time required by the operator to scan his information sources and the time required to detect the information of interest. Many studies (see Miller, 1956; Quastler, 1956) indicate that the rate of information processing can be increased by utilizing many separate stimulus dimensions with the relevant information grossly quantized along each dimension. Massa and Keston (1965) in developing the philosophy of "Minimum Attention Displays" state that "the first problem in the maximization of information intake through the visual system is one of selecting the appropriate visual dimensions to be used in the display. The basis for selection of these dimensions is their inherent information transmission capability, i.e., how many different states in a given dimension can be reliably distinguished, at what rate can the distinctions be made, and what the cross talk or interaction is between dimensions in an information transmission task." To minimize interaction between display, stimulus dimensions and normal visual contact, they suggest using the natural partition between fovea and periphery. After a brief review of the literature dealing with the psychophysiology of peripheral vision, they conclude that: 1) "A sizable set of dimensions (3 or 4 at the very least) can be found having significant information transmission capability and minimum cross talk and interaction," and 2) "This set will interact minimally with normal foveal vision." One of the problems associated with this line of thought, however, is the assumption that an operator can attend to both a central source of information and peripheral displays simultaneously. As pointed out earlier, there is strong evidence which indicates that attention is sequential in nature, and that the peripheral retina should be viewed as an independent input channel. It can, therefore, be compared to and treated as a separate sense modality. As mentioned above, additional input channels of information do not increase the total amount of information that an operator can process in a system; his capacity is limited by his single channel central processing mechanisms. The unique advantage of peripheral vision displays, therefore, is not that they require minimum attention or that they provide an opportunity to increase the number of stimulus dimensions used to maximize information transfer, but that they do not have to be fixated in order to be used. Improvements in the rate of information transfer realized from the use of peripheral displays should, therefore, be due to a reduction in the time for visual switching.

C. Summary and Conclusions

The operator has been viewed as possessing a limited capacity for processing information in a manual control system. Human time lags involving visual switching, attention switching, detection, decision, and response were identified as being major contributors to the rate with which the operator can process information in such a system. Evidence was cited which indicates that both central and peripheral sources of information cannot be attended to simultaneously and suggests that the peripheral retina is a separate sensory input channel. In addition, providing redundant information through an additional input channel does not necessarily improve performance. Since the periphery is a separate input channel, providing redundant information in the periphery should not improve the rate of information transfer and would not be attended to especially during complex control tasks where visual switching is not a critical factor and where task induced stress is taxing the limits of the operator's channel capacity. In summary, the utility of peripheral displays appears to be in their ability to reduce or eliminate visual switching time during difficult control tasks. In such tasks, it is inefficient for the operator to waste time shifting fixation from one information source to another, e.g., looking for the runway and, at the same time, attempting to scan his cockpit instruments to obtain needed tracking information. Therefore, if switching is not required and central displays are adequately designed, no benefit would be expected from the use of peripheral displays regardless of task difficulty. On the other hand, if switching is required in a complex tracking task using conventional instrumentation, peripheral displays will aid performance.

The above hypotheses must be verified to establish why peripheral displays improve performance. It will then be possible to answer questions dealing with how peripheral displays should be used and what information they should present to the operator. Attention can be given to the identification of suitable stimulus dimensions for incorporation in the design of peripheral displays. Dimensions should be selected based on the perceptual capabilities of the peripheral retina against anticipated operational requirements and constraints. Once these are determined, actual display concepts can be developed and subjected to verification and evaluation under simulated and actual operational conditions.

III. PHASE I--EXPERIMENTATION

The purpose of Phase I was to determine the feasibility of using peripheral displays to improve performance in complex control tasks and to identify the underlying factors responsible for such improvement. In an effort to accomplish these objectives, the following specific hypotheses were investigated.

- The contribution of peripheral display to improved performance in a complex tracking task is attributable to a reduction in visual switching.

- Redundant information provided peripherally will not contribute to performance on a task requiring little or no visual switching among displays designed for foveal viewing.

A. General Method

These hypotheses were tested by comparing the performance on a two dimensional compensatory tracking task under conditions in which the requirements for visual switching and the provisions for peripheral displays were systematically varied and controlled. The two dimensions of the task were presented to the operator simultaneously in the form of continuous vertical and horizontal error information. The operator's task was to correct the error in the two dimensions by means of compensatory tracking using a hand control. A photograph of the experimental apparatus is shown in Figure 2.

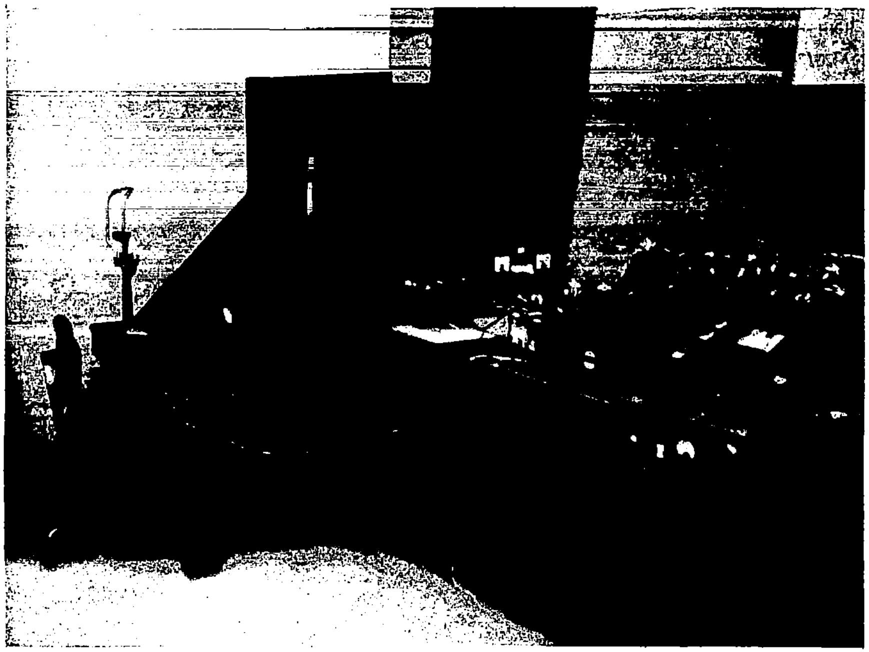


Figure 2. Experimental Apparatus.

A total of eleven experimental conditions were examined as illustrated in Figure 3. In three conditions (A through C), vertical and horizontal error information were presented on the same plane directly in front of the operator on two separate displays in the center of his field of view. Both displays were identical except for their orientation. They were located near the operator at a viewing distance of approximately 76.2 cm., with minimum separation between them in order to minimize visual switching. In Condition B, a pair of peripheral displays were provided to present redundant, horizontal tracking information. In Condition C, another pair of peripheral displays were added in the visual field to present redundant vertical information as well.

In three additional conditions (Conditions D through F), the two central displays were separated vertically by approximately 30° (on center) of visual arc. The central display presenting vertical error was located at

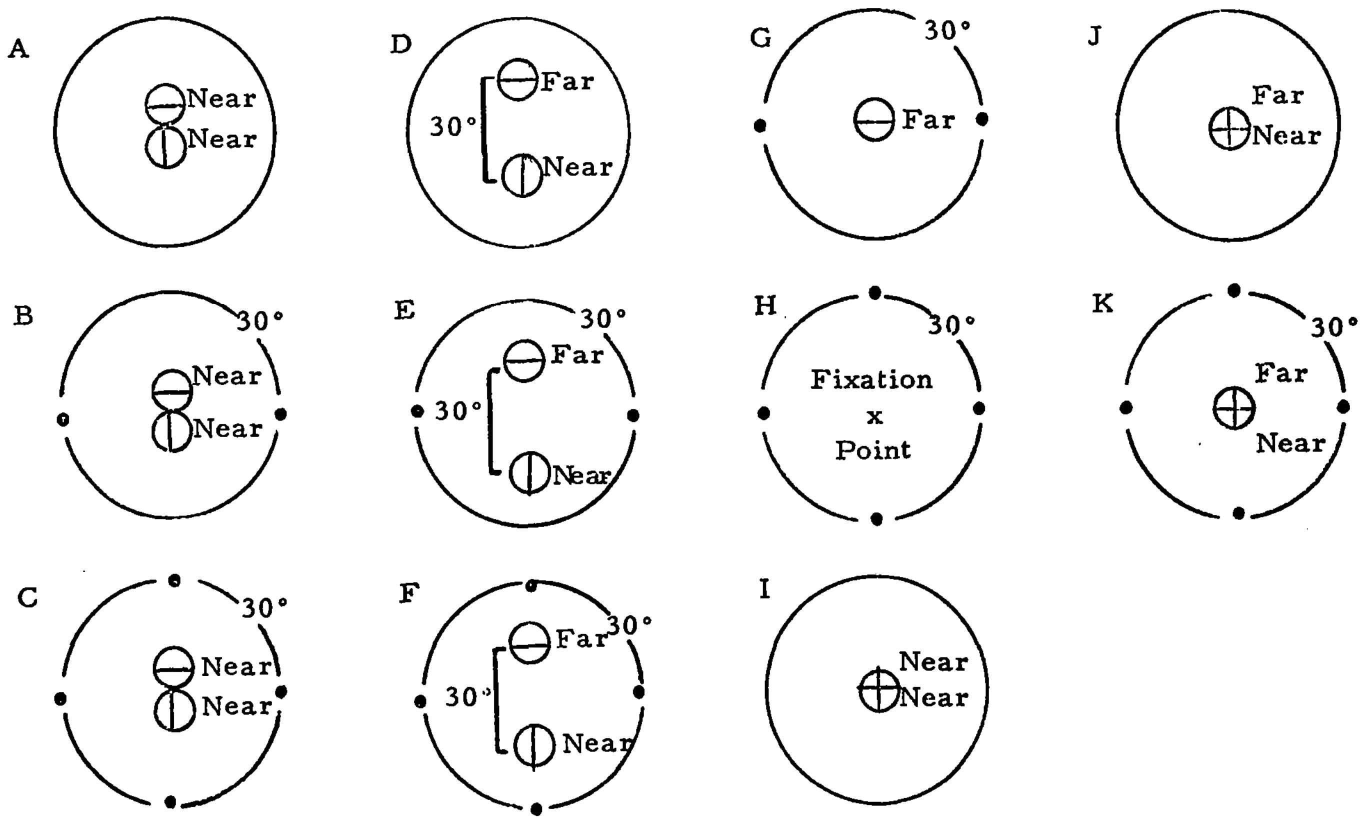


Figure 3. Experimental Conditions Illustrating the Location of Central and Peripheral Displays in the Operator's Visual Field.

a greater distance approximately 3.66 m., from the operator's eyes. The horizontal error display remained near the operator at a distance of 76.2 cm. Under these conditions, the operator was required to scan the displays in order to obtain tracking information in the two different planes, i.e., move his eyes and refocus to perform the tracking task. The "far" display was proportionately larger than the near display so that the elements of both displays subtended approximately the same visual angles at the operator's eye. During Condition E, horizontal tracking information was presented in the periphery as well as on the near central display so that the operator could maintain his gaze on the "far" central display to obtain vertical tracking information. Condition F was studied to determine the effects of complete peripheral redundancy on performance. In this case, the operator could fixate either the near or far central display and obtain supplementary information (vertical or horizontal as the case may be) peripherally.

Condition G was similar to Condition E except that the near display was eliminated, forcing the operator to use the peripheral displays for horizontal tracking information i.e., the peripheral displays were not used to present redundant information as in the previous conditions. Condition G, therefore, was used as a control to determine if the operator was actually using the peripheral displays during Condition E and to establish if peripheral displays can be effectively used in combination with a foveal display as the only source of information on one dimension of the control task.

In Condition H, no central displays were used; the operator was to track in both dimensions using only peripheral displays. Here a central fixation point was used to stabilize the peripheral displays in the field of view. This condition was included in the experiment to establish the efficiency of presenting information entirely in the periphery and to obtain baseline data for future research in which other stimulus dimensions would be investigated.

In Conditions I, J, and K, both vertical and horizontal tracking information were combined into a single central display, i.e., the vertical dimension was superimposed on the horizontal dimension. Here, the operator's task was quite different than that found in the previous conditions since he merely was required to "null" the intersection of the two lines rather than to "null" each line separately. With separated central displays, the operator would work with each line independently or attempt to integrate the two mentally. Conditions I, J, and K, therefore, should place fewer demands on the operator because of reductions in requirements for eye movements and mental integrations. In Condition I, both dimensions of the central display were located near (76.2 cm.) the operator. In Condition J, however, the vertical dimension was placed at the "far" location (3.66 m.) and was proportionately larger than the near dimension, Here a requirement for accommodation and convergence rather than eye movement was the predominant factor distinguishing this condition from Condition I. Both dimensions, therefore, subtended the same visual angles at the operator's eye. Condition K was identical to Condition J, except that two sets of peripheral displays were provided to present redundant information in both dimensions.

The operator's head was held stationary by means of a Bausch and Lomb adjustable head and chin rest. The operator's station is shown in Figure 4. In all conditions, brightness and color of central displays were held at a constant level. Brightness was maintained at 1.04 foot-lamberts. Color was balanced using wratten filters. Brightness of the peripheral displays could be varied from 0 to 250 foot-lamberts. In order to attenuate any interactive effects between displays and the general level of illumination of the operator's environment, ambient illumination was maintained at a constant and low level throughout the experiment.

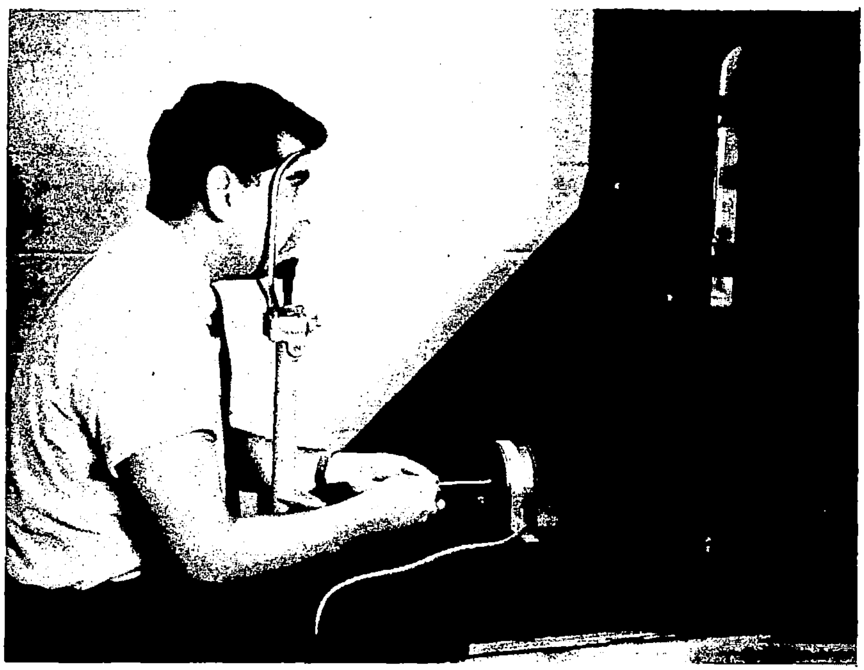


Figure 4. Operator's Station

B. Tracking System

The operator's task was to control a second-order vehicle. Equations of motion in two orthogonal dimensions were programmed on an analogue computer to provide the dynamics for the control task. The second-derivative of the vehicle output was obtained by summing the outputs of a control stick and a random function generator for each dimension of the control task. A block diagram of the tracking system is shown in Figure 5. A circuit diagram for the analogue computer, tracking displays, and function generators are shown in Figure 6.

Two uncorrelated random function generators were programmed to produce acceleration disturbances in the x- and y- dimensions of the vehicle to provide the operator with a difficult control task. Each generator consisted of three independent sine-wave oscillators whose frequencies were 0.066, 0.363 and 1.0 H_z. For x-dimension of the vehicle, the sine-wave amplitudes were 20, 5, and 5 volts peak-to-peak respectively. The y-dimension amplitudes were 15, 5, and 5 volts peak-to-peak respectively. These were summed and scaled so that the maximum peak-to-peak disturbance was 1.4 volts for the x-dimension and 1.62 volts for the y-dimension. The frequencies of oscillation were selected to generate a quasi-random waveform whose period would be large enough to preclude the possibility of the operator memorizing or anticipating any portion of the control task inputs. The amplitudes of oscillation were selected empirically to ensure a high level of difficulty so that even the better operator would have a challenging control task.*

C. Central Displays

Central displays were generated using optical techniques as illustrated in Figure 7. Both vertical and horizontal tracking information were presented to the operator on a rear projection screen in the form of vertical and horizontal lines. The displacement of the line from the center of the display indicated the amount of tracking error to be corrected by the operator.

The image of the line was produced by means of a film strip placed at the focal point of two 80 mm projection lenses. The film strip was "driven" through appropriate gearing by means of a zero-order servo system in response to vehicle position error signals generated by the analogue computer. The servo-system was Model SU-102 DC manufactured by Servo Systems, Inc. With the use of this technique, it was possible to generate both near and far displays so that they subtended the same visual angles at the operator's eye. The images of the two lines were superimposed by means of a beam splitting mirror to produce the combined display configurations required for Conditions I, J, and K, of the experiment.

The position of the horizontal line was in the center (null position) of the display when the y-dimension (vehicle position) error signal (ϵ_y) was

*See Appendix B for comparison of task difficulty.

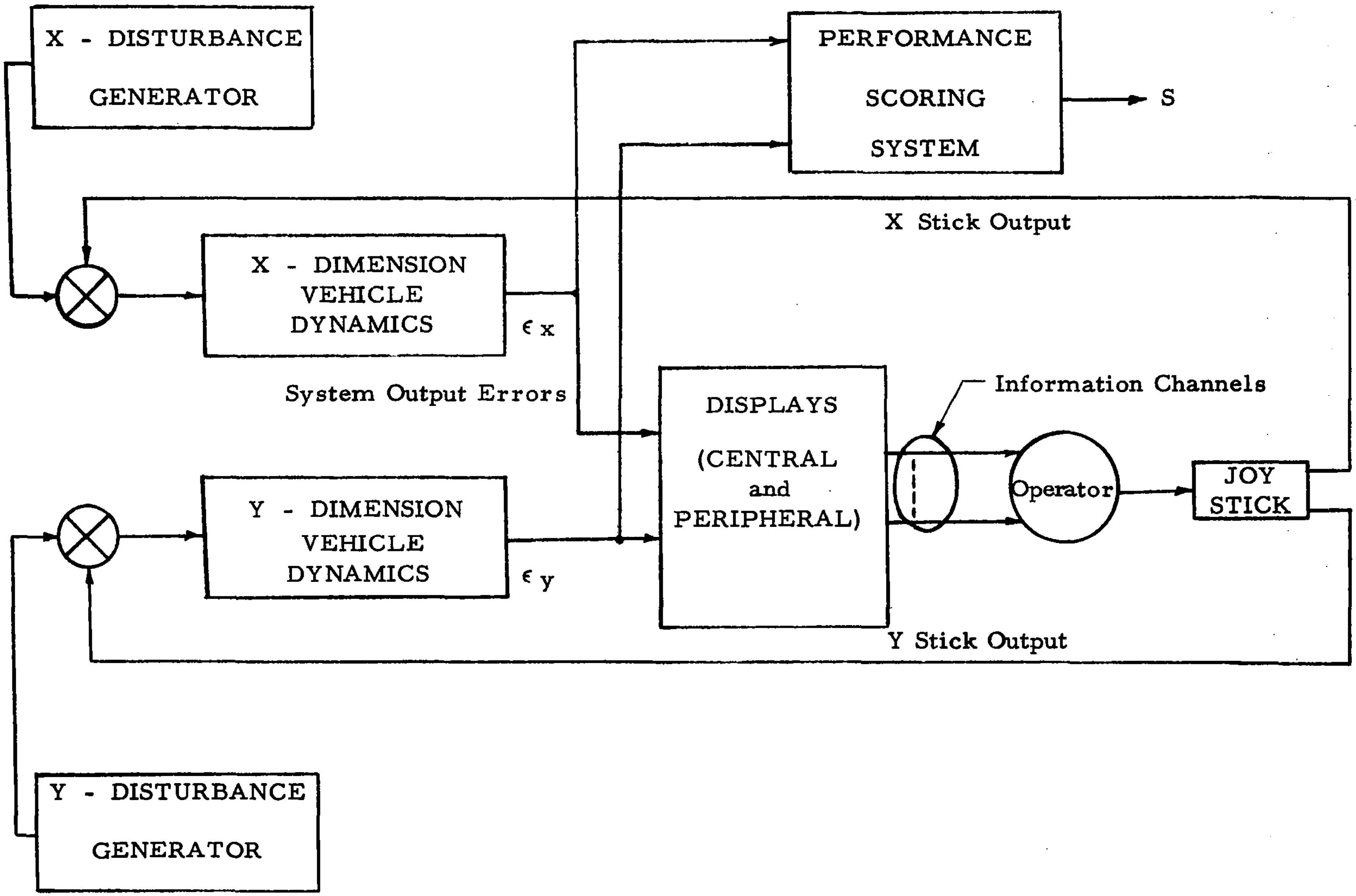


Figure 5. Block Diagram of Tracking System

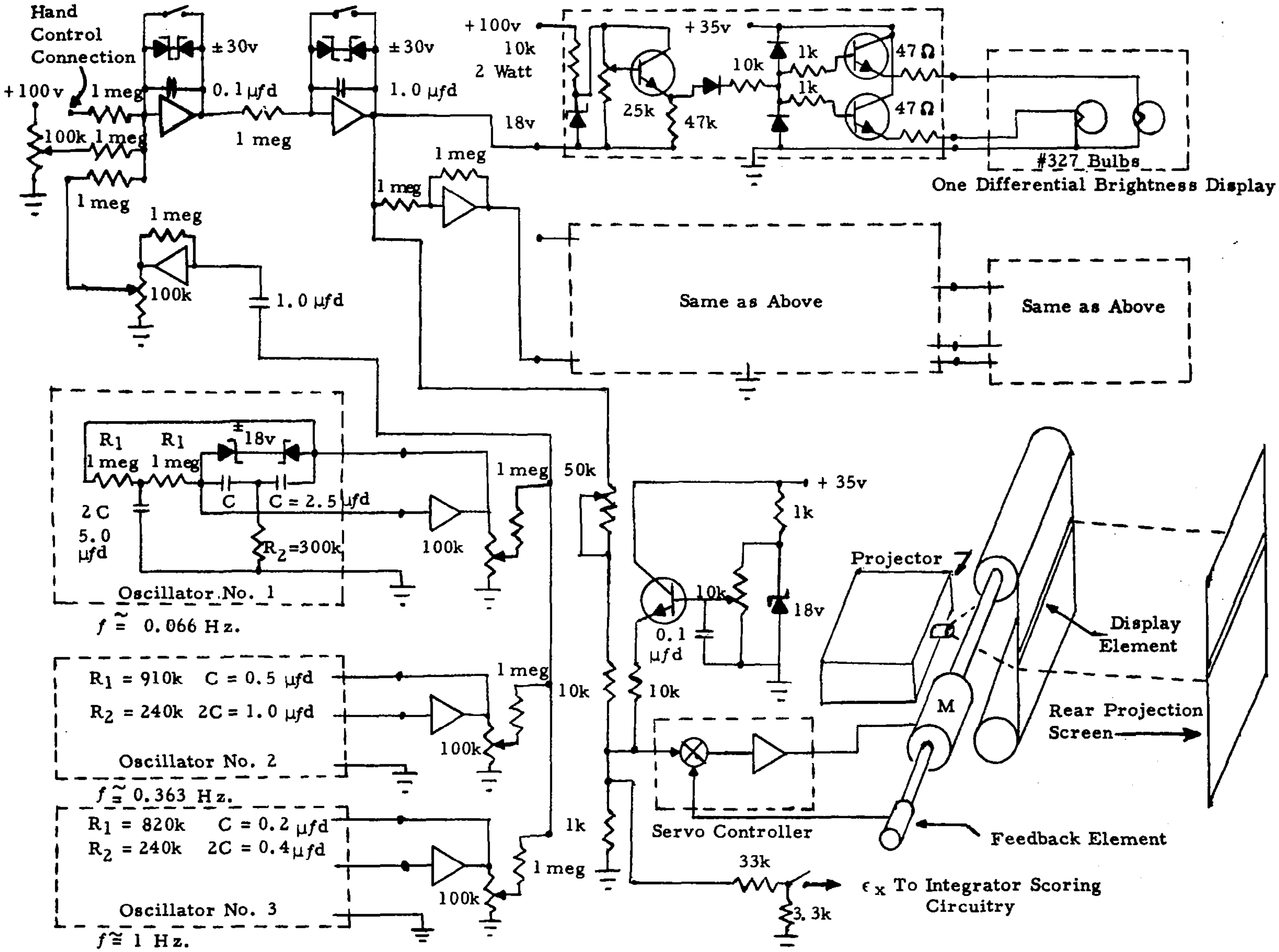


Figure 6. Circuit Diagram for the Analogue Computer, Tracking Displays, and Function Generators.

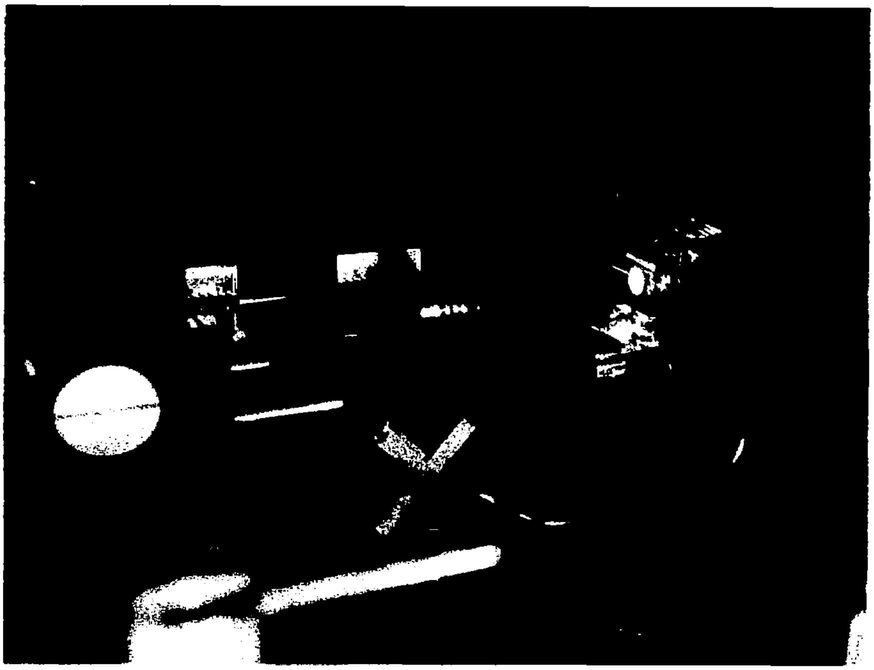


Figure 7 . Projection System for Generating Central Displays.

zero. The line was displaced upward (downward) away from its null position as ϵ_y increased in the positive (negative) direction. In a similar manner, the vertical line element in the display displaced to the right (left) of the null position as ϵ_x increased in the positive (negative) direction.

D. Peripheral Displays

In some experimental conditions, error information (ϵ_x and ϵ_y) was also presented to the operator by means of four differential brightness displays (two per x- and y- dimension) located in the operator's periphery. Research dealing with the psycho-physiology of peripheral vision indicates that the peripheral retina is particularly sensitive to changes in brightness. In view of some of the constraints and limitations encountered in the operational environment, it is doubtful that brightness discrimination in the periphery would prove more satisfactory for operational use than sensitivity to other stimulus dimension, e.g., motion. Nevertheless, brightness was chosen primarily because of cost considerations and the simplicity of mechanization.

The peripheral displays operated in the following manner. As the x-dimension central display line moved to the right due to a positive increase in the x- dimension vehicle position error (ϵ_x), the peripheral lamp located on the right side of the central display illuminated and became progressively brighter as the value of ϵ_x increased further. The brightness of the lamp was a monotonic increasing function of $|\epsilon_x|$ for $\epsilon_x > 0$. The right lamp remained off for $\epsilon_x \leqq 0$.

The left hand peripheral lamp operated in an analogous manner. When $\epsilon_x < 0$, the vertical line element displaced left of center and the left-hand peripheral lamp would illuminate and become progressively brighter as ϵ_x became more negative. Again, the brightness was a monotonic increasing function of $|\epsilon_x|$, in the range $\epsilon_x < 0$. The left lamp remained off for $\epsilon_x \leq 0$. The y-dimension peripheral display consisted of two lamps with identical characteristics to those used in the x-dimension. The y-dimension lamps were located above and below the central display and operated in response to the y-dimension error signal, (ϵ_y) in an analogous manner.

E. Hand Control

The operator controlled the horizontal and vertical (x, y) dimensions of the tracking task with a pressure stick hand control, illustrated in Figure 8. The control was Model 435 DC manufactured by Measurement Systems, Inc. The x and y signals from the control stick were summed with the output of the associated random function generators and coupled to the dynamics of the simulated vehicle. A diagram of the pressure stick circuit is contained in Figure 9.

The control-display relationship was arranged in an "outside-in" configuration, i.e., the operator was required to move the control stick in opposition to the displacement of the control display lines and away from the illuminated peripheral display in order to restore them to their "on course" positions.

Figure 8. Pressure Stick Hand Control

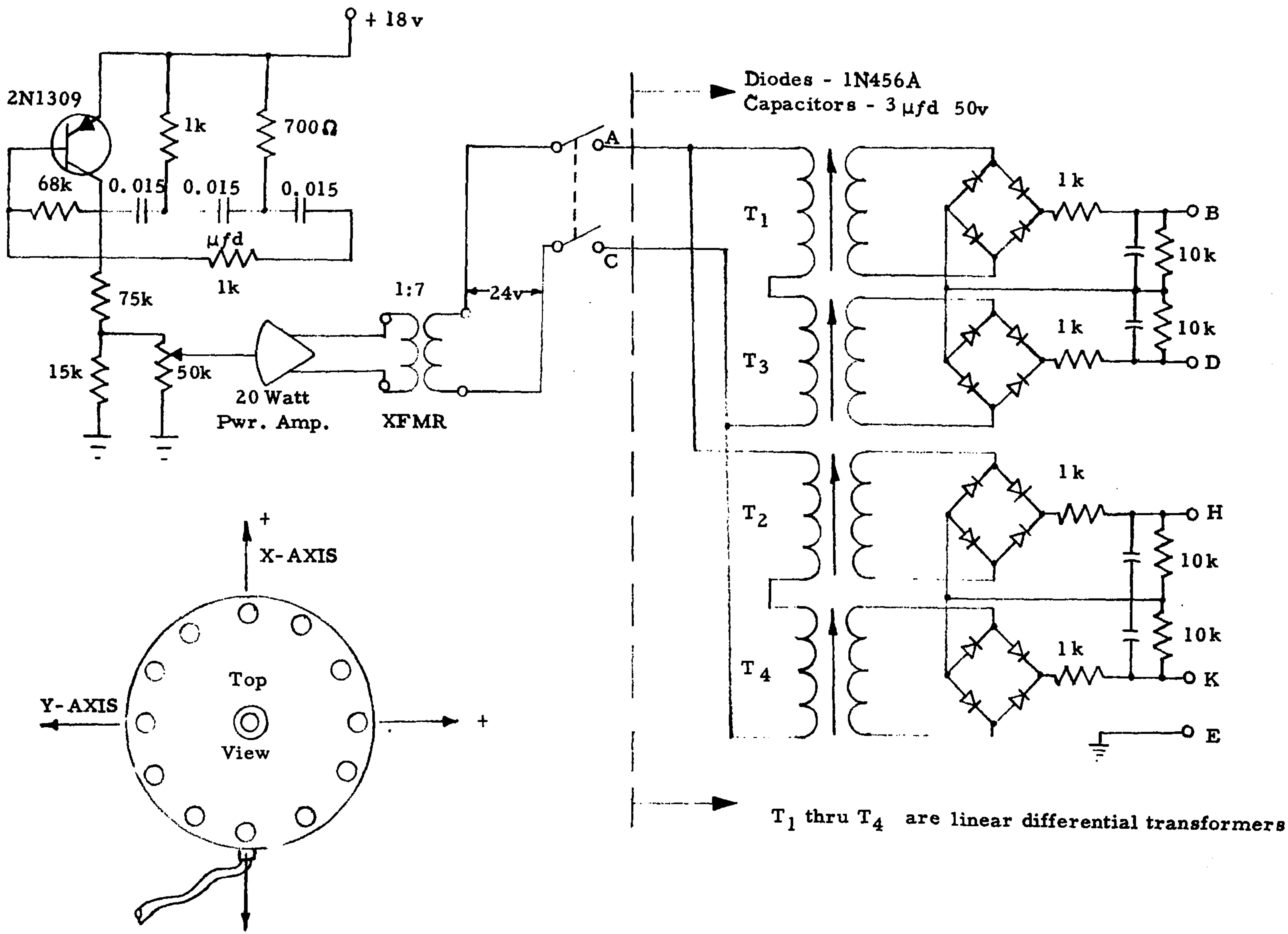


Figure 9. Pressure Stick Circuit

F. Performance Scoring System

The performance scoring system was designed to compute, on line, the integral of the sum of weighted absolute x and y errors. Analogue computing elements were used to perform the mathematical operations of summing, scaling, integration and absolute value. The value of the integral is denoted by S and is given below:

$$S = K_o \int_0^T \{ K_1 |\epsilon x| + K_2 |\epsilon y| \} \, dt$$

K_o = overall scale factor

K_1 = weighting factor for x-dimension error

K_2 = weighting factor for y-dimension error

T = period of integration (five minutes run time)

$|\epsilon_x|$ = absolute value of x-dimension error

$|\epsilon_y|$ = absolute value of y-dimension error

A computer diagram for the scoring system is shown in Figure 10. Figure 11 contains a photograph of the Performance Scoring Integrator. The experimenter obtained the value of S from the display on the right side of the unit at the completion of each trial.

G. Subjects

Eight subjects were provided by Dunlap and Associates, Inc., NASA-ERC, and the University of Bridgeport, to serve as operators during the experiment. Of these, two subjects (Numbers 2 and 8) had previous experience in tracking tasks similar to that used in this experiment. Subject Number 2 had extensive flying experience. Eyesight was tested using the Keystone Telebinocular and a Ferree-Rand Perimeter. Subjects who had less than normal central or peripheral vision were not allowed to participate in the experiment. Eyedness and handedness of subjects was determined and recorded. Every attempt was made to avoid smokers; however, subjects Numbers 1 and 8 reported they smoked one pack per day.

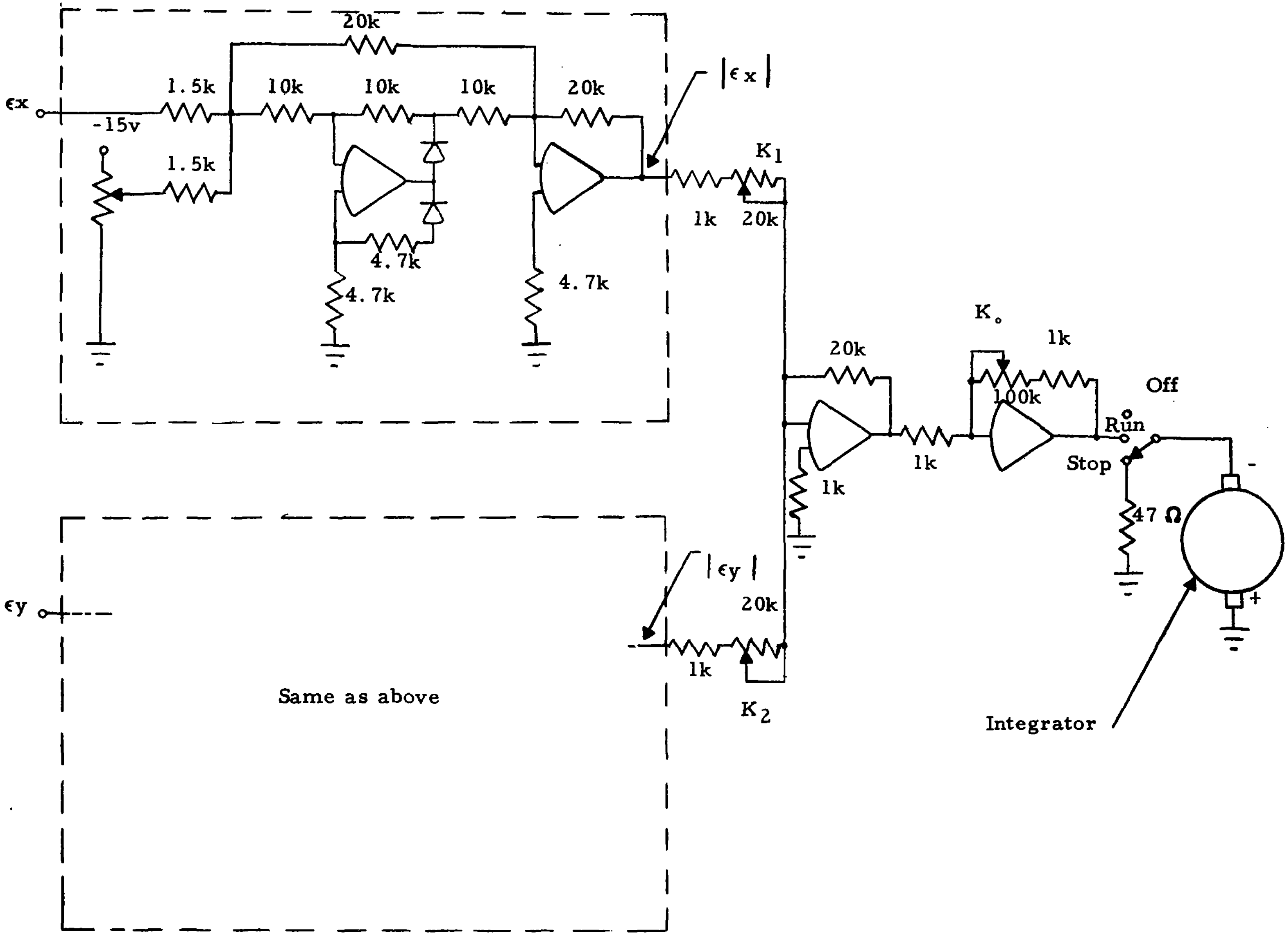


Figure 10. Performance Scoring Circuitry.

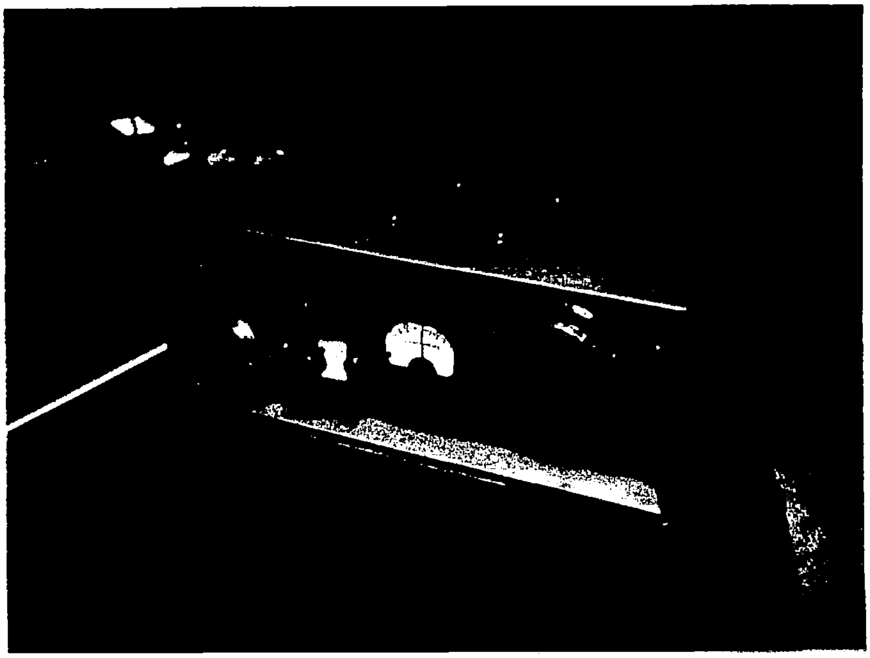


Figure 11 . Performance Scoring Integrator.

H. Procedure

The eleven experimental conditions were presented to each operator (Treatment x Subjects Design) in a different random order. In this way, it was possible to attentuate any learning and sequence effects or uncontrolled variations in the experimental environment which might adversely influence the results. The tracking problem was consistent for all conditions. Standard instructions were given to all operators. They contained an explanation of the overall purpose of the experiment, the tracking task and the operation of the control stick and displays. Care was taken not to bias the operator in any way; he was allowed to use any source of information displayed in his visual field provided he fixated only the central and not the peripheral displays. Each operator received one hour of practice on the various display configurations prior to his participation in the experiment. A score of 1500 on Condition I was used as the criterion to determine if the subject had reached an acceptable level of performance. All subjects attained this level within the allotted practice period. Each operator was also allowed to practice for a period of five minutes immediately before his experimental session. Each trial lasted for a period of five minutes. A five minute rest period was given between trials. The experimenter monitored the operator's eye movements to insure that he did not fixate any of the peripheral displays. Upon completion of each trial the experimenter recorded any such instances of "peeking" together with operator's error score. The experimenter also noted any comments made by the operator with regard to the various display configurations.

I. Results and Discussion

The primary results of the experiment are presented in Figure 12. Individual error scores for each subject are contained in Appendix C. Figure 12 contains the mean error scores for each experimental condition. The data appear to support the hypotheses developed above, viz: tracking performance improved with the use of peripheral vision displays during those conditions involving visual switching. As defined earlier, visual switching includes eye movement as well as accommodation and convergence.

The data was subjected to a series of analyses of variance to determine if there were sufficient differences between the mean error scores to warrant acceptance of the hypotheses on a statistical basis. The results of the analyses are presented in Tables I and II. The first analysis was performed to determine whether the differences between the mean error scores for the conditions not involving peripheral displays (A, D, I, and J) were real or could be accounted for on the basis of chance fluctuation of the data. The results of the analysis indicate that the means are significantly different from one another except for Conditions D and J. This appears to indicate that tracking with the integrated near/far displays were about as difficult as tracking with separate near/far displays. Rank order of these conditions in terms of average error scores was I, A, J, and D with Condition I yielding the best performance. This progression of difficulty correlates positively with the amount of visual switching required for a particular display configuration, i.e., as visual switching increased tracking error also increased in a similar manner.

The next analysis was concerned with the comparison of mean error scores for Conditions A, B, and C which, theoretically, should not be significantly different from one another since they involve little visual switching. In these conditions, both central displays were located immediately adjacent to one another at the same distance (76.2 cm.) in front of the operator. The operator, therefore, was not required to perform a great deal of visual switching to obtain tracking information. The results of this analysis indicate that the differences between the means can be accounted for on the basis of chance fluctuation of the obtained scores. Consequently, the addition of peripheral displays during Conditions B and C, as predicted, did not lead to a significant improvement in performance.

In contrast, during Conditions D, E and F the central displays were separated by 30° of visual arc and the upper display, presenting vertical information, situated at a greater distance (3.66 m.) from the operator. Here, the operator was required to switch between the two central displays which

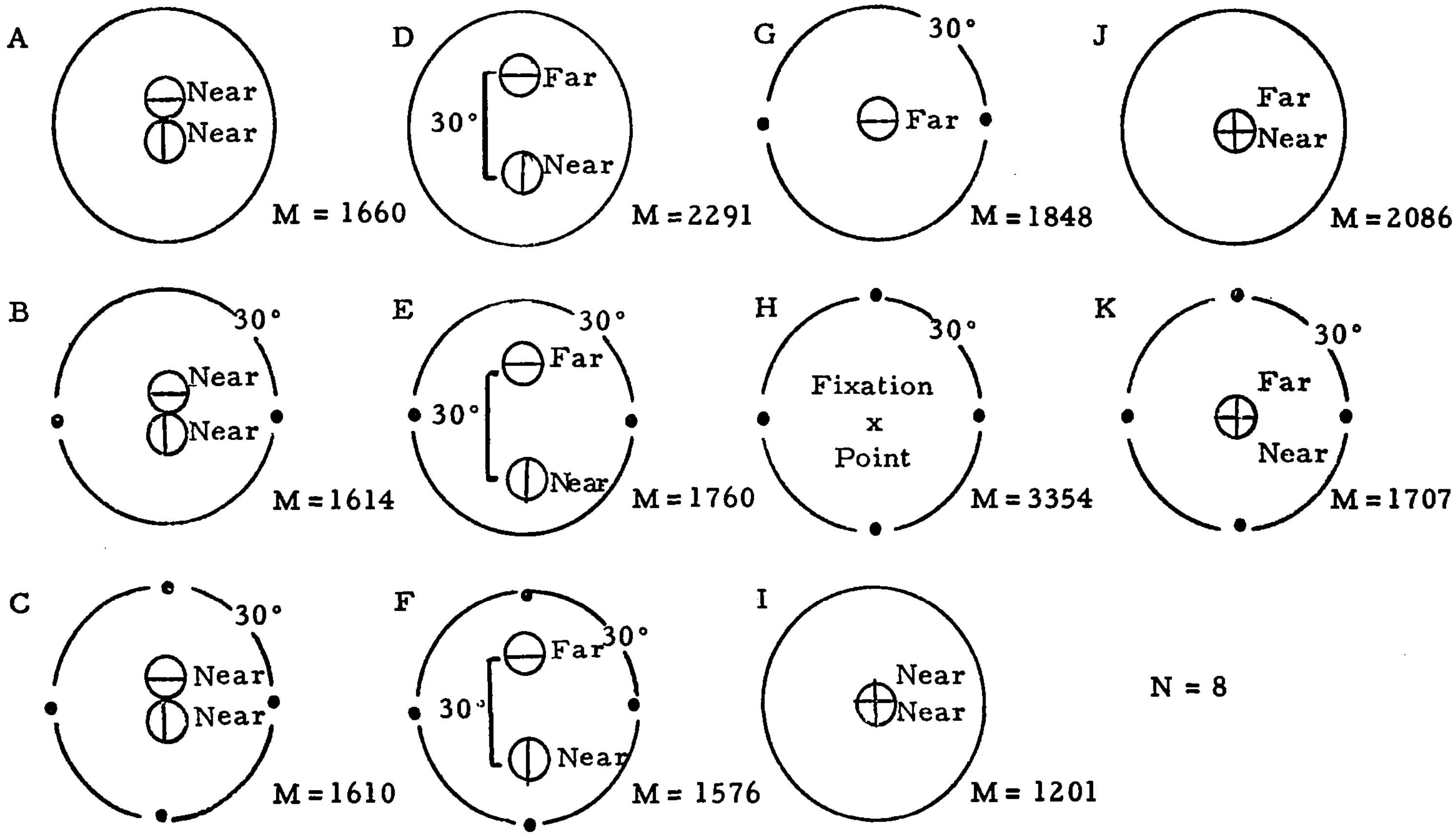


Figure 12 . Mean Error Scores For The Experimental Conditions.

accounts for the increase in tracking error obtained during Condition D. In Conditions E and F, however, errors decreased with the addition of peripheral displays. Here, the operators reported that they fixated one of the central displays (usually the upper one), and obtained information on the other tracking dimension through their periphery disregarding the other (usually the lower) central display. Visual switching between the two central displays was perceived as being an inefficient mode of operation when peripheral information was available to replace it. During Conditions E and F, almost no visual switching was observed by the experimenter. This was verified by the operators. The results of the analysis of variance, in which the mean error scores for these conditions were compared, yielded positive results as shown in Tables I and II. The differences between mean scores are real except for the difference between E and F. This appears to indicate that the operators worked in essentially the same manner during both of these conditions. The extra pair of peripheral displays for the far dimension during Condition F, therefore, was superfluous and was not used to any large extent. This was observed to be the case by the experimenter and reported by the operators on completion of their experimental sessions. There was also no tendency for the operators to fixate the peripheral displays during any of the conditions.

The next analysis was concerned with the difference between mean error scores for Conditions G and E. Condition G was similar to Condition E except that the operator was "forced" to utilize the peripheral displays to obtain horizontal tracking information. The results of the analysis indicate that the difference between the means is not significant and can be attributed to chance fluctuation of the scores. This finding appears to support the conclusion that the operators were using the peripheral displays for horizontal tracking information and fixating the far display for vertical information during Condition E.

Condition H was included in the experiment to obtain baseline data concerning performance with differential brightness displays alone. This condition, therefore, was not statistically compared with the other conditions of the experiment. Nevertheless, it was not surprising that performance with these displays was noticeably poorer than that obtained during any of the other conditions since the information content of the peripheral displays was significantly less than that of the central displays, regardless of their position in the visual field. The discriminable differences in brightness within the range (0-250 foot lamberts) provided by the peripheral displays did not exceed fifteen and more likely fell within eight to twelve steps. Furthermore, the majority of these discriminable steps were concentrated near the upper end of the error scale making precise control extremely difficult for the operator. On the other hand, the central displays each

Table I.

Summary of Analyses of Variance

HYPOTHESES	F - RATIO
A = D = I = J	19.5*
A = B = C	.1
D = E = F	14.5*
E = G	.3
I = J = K	11.1**
$Trial_1 = Trial_2 = \ldots = Trial_{11}$	.7

*P < .001
**P < .01

Note: The results of the individual analyses are contained in the Appendix.

Table II.

Differences Between Means for Individual Pairs of Conditions

Condition

Condition	B	C	D	E	F	G	I	J	K
A	-46	-50	+631*				-459*	+426*	
B		-4							
D				-531*	-715*		-1090*	-205	
E					-184	+88			
I								+885*	+506*
J									-379**

*P < .05
**P < .10

occupied 345' of visual angle providing a potential of over 150 discriminable steps from the center or zero error position to its circumference based on simple resolution or acuity measures. Since the display had less than optimum contrast and no reticle lines were provided, it could be conservatively estimated that approximately one third of the maximum number of discriminable steps (about 50) were available as cues to the operator. As a crude comparison, therefore, it would be expected that the operator could derive over three times as much error information from the central displays alone as he could from the differential brightness displays. The optimum relationship between brightness changes in the periphery and input error is unknown at the present time and beyond the scope of this experiment.

In Conditions I, J, and K, both vertical and horizontal tracking information were combined into a single central display, i.e., the vertical line was optically superimposed over the horizontal line. Here, the operator's task was quite different than that found in the previous conditions since he merely had to "null" the intersection of the two lines rather than to "null" each line separately, i.e., the integration of the two information sources was performed on the display rather than by the operator mentally. Conditions I, J, and K, therefore, should have placed fewer demands on the operator because of reductions in the requirements for mental integration as well as eye movements. This was found to be the case, as indicated above, where mean performance during Condition I was found to yield the best performance among all the conditions. In this condition, both dimensions were located near (76.2 cm.) the operator. In Condition J, however, the vertical dimension was placed in the far location (3.66 m) and was proportionately larger than the near dimension, i.e., the elements of both central displays subtended the same visual angles at the operator's eyes. Here, performance deteriorated as indicated by the large increase in the mean error score. Since eye movement was not a predominant factor, the deterioration must be due to time lost in visual accommodation and convergence only. The difference between the mean scores for Conditions I and J were found to be highly significant. With the addition of peripheral displays during Condition K, however, performance improved by a significant amount. As explained by the operators, the double images and the requirements for refocusing made the "combined" display configuration difficult to use when one dimension was moved to the far position. By adding the peripheral lights, the far display could be fixated and the lights used to obtain information on the other tracking dimension disregarding the near display.

The final analysis of the data involved an investigation of systematic effects on tracking performance due to practice and fatigue during the experiment. As mentioned above, the conditions were given to each subject in a different random order in an attempt to attenuate and balance out these effect.

To carry out this analysis, the obtained error scores were first arranged in terms of the order in which they were given to the subjects. This arrangement of scores is contained in Appendix C. The data were then analyzed for sequence effects using standard statistical techniques. The primary results of the analysis are also reported in Table I. They indicate that the differences between trial means can be accounted for on the basis of chance fluctuation of the data and that there appears to be no systematic trends which could be explained in terms of practice or fatigue. It would appear appropriate to conclude, therefore, that these factors did not affect performance significantly during this experiment.

J. Summary and Conclusions

Time lost in visually switching between displays designed for central vision was shown to seriously affect man's ability to perform complex control tasks. It was also shown that peripheral vision displays can be successfully utilized to improve performance in such tasks. In general, the contribution of peripheral displays to improved performance appears to be attributable to a reduction in visual switching which was defined as including eye movement as well as accommodation and convergence. Redundant information provided peripherally, however, does not contribute to performance on tasks requiring little or no visual switching among displays designed for foveal viewing. It would appear reasonable to conclude, therefore, that peripheral displays may have special applications in such tasks as landing high performance aircraft, in operating airborne weapon systems while flying at supersonic speeds, or maneuvering and rendezvousing spacecraft using multidimensional control systems.

IV. PHASE II--DESIGN OF PERIPHERAL VISION DISPLAYS

During Phase I of the research program, visual switching was demonstrated to be the critical factor involved in the use of peripheral vision displays. Phase II of the program is being devoted to the identification of the most suitable methods for encoding and positioning information in the periphery. To accomplish this objective, it is first necessary to examine the state-of-the art, to understand the psycho-physical properties of the peripheral mechanisms and the role that peripheral vision plays in everyday life.

A. Role of Peripheral Vision in Everyday Life

In our daily experiences, peripheral vision is used to obtain information about our environment. For example, when driving at high speed on a super-highway, we use our peripheral vision to note the relative speeds and positions of cars on either side of us while keeping our eyes on the cars ahead. Peripheral vision makes available to a man more information at any one time than would be available with central vision alone. To the extent he is able to use it, he is likely to perform better. The validity of this statement will be attested to by anyone who has had to work with his hands while wearing protective glasses or a face mask that restricts his field of view. Peripheral vision is particularly important in performing control tasks that require a man to move himself or manipulate objects in a spatial environment. Peripheral vision is also important to men performing tasks that require them to monitor many sources of information in order to detect occasional alerting signals as, for example, an engineer in a control room of a processing plant or a pilot of an aircraft or space vehicle. Clearly, information, used to perform a variety of everyday control and monitoring tasks safely and efficiently, is obtained via peripheral vision.

In the field of aviation, there are numerous studies which point out the key role that peripheral vision plays in controlling aircraft. As early as 1918, Fridenberg (in Hopkin, 1959) stated that too little attention was being given to the role of vision in orientation. He wrote: "The sharpness of the sense of motion. . . a function of the periphery of the retina that has been studied but little." Since that time, numerous studies (reviewed by Berens and Sheppard, 1953 and Hopkin, 1959) have verified the key role that peripheral cues play in maintaining balance, equilibrium and orientation in the air. Postural cues in the absence of vision were found to be inadequate as a guide to the vertical in the flight situation despite some indications to the contrary in the ground based laboratory. In addition, tactile-kinesthetic cues as a reference to the vertical were discovered to be highly subjective in nature and easily disorganized. Research has also shown the importance of visual cues over vestibular and kinesthetic cues in the detection of movement and rotation of the body.

Grindley (1941) emphasized the role of peripheral vision and investigated the pattern of velocities in the visual field as a clue to height when landing an aircraft. Gibson (1947) also studied the peripheral environment and its velocity patterns. He (1950) related banking and pitching to corresponding peripheral movements and plotted the velocity gradients involved. Calvert (1954, 1955) and Gibson (1954, 1955) performed further work on the expanding visual pattern during landing of an aircraft. They explain that, in landing, objects in the visual field appear to expand or radiate from a point to which the aircraft is flying. Objects in the scene appear to flow from this point toward the periphery of the retina in the form of a "multitude of motion parallaxes" (asymmetrical expansion). The velocity of expansion increases from zero at the aiming point and then decreases again to zero at the horizon. The expanding pattern, together with the horizon, enables the pilot to judge his position in space and his rates of closure and descent. Calvert (1954, 1955) refers to the expansion pattern of velocities as "parafoveal streamers." He states that streamers are similar to those on the retina of the pilot's eye only so long as he looks along the center-line in a fixed direction in space, and that this is why pilots stare straight ahead during the final portion of the approach and during landing.

Wulfeck, et al. (1958) and Hopkin (1959) reviewed the research dealing with eye movements during landing. Wulfeck states: "Data on eye movements seem to indicate that the pilot during landing is largely occupied with watching this zero point in the expansion pattern. Since he never looks at the runway under him, he must judge his height (1) from perspective and (2) from differences in apparent movement (movement gradients) in the expansion pattern--including the portions of the pattern in the periphery of the visual field. For example, the apparent movement of the ground under the aircraft (or as nearly under it as the pilot can see) relative to the surrounding land is a function of his height, and the rate of increases in this relative apparent movement is a function of this rate of descent." Calvert (1955) points out that distractions of any kind which cause the pilot to move his eyes or head will reduce the accuracy of his rate judgements. Similarly, the difficulty pilots experience in estimating height and rate during approaches over featureless terrain (e.g., sea, desert) is related to indefinite streamers which increase the probability of over- or under-shooting the runway or carrier.

In a study carried out by Gainer and Obermayer (1964), pilot eye fixations were recorded while flying various maneuvers using two instrument panels. While analyzing the film records, it was discovered that in four instances, while using vertical instruments, skillful level-offs were achieved without fixating the rate of climb, altimeter, or altitude planning scale. Since altitude information is absolutely necessary to perform an accurate and skillful level-off, they concluded that peripheral access of information must have occurred and that "this particular set of instances lends credence to making use of peripheral vision in flying instruments..."

In 1955, Senders, et al., noted "that the amount of time spent by pilots in reading of any particular instrument in flight is much shorter than the time taken by Ss in a laboratory situation." One explanation offered to account for this phenomenon was that peripheral images of the instruments were conveying some information to the pilot which allowed him to make a qualitative check reading in accordance with his set of expectancies developed through previous experience. As a result, a study was carried out to investigate the ability of subjects to see the pointer position for four types of pointers at various locations in the periphery. No differences were found between pointers; however, the ability to discriminate pointer position for displacements as much as 40° from the point of fixation was good. Observers could discriminate settings differing by 45° almost perfectly out to 40° displacement when pointer movement was limited to less than 180° or the rate of change was slow. Even at 80°, readings were correct twice as often as they would be by chance alone. In 1958, Haish also was concerned with the "extrafoveal discriminability" of visual cues used in flight instruments. He concluded that "linear cues are greatly superior to area cues..."

Numerous other studies in the field of aviation also emphasize the key role that peripheral vision plays in controlling aircraft. It can be concluded that information, used to perform a variety of every day control and monitoring tasks safely and efficiently, is obtained via peripheral vision.

B. Psycho-Physiology of Peripheral Vision

The size of the visual field is limited by the dimensions of the functional retina as well as the shape of the cornea, the nose, cheek bones, eyebrows and other features of the face. The outline of the average binocular field is illustrated in Figure 13. The overlap of the fields of the two eyes is indicated by the unshaded area in the figure.

1. Anatomy of the Retina

The retina is a light-sensitive layer that receives radiant energy from the environment and changes it into nerve impulses which are, in turn, transmitted to the brain to create the visual sensation. The transformation of energy occurs in the photosensitive receptors of the retina. The receptors and their neural transmitters consist of two systems, the cone system and the rod system. The two systems differ in structure, in distribution on the retina, and in function. At high levels of illumination, the cone system is functioning and both color and detail can be seen (photopic vision). At low levels, only the rod system functions and objects are seen as colorless shades of gray with very little or no detail (scotopic vision).

. Cone System

Cone receptors are evenly distributed over the entire retina layer (see Figure 14) except for high concentrations in the central area (fovea) and the extreme edges. The greatest number of cones are located in the center of the fovea (fovea centralis) which is the area of highest acuity. It subtends about 5° of visual angle ($\cong$ 1.50mm in diameter). The density of cones near the extreme periphery of the retina (ora serrata) is comparatively large, but this area is little used in vision. The cone receptors in the fovea are connected individually to the brain, while the cones outside the fovea are linked together with other receptors (cones, rods, or both) to form single neural pathways.

The cones contain a photosensitive substance called iodopsin which changes chemically when it is stimulated by sufficient light. They respond to a wide range of light intensities and can adapt or adjust their sensitivity from about .003 mL to high levels of illumination (Wulfeck, et al., 1958).

. Rod System

The rod receptors are not evenly distributed over the retina (see Figure 14). The central area of the fovea, subtending approximately 1° of visual area, contains no rods. From this area out to about 18 to 20° they increase rapidly and then gradually decrease to the outer edge of the periphery. Rods are not individually linked to the optic nerve pathway, but are connected in groups to a single nerve cell which is joined to another nerve cell that sends a fiber to the brain.

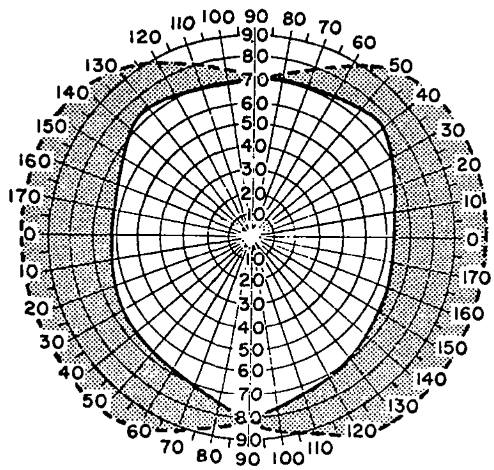


Figure 13. Binocular Visual Field.
(in Wulfeck, et al., 1958)

The fields of the two eyes overlap in the white area.

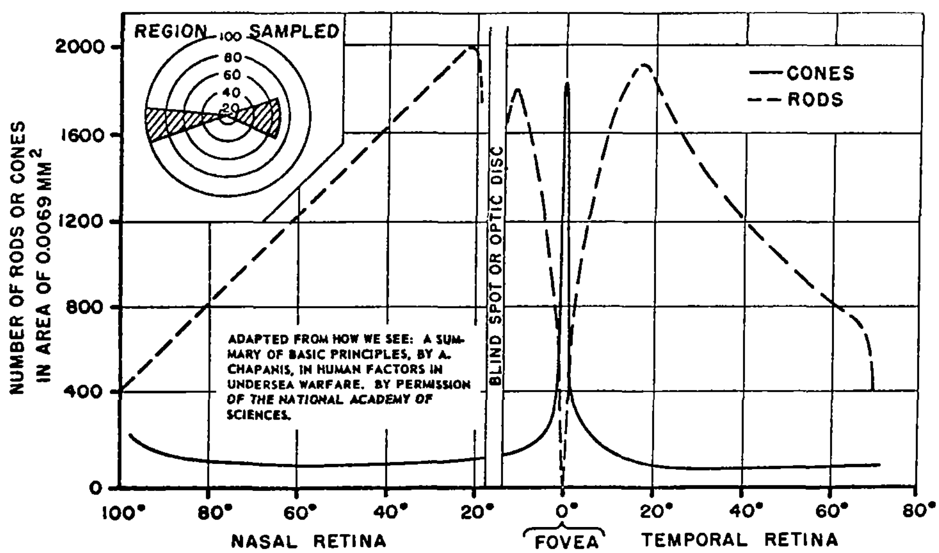


Figure 14. Density of Rods and Cones from Nasal to Temporal Edge of Retina. (in Wulfeck, et al., 1958)

Rods are sensitive to lower levels of illumination than are cones and contain a highly photosensitive material called phodopsin which breaks down at very low light intensities. Since several rods are connected to a single nerve fiber, impulses from several rods can combine to increase sensitivity to low levels of illumination. The rods lose their sensitivity to dim light when rhodopsin is broken down due to exposure to relatively bright light. Approximately 35 minutes is required for them to recover their full sensitivity (complete dark adaptation). The sensitivity of the rod system, however, varies over the retina. The most sensitive area is 18 to 20° from the fovea, the zone of highest density.

. Optic Disc

The retina contains few or no receptors in the area where the optic nerve fibers leave the eyeball. This area is referred to as the optic disc or blind spot. It is located approximately 15° from the fovea on the nasal side of the retina (see Figure 14). In binocular vision, the blind spot of one eye is "filled in" by the other.

2. Visual Performance in the Periphery

Visual sensitivity varies with the location of an image on the retina of the eye. Performance in the peripheral field depends on the angle subtended by an object and its absolute brightness as well as its distance and direction from the line of sight, its contrast with its background, its color, its movement and duration of exposure, its familiarity, etc. These and other aspects of visual performance are discussed below.

. Light Discrimination

Light discrimination includes brightness sensitivity, brightness discrimination and color perception. Brightness sensitivity is the ability to detect a very dim light; brightness discrimination is the ability to detect differences or changes in light intensity; and color perception is the ability to detect wavelength of radiant energy in the visible spectrum.

- Brightness Sensitivity

Different regions of the retina are approximately equal in sensitivity to light at high (daytime) levels of illumination. At low (night) levels of illumination, however, the center of the eye (fovea) is not sensitive to dim lights. Under these conditions, sensitivity increases toward the periphery as illustrated in Figure 15.

The eye sees best in the zone 10 to 20° from the line of sight in almost all directions. Brightness sensitivity depends on the degree of dark adaptation of the eye; sensitivity increases with dark-adaptation time. Figure 16 indicates how eye sensitivity varies as a function of the time in the dark and the region of the retina stimulated.

As pointed out above, approximately 30 to 35 minutes of darkness are required for maximum rod sensitivity. Brief exposure to low illumination reduces the sensitivity of the rods far more than that of the cones. The rods require two minutes to recover from a 100-ft.-L-sec. exposure of light. Sensitivity also differs from one location in the periphery to another. At 2° from the fovea, exposure to 0.01-ft.-L-sec. produces a measurable decrease in sensitivity. At 6 and 18°, there is little loss after exposure to as much as 0.1-ft.-L-sec.

- Spatial Summation in the Periphery

A small bit of a surface of uniform objective brightness appears less bright than a larger bit. Perfect spatial summation would require the same quantity of light to be barely perceptible regardless of the size of the stimulus and area and brightness would be interchangeable factors in perceptibility (Ricco's Law, $I \times A = K$). The degree of summation, however, is imperfect. Pieron (1929) found that $I \times A^{0.3 - 0.5} = K$ expressed the degree of summation in the fovea. In the periphery, however, no simple power function of the form $I \times A^{k} = K$, can be considered an adequate description of the area-intensity relation (Graham, Brown and Mote, 1939), i.e., the equation used changes from one position in the visual field to another depending on the distance from the fovea (deGroot, Dodge and Smith, 1953). In general, the degree of summation increases towards the periphery of the retina (e.g., Beitel, 1934; Gross and Weiskrantz, 1959). The further from the fovea the stimulated area, the broader it could be and still show some summation. Sensitivity, therefore, must be expressed in terms of size, brightness, and location on the retina.

There are numerous reports in which binocular and monocular absolute thresholds under dark adaptation have been compared. Approximately half conclude they are equal while the remainder state that binocular threshold is lower.

- Spectral Sensitivity

The difference in sensitivity of rods and cones over the visible spectrum is shown in Figure 17. The maximum sensitivity shifts

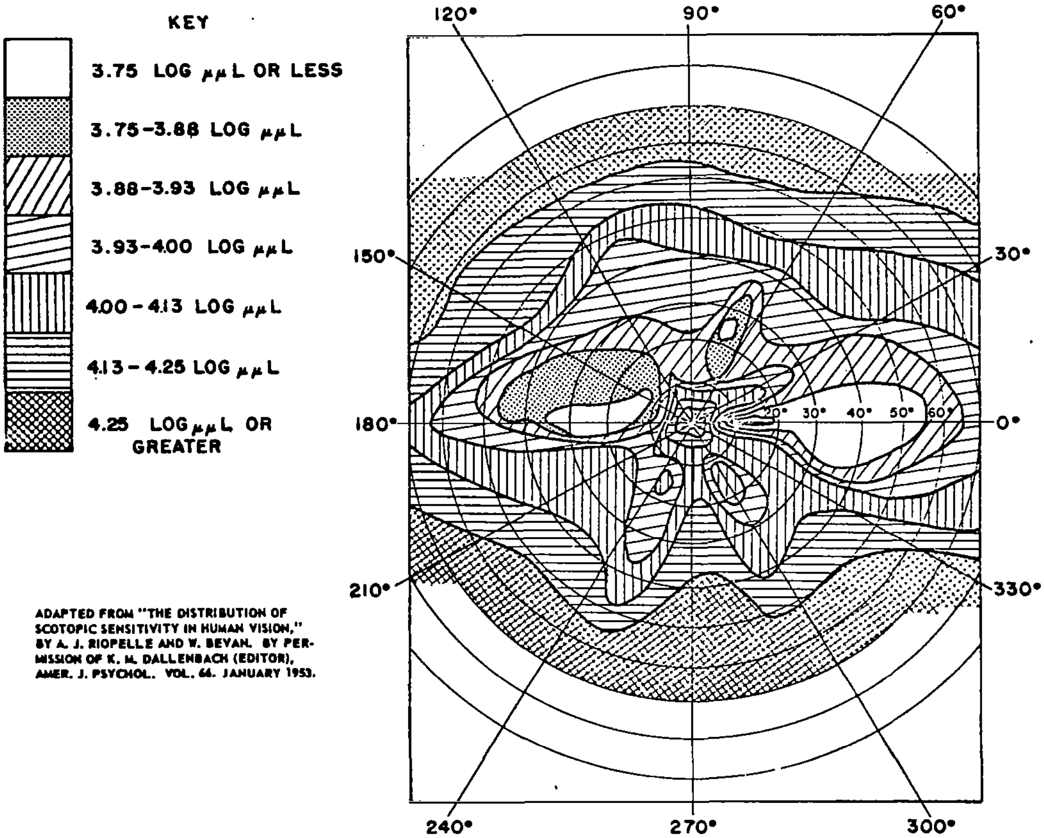


Figure 15. A Map of Sensitivity to Light for the Visual Field of the Dark Adapted Right Eye. (in Wulfeck, et al., 1958)

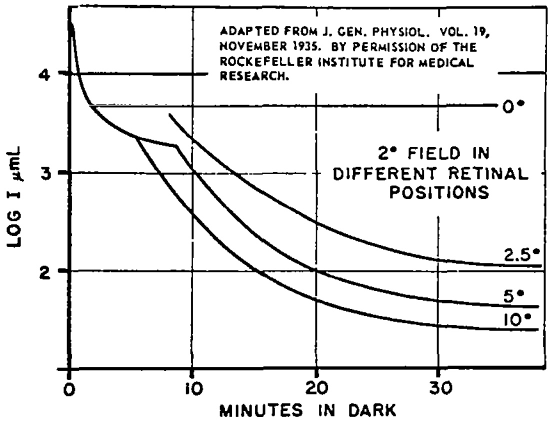


Figure 16. Dark Adaptation as a Function of the Region of the Retina Stimulated. (in Wulfeck, et al., 1958)

Dark-adaptation curves measured with a 2° test object placed at various angular distances from the fixation point.

from 555 $m\mu$ for cone vision to 510 $m\mu$ for rod vision. This shift is gradual as the level of illumination is decreased (Purkinje shift). Generally, the rods require less radiant energy for vision than cones. The rod response, however, is colorless (achromatic) while the cones response is chromatic.

Figure 18 illustrates the photopic and scotopic relative luminosity curves. The curves indicate that different parts of the spectrum do not appear to be equally luminous even though the light source emits equal radiant energies at all wave lengths. The scotopic curve is based on the dark adapted eye. The photopic curve is based on intensities well above threshold.

Wulfeck, et al. (1958) also replotted the relative luminosity curves in terms of the amounts of energy involved, as shown in Figure 19. The rods are found to be as sensitive as the cones to long wave lengths up to approximately 660 $m\mu$.

Brightness Discrimination

Brightness discrimination is the ability to detect small changes in the amount of light or small differences between light sources. The difference between the brightness of an object and a background of the same hue is referred to as brightness contrast. Brightness contrast is equal to $\Delta B/B \times 100$, where ΔB is the difference in luminance between an object and its background and B is the luminance of the background. Threshold contrast is the least contrast required to detect an object against its background. As shown in Figure 20, contrast threshold decreases as luminance increases until it attains a limit at a high level of illumination. The eye, therefore, can detect differences easier as the level of illumination increases. Notice that the change from rod to cone vision causes a change in the slope of the curves. As shown in Figure 21, the contrast threshold also depends on the region of the retina stimulated. Contrast discrimination also increases with the size of the test object.

The threshold for simultaneous brightness contrast, in general, is found to be greater in the periphery (3° or 6°) than in the fovea. Contrast also increases with prolonged viewing and with blurring of the stimuli (Burgh, 1964).

Color Vision

The color of an object varies with its position in the visual field. At moderate levels of illumination, all colors appear as grays at the extreme edges of the field. A little farther in, a blue or yellow can be recognized, but only at positions near the center can a red or green be observed. As shown in Figure 22, only in a restricted area in the center of

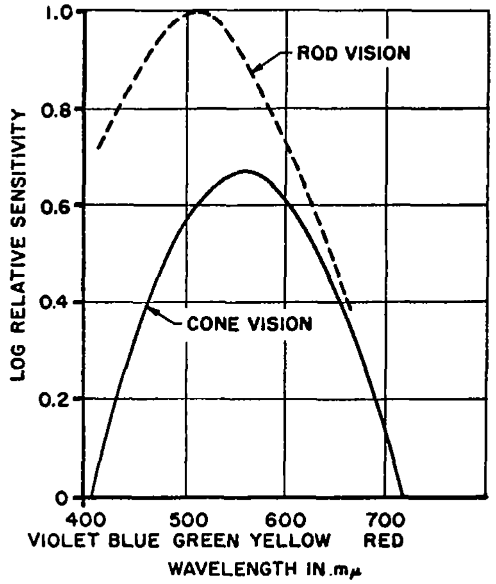


Figure 17. Spectral Sensitivity Curve.
(in Wulfeck, et al., 1958)

Relative sensitivity to radiant flux as a function of wavelength.

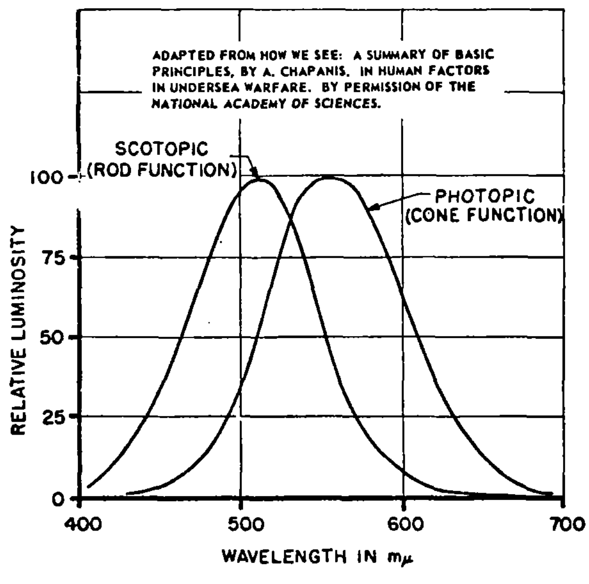


Figure 18. Photopic and Scotopic Relative Luminosity Curves. (in Wulfeck, et al., 1958)

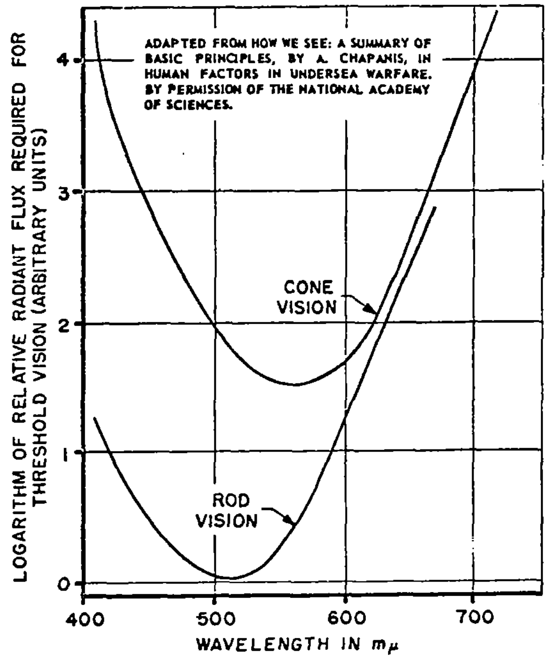


Figure 19. Relative Amounts of Radiant Flux Required to Stimulate the Rods and Cones. (in Wulfeck, et al., 1958)

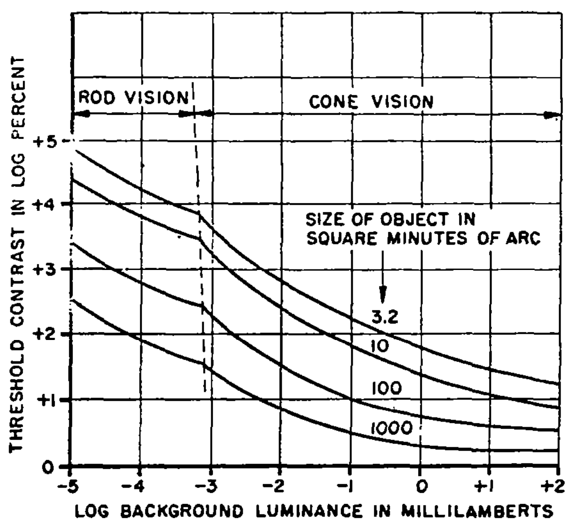
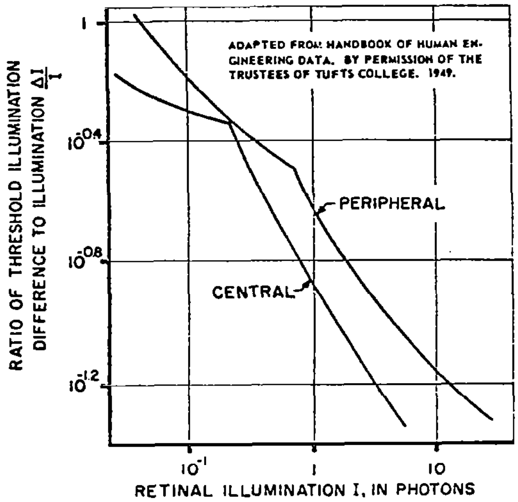


Figure 20. Contrast Discrimination Curve--The Smallest Brightness Contrast that Can be Seen, as a Function of Background Luminance. (in Wulfeck, et al., 1958)



Just noticeable difference in retinal illumination as influenced by illumination for foveal and peripheral vision. In peripheral vision, where rods predominate, transition from rod to cone vision occurs at higher illumination level. Discrimination in generally poorer in periphery than in center of visual field.

Figure 21. Contrast Threshold as a Function of Region of the Retina Stimulated. (in Wulfeck, et al., 1958)

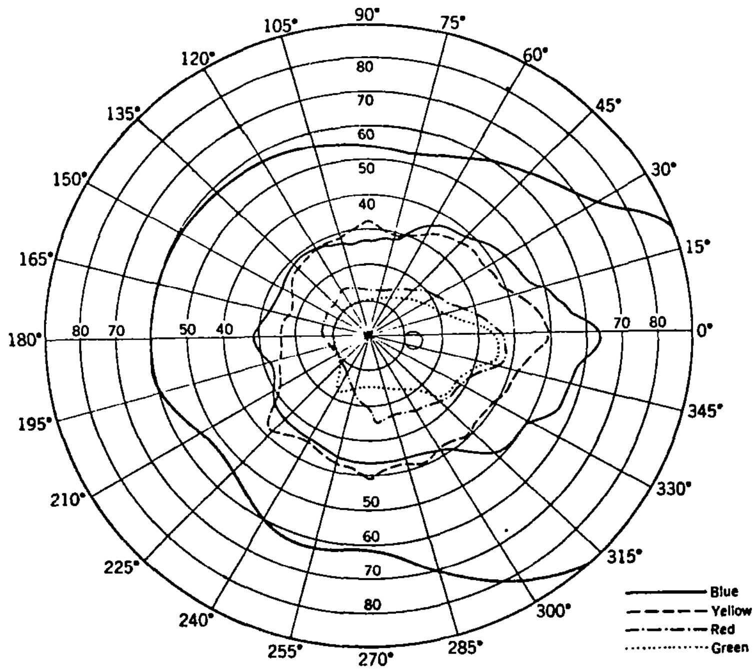


Figure 22 Chart of the Retinal Color Fields. (in Geldard, 1953)

The limits of the visual field of the right eye for each of the colors blue, yellow, red, and green when the test object is a small, homogeneous patch of light of moderate intensity.

the field can all color be seen. Outside of this central zone, no red or green is visible as such, but blue and yellow can be recognized. Even blue and yellow cannot be seen toward the extreme periphery at moderate levels. At high intensities, however, red, yellow, and blue are visible at the extreme edge of the periphery. Green cannot be seen in the extreme periphery even at very high brightness (Rinde, 1932, in Geldard). The limits of the color zones are also not smooth but show irregular peaks and dips and do not have sharp cutoffs in sensitivity (Kelsey and Schwartz, 1959). The peaks and dips are reliable for any given person, but are different from one person to the next.

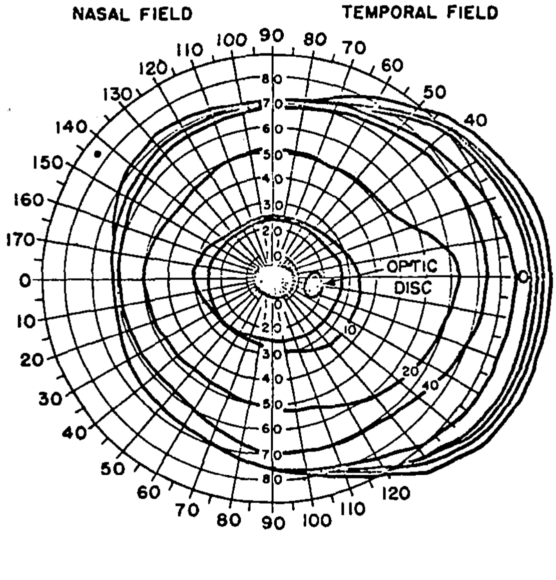
Spatial Discriminations

Differences in wave lengths and intensities of light produce outline and form to images striking the retina. Spatial discrimination is the ability to see these images sharply and to judge their locations and relationships in the environment. It includes such factors as visual acuity, form discrimination, movement discrimination, and depth discrimination. Tests of these factors involve the use of lines, dots, point sources of light, and abstract shapes. It is known that previous experience affects the perception of relationships and form especially when images are blurred or barely above threshold.

Acuity

Visual acuity is the ability to see detail. There are many different types of acuity measurements: minimum visible, minimum perceptible, minimum separable, and minimum distinguishable. Acuity, therefore, varies widely, depending on the type of measurement involved. A chart of relative acuity for monocular vision is presented in Figure 23. Acuity is best within the center of the field of view (fovea). The figures on the rings (isopters) in the figure indicate how many times larger an object must be in order to be seen clearly in that position as compared with the fovea. The figure indicates that, under daylight conditions, acuity decreases in all directions from the center toward the periphery of the retina. Notice also that all meridians do not have the same acuity. In general, the horizontal meridian exhibits best acuity and the vertical the poorest. Hence, measurement of peripheral acuity made along one meridian may not be applied to any other meridian.

The curve in Figure 24 also shows size threshold as a function of retinal position for daylight levels of illumination. Notice that size threshold also increases as a function of the distance from the area of the fovea, i. e., if an object is large enough, it can be detected at greater distance from the fovea. A target twice the threshold size for central vision can be detected over an approximately 10° cone in the periphery (Koomen, 1954, in Wulfeck, et al.). A target four times threshold size can be detected anywhere in an approximately 26° cone.



ADAPTED FROM TRAQUAIR'S CLINICAL PERIMETRY. 1957.
BY PERMISSION OF HIRSCHFELD BROTHERS, LIMITED

Figure 23 . Monocular Daylight Acuity Relative to Central Acuity. (in Wulfeck, et al., 1958)

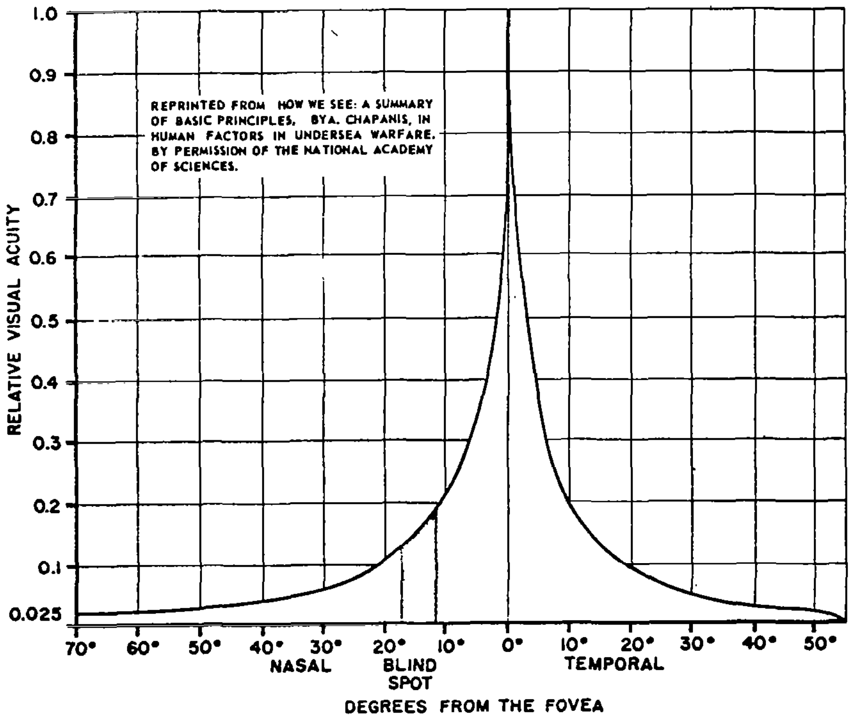


Figure 24 . Curve of Daylight Visual Acuity for Different Parts of the Eye. (in Wulfeck, et al., 1958)

Mandelbaum and Sloan (1947) studied peripheral visual acuity in the temporal area of the retina using Landolt Rings. The primary results of their research are presented in Figure 25. The curves in the figure indicate that at

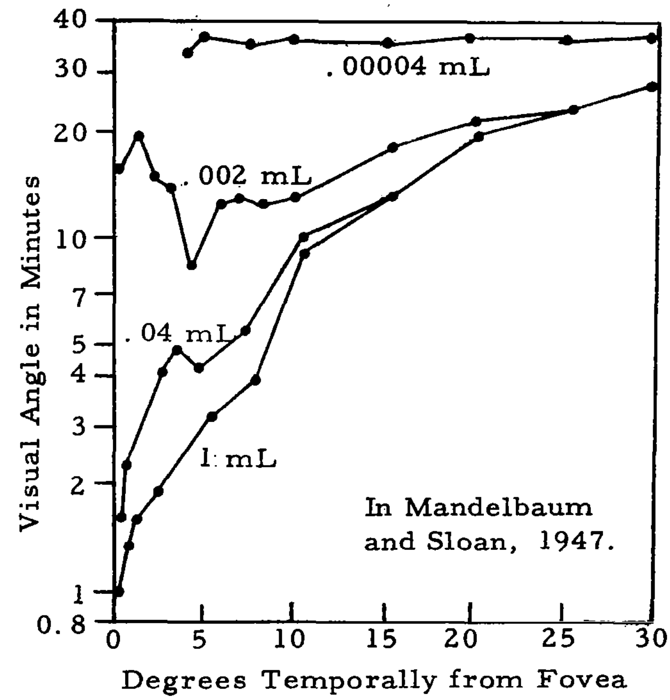


Figure 25. Visual Acuity and Retinal Location.

higher levels of illumination (1 mL), acuity is best in the fovea and then rapidly decreases out towards the 30° area in the temporal periphery. The correlation coefficient between central and peripheral acuity is 0.38 at 30° from the fovea (Low, 1943). However, at low levels, maximum but poor acuity occurs between 4 to 8° from the fovea. At very low levels, visual acuity is generally poor across the entire temporal periphery.

Curves in Figure 26 show visual acuity as a function of luminance and retinal location. Larger objects can be discerned at both 4 and 30° from the fovea under very low levels of illumination. At 30°, however, acuity does not improve at levels just above those where foveal vision begins. In this area of the retina, the smallest angle that can be discriminated is approximately 30 minutes. At 4°, acuity improves with increased luminance up to 1 mL, but is still worse than acuity in the fovea. A minimum of three minutes of visual angle can be discriminated at this location (4°) compared to only one minute for the fovea. This would be expected since the density of rods is greater at 4 and

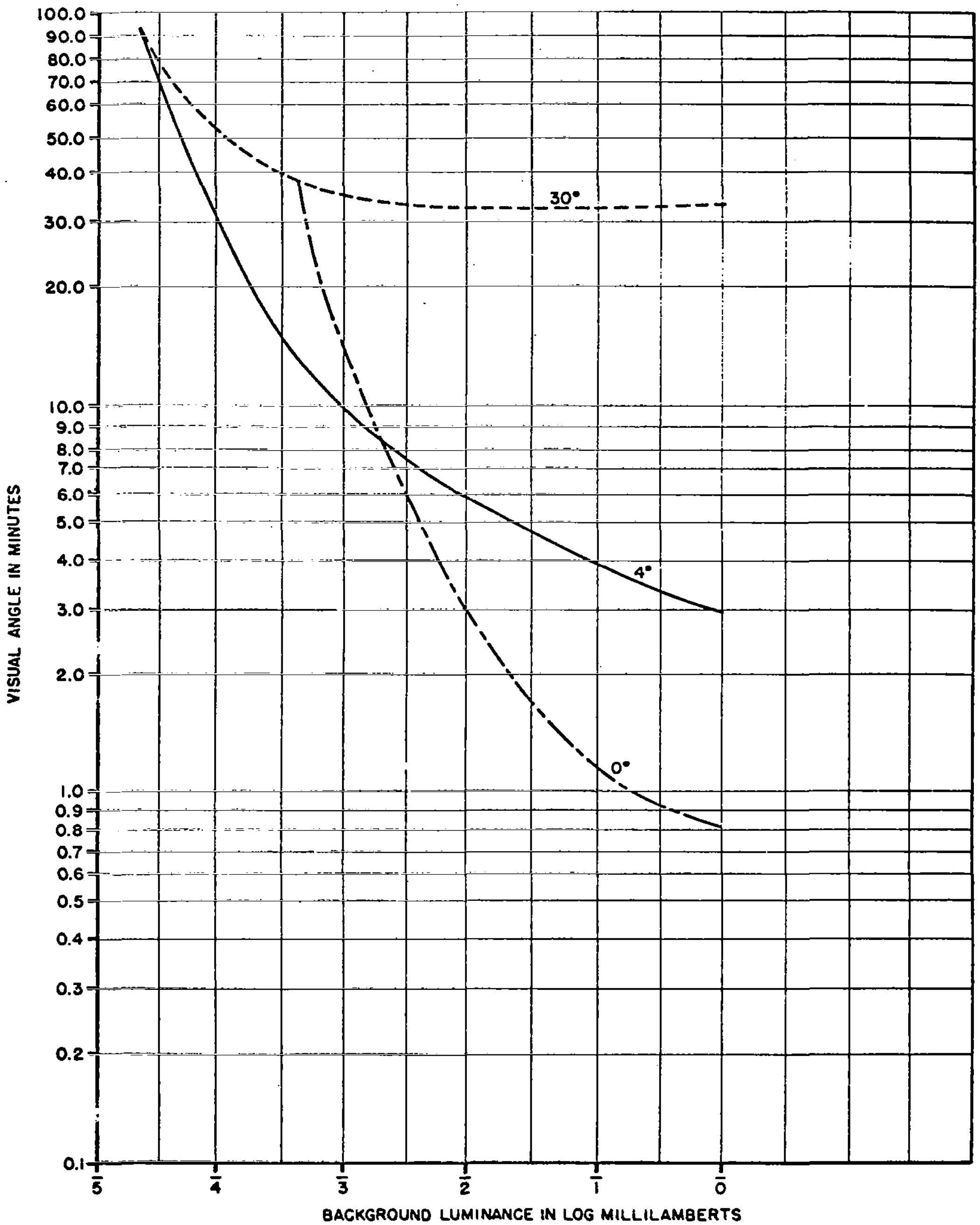


Figure 26. Visual Acuity Curve. Visual Angle Subtended by Smallest Detail that Can be Discriminated, Plotted as a Function of Background Luminance. (in Wulfeck, et al., 1958)

Curves are shown for discriminating images at 0°, 4°, and 30° away from visual axis on retina.

30° while more cones are located at 4° than 30° (see Figure 14). In general, beyond 30° there is little difference between photopic and scotopic acuity.

Acuity of moving objects in the periphery is half that of a stationary object (Low, 1947). The ability to discern detail within a moving object also decreases as the distance from the fovea increases. Beyond 60°, it is unmeasurable.

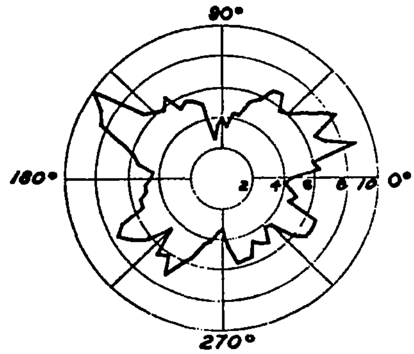
- Temporal Factors Affecting Visual Acuity

During fixation, peripheral stimuli may disappear or vary without any apparent reason. This phenomenon is known as the Troxler Effect" after its original discoverer in 1804. Both stationary and moving stimuli are affected (Low, 1943, 1946a, b and 1948). These fluctuations are independent of efforts to attend or concentrate on the peripheral stimulus and are greater, regardless of practice, for individuals with good acuity.

More recent work on the Troxler Effect (Clarke, 1957, 1960, 1961) indicates that an image desaturates and loses detail immediately after viewing in the periphery and then, after a delay of a few seconds, begins to decrease in brightness very rapidly until vanishing. The effect is the same for white on dark or dark on white stimuli regardless of the level of dark adaptation and the wavelength of light. Fading characteristics do, however, seem to be somewhat affected by the size and eccentricity of the stimulus.

- Localization

Localization is the ability to determine the position of a target. Provided the target is above threshold, localization accuracy has been shown to be independent of luminance and exposure duration, but does vary with its radial position (Liebowitz, Myers and Grant, 1954). Localization error in degrees of arc for various radial positions is shown in Figure 27. Localization accuracy is best above, below, left, and right of fixation, and poorer on the radii in diagonal directions from fixation. These results were verified by Attneave (1955). Harcum (1958) also found that accuracy is poorer along the diagonal radii with easily detected targets, but worst along the vertical meridian with less detectable targets. He (1959) also found detection better along the horizontal meridian than along the veritcal meridian. In general, localization accuracy is better hear both the vertical and horizontal meridians than at the



In Leibowitz, Meyers, and Grant, 1954.

Figure27 . Mean Localization Error in Degrees of Arc for Various Radial Positions.

diagonal meridians; the vertical and horizontal meridians are nearly equal, provided targets are above threshold levels of brightness. Karn and Gregg (1961) studied the effects of location on visual perception of elements of a stimulus complex. They found that more errors are made in the vertical meridian. Here, the observer knew the test stimulus would appear in one of these locations which, generally, was not the case in the studies cited above.

- Form Discrimination

Form discrimination is the ability to distinguish objects on the basis of their shape. It involves visual acuity as well as experience in recognizing and describing the shape. Depth perception is also involved in the case of three dimensional objects. Form discrimination depends on the context in which an object is viewed; i. e., by itself, against a homogeneous background, with similar or dissimilar objects, etc. The level of illumination and exposure time also are important factors influencing from discrimination. In general, form discrimination decreases towards the periphery of the retina; the horizontal axis yielding better performance than the vertical axis, particularly in the case of binocular viewing (Munn and Geil, 1931; Renshaw, 1945; Harcum and Rabe, 1958).

The discriminability of six basic forms of approximately equal area ($10cm^2$) were studied under conditions of dark adaptation by Whitman in 1933 (in Wulfeck, et al., 1958). Relative rank of the forms in terms of percent accuracy was: triangles, 86%; diamond, 73%; square, 66%; rectangle, 57%; circle, 57%; and hexagon, 40%. Wulfeck, et al. (1958), concluded that "at 40° from the line of sight, a warning expressed only as a change of shape in the signalling device will go unheeded much of the time; a change in brightness or some other characteristic is required."

The discriminability of four figures (circle, square, triangle, and five-pointed star) was studied by Kleitman and Blier in 1928 (in Zigler, et al., 1930). The limits of perceptibility of all four figures (approximately equal size) were found to be almost identical across the visual fields. The average limit for figures of a given size was approximately the same. Discriminability, however, was greater horizontally than vertically and the temporal field was larger than the nasal.

Geissler, in 1926 (in Zigler, et al., 1930), studied five forms (square, triangle, diamond, sector, and circle) of equal areal size. There were more incorrect judgements toward the periphery with few inversions. The circle was most accurately perceived and the sector least. Again, more errors were made in the vertical than the horizontal meridian.

The purpose of the above mentioned studies was to determine the outer limit at which various forms can be accurately perceived. However, as pointed out by Zigler (1930) they do not shed much light on the nature of form perception in the periphery. Zigler distinguished between four modes of appearance as a figure is moved in from the periphery over the visual field. "In order of appearance, the modes were labelled (1) none--the field was figureless, (2) formless figure, (3) form-like figure, and (4) clear figure." Figure 28 shows the average point in degrees at which the 10 figures studied entered these zones.

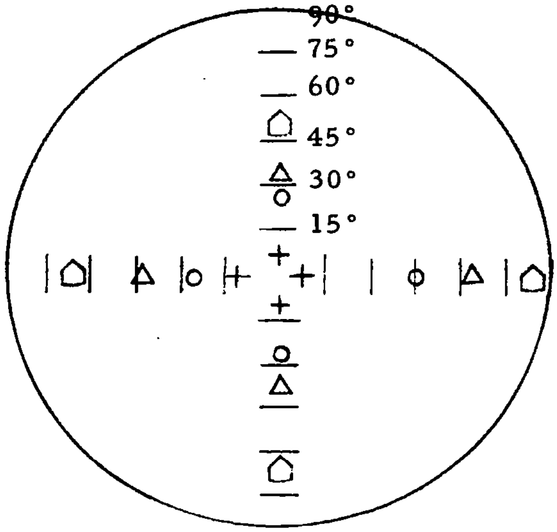
The form zones are most extensive in the temporal and the superior quarter. The nasal and inferior fields have roughly the same extent. Transition from one mode of appearance to the next occurs at approximately the same point for all the figures. The extent of the zones, however, is different for each individual.

- Size Discrimination

Differences have been found between the apparent size of stimuli located on different meridians and on opposite halves of the same meridian (Brown, 1953). These differences appear to be due to two factors--a small and stable ocular factor which is explained by different visual angles for corresponding retinal points and a temporal factor which accounts for a gradual but very marked variation with respect to time.

Temporal Discriminations

A finite amount of time is required for the eye to respond to change. Wulfeck, et al. (1958), states that "periods of 0.05 to 0.2 seconds have been noted between a change in the stimulus and the resulting sensation change. These latent periods depend primarily on the color and intensity of the stimulus."



Adapted from general average data given in Zigler, M.J., et al., The perception of form in peripheral vision Amer. J. Psychol, 42, 1930, 246-259.

Key

+ Clear
o Formlike
Δ Formless
⌂ None

Figure 28. Average Point of Appearance Modes for Stimulus Figures.

They are the basis of several kinds of visual performance such as flicker discrimination.

- Flicker Discrimination

Flicker discrimination is the ability to see flashes of a pulsating light source as separate rather than as a single steady light. The frequency at which pulses can no longer be discriminated is referred to as the critical fusion frequency (CFF). CFF depends heavily on the level of illumination. In dim light, it may be as low as 5 hz. and as high as 50 hz. in bright light (Woodworth and Schlosberg, 1955). CFF is generally lower in the periphery than in the fovea, regardless of background brightness (Ettlinger, 1956; Creed and Ruch, 1932; Hecht and Verrijp, 1933) and with small stimuli (Granit and Harper, 1930). Ettlinger (1956) found some evidence that peripheral CFF tends to exceed central values with larger stimuli ($>1.5^{o}$) when considerably more intense than their backgrounds. CFF also appears to decrease in the periphery with prolonged fixation (Ives, 1912; Lythgoe and Tansley, 1929; Legrand and Geblewicz, 1937; Brown, 1945).

A light flashing at a constant rate below CFF is perceived as flashing at a slower rate in the periphery than in the fovea even though the counts of flashes perceived are approximately the same in both locations of the retina (White, 1962; Lichtenstein, et al., 1963). In general, apparent flicker rate decreases with increasing retinal displacement, but count rate remains approximately the same. This paradox was studied by Lichtenstein, et al. (1963) who found that the ratio of apparent flash in the fovea to the apparent rate in the periphery (70^{o} temporal) was almost 3:1 while the ratio of count rates was about 6:5. He used a stimulus flashing at a constant rate of 25 hz.

Also, below CFF, the ability of the eye to detect differences (difference limen) in the interruption rate of light is a decreasing function of the rate of intermittance in the periphery, (i.e., ability better at higher frequencies) (Mowbray and Gebhard, 1960). There also appears to be no consistent effects on the difference limen due to location in the peripheral retina except for increased variability of threshold judgments in the far periphery.

Movement Discrimination

Movement discrimination is the ability to detect a change in position of an object. There are two types of movement--real and apparent. Here, the concern will be with the perception of real movement only.

Vernon (1952) points out that moving objects in the periphery are detected very rapidly and that the eye responds by immediately looking directly at them. She also stresses that, even while attending to a central task, movement of objects in the periphery is detectable after some practice.

Thresholds for rotary and linear motion under photopic levels of illumination are shown in Figures 29 and 30 (McColgin, 1960). As illustrated in the figures, sensitivity to movement decreases as a function of the retinal position from the fovea to near the edge of the periphery. The threshold isograms for both types of motion are elliptical in shape with the horizontal axis about twice as wide as the vertical axis. The ability to perceive vertical movement is slightly better than horizontal movement in the area adjacent to the horizontal axis out to approximately the 70^{o} meridian. In other areas, no significant difference exists in sensitivity between the two types of motion (McColgin, 1960). There also appears to be no difference between the ability to see clockwise or counterclockwise rotation. McColgin's subjects reported they favored rotary to linear motion.

The effect of velocity was found to be more significant than the area swept by a moving pointer, and the area of the tip of the hand was the most significant influence on threshold in rotary motion.

Judgments of the direction of movement are also more accurate for targets traveling less than 50° per second (Pollock, 1953). With target luminances well above threshold, direction of movement of a target is more easily discerned when its path is entirely in the periphery and does not cross the fovea. With high target speeds (50-2000° per second), threshold increases with increases in speed, and thresholds for vertical movement are lower than horizontal movement.

Reaction Time to Peripheral Stimuli

Several studies have shown that intentional response time increases from the center of the visual field outwards, towards the edge of the periphery (Poffenberger, 1912; Lemmon and Geisinger, 1936; Hyman, 1953; Slater-Hammel, 1955; Bartz, 1962). Data from Poffenberger's study (1912) are plotted in Figure 31 (from Woodworth and Schlosberg, 1955). The curve indicates that reaction time to light varies with the retina location stimulated. Generally, the farther out from the fovea, the longer the reaction time. Notice the curve parallels that for visual acuity. Poffenberger's study, as well as others mentioned above, dealt with monocular vision and was concerned with either the horizontal plane or a small central area of the visual field. Preparatory signals were also used in some instances. Kobrick (1965), in contrast, investigated response times to visual stimuli (flashing lights) appearing at random in the entire visual field using binocular vision. The primary results of his study are presented in Figure 32. The figure shows that intentional response times increase symmetrically with displacement from the fovea for the visual field as a whole and that the most significant decrements occur in the upper visual hemisphere, at a bow inclination (BI) higher than 30° above the horizontal for lateral displacements greater than 55° from the fovea. Response times are unaffected for locations along the horizontal line of sight. In general, this also holds true for the lower hemisphere. Kobrick concluded that flashing indicators can be safely positioned in peripheral locations within the area specified in Figure 33, leaving more space for displays requiring continual monitoring in the central field of view. Kobrick made no mention regarding the effects that a visual task in the central field might have on response to peripheral stimuli.

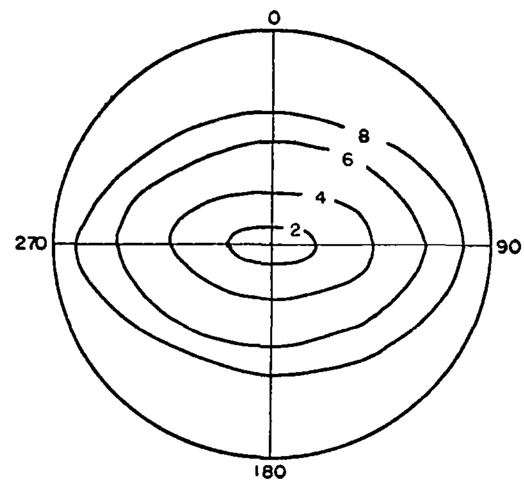


Figure 29. Perimetric Chart Showing the Absolute Threshold Isograms (rpm) of Rotary Motion. (in McColgin, 1960)

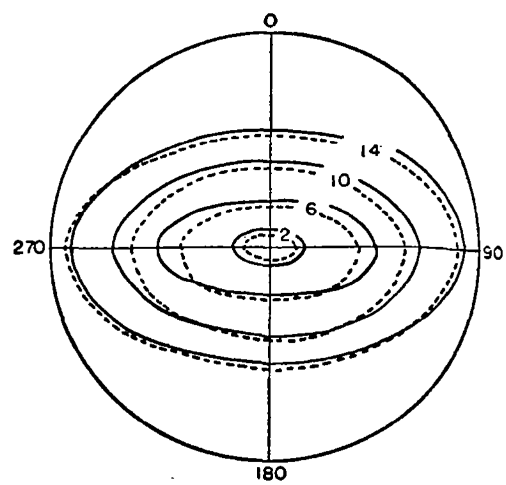


Figure 30. Perimetric Chart Showing the Absolute Threshold Isograms in Strokes/Min. of Linear Motion. (in McColgin, 1960)

Vertical motion is represented by solid lines and horizontal motion by dashed lines.

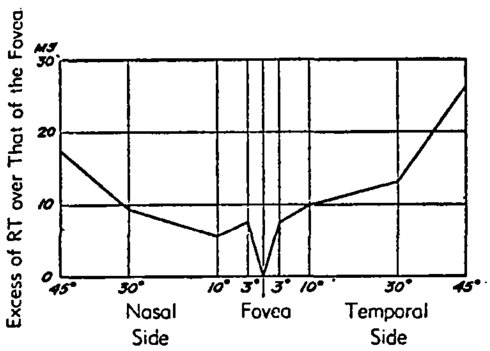


Figure 31. Reaction Time to Stimuli Applied Along the Horizontal Meridian of the Retina. (in Woodworth and Schlosberg, 1955)

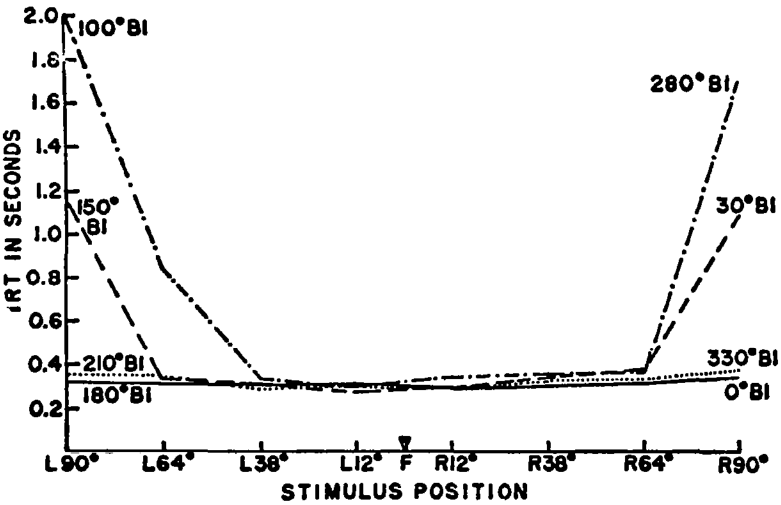


Figure 32. Group Mean Intentional-Response Times for the Experimental Treatments. (in Kobrick, 1965)

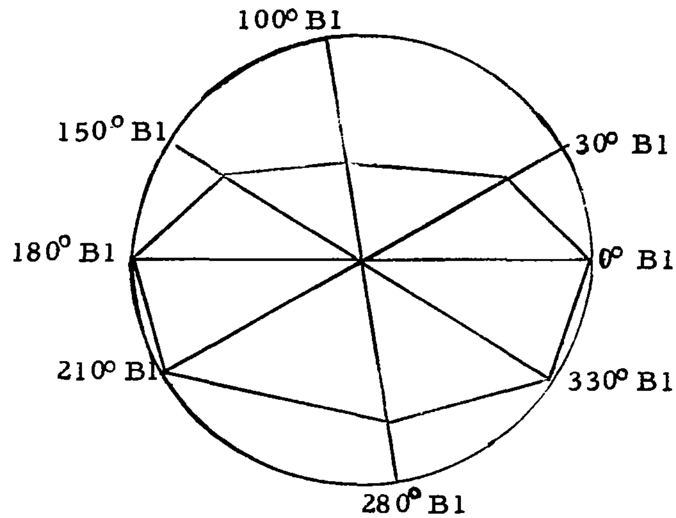


Figure 33. Area of Unaffected Intentional-Response Times in the Visual Field.

Effects of Practice and Experience

It has been generally accepted that peripheral acuity improves with practice. This improvement is said to transfer to the other eye and to other parts of the retina, to night vision, and to other situations where peripheral vision is involved. The amount of improvement and transfer varies from one individual to another. More recently, however, Crannell and Christensen (1956) found little evidence that perimeter training would improve performance on tasks involving material which was different from that employed during training. Perimeter training showed transfer only to perimeter tests involving very similar materials, but not to different materials or to reading or checking dial patterns. They concluded that even extensive amounts of training in peripheral reading are unlikely to constitute a worthwhile method for enhancing the perceptual capacities of aircraft pilots. Bruce and Low (1951) also found "no clear evidence that the training in the recognition of complex visual forms, presented predominantly to central visual areas, significantly improved peripheral visual acuity." Bruce and Low pointed out that Renshaw (1945) found a significant increase in the form field after tachistoscopic training. Drury (1933) found that repeated exposures of simple unfamiliar figures in the periphery gradually became stabilized and observers became certain of them even though drawings of them bear little resemblance to the actual figures. Vague and uncertain impressions, therefore, became stabilized and certain with repeated exposure.

Familiarity of objects also is a factor in peripheral vision. For example, previous experience has been shown to assist in the perception of peripheral stimuli (Henle, 1942; Postman, Bruner and Walk, 1951). Unfamiliar objects are, therefore, not perceived as often as familiar ones.

Perception of elements of a stimulus complex is also influenced by prior practice with the complex (Karn and Gregg, 1961). They found a reduction of error in reporting the state of three simultaneously presented targets as a function of the amount of previous practice with the targets. Using the same location in the periphery (55^{o} horizontal-lateral) for training and tests, Saugstad and Lie (1964) found that "peripheral visual acuity can be improved under conditions of peripheral flash stimulation, provided the subject is trained with a test object which is difficult to discriminate." They explain this finding in the following way: "...the subject, while keeping constant fixation, learns to shift his maximum momentary level of attention from the central part of the visual field to the periphery."

Binocular Rivalry in the Periphery

Different objects presented simultaneously to corresponding areas of the two eyes are not necessarily seen as combined but may be seen alternately --first one and then the other in a rapid succession depending on exposure time and other factors--or one image may persist due to eye dominance. Breese, in 1899 and 1909 (in Hopkin, 1959), found slower alternation in the periphery than in the fovea. At low levels of illumination, the cycle duration averaged 8.5 seconds, while at high levels, duration was lowered to 2.5 seconds; i.e., high intensity yielded more rapid alternation. Increased area of field also produced more rapid alternation while blurring the image reduced alternation. The effects of eye dominance on peripheral vision have not been systematically investigated, although some evidence relating eyedness to extra-foveal performance is reported by Hilborn (1964).

3. Summary and Conclusions

A review of the literature dealing with the psychophysiology of peripheral vision results in two basic correlative conclusions which are important in the design and evaluation of peripheral vision displays.

Visual sensitivity, generally, decreases with displacement from the fovea as would be expected based on the fact that the density of receptors decreases out into the periphery of the retina.

Despite reductions in sensitivity, many visual functions persist in the periphery, especially brightness and motion discrimination which are, presumably, due to summation.

The first conclusion suggests one critical factor that must be considered in the design of peripheral displays. Regardless of the stimulus dimension under consideration, the range and the number of discriminable intervals within this range cannot be the same as those normally employed in conventional displays designed for foveal viewing. Therefore, peripheral displays will have to be designed expressly for peripheral viewing.

The second conclusion relates to the class of stimuli most adaptable for use in peripheral displays. Motion and brightness change, or flicker are especially pertinent, here, because they can provide continuous tracking information in the form of variations in direction and rate.

The relative merits of motion versus brightness as suitable stimulus dimensions for peripheral presentation, however, must be tested both for this information transfer capacity in the context of a complex tracking task and for their operational feasibility. A differential brightness display, for example, might prove to be satisfactory only under relatively low or moderate levels of ambient illumination while a velocity display involving motion is satisfactory under a wide range of illumination. Only careful experimentation under controlled laboratory conditions will yield the answers to such questions.

C. State-Of-The-Art

The most familiar type of visual display, specifically designed for peripheral viewing, is the simple warning light. Warning lights are most frequently used to present two-category information concerning the operation of equipment. If the equipment is functioning properly, it is off; if some out-of-tolerance condition exists, the light illuminates to warn the operator. Research carried out by Elliott and Howard (1956) is pertinent to our present interests because it was concerned with the effect of position on warning light effectiveness in the context of an on-going tracking task. Most experiments dealing with this problem have been carried out without "loading" the operator with a central (primary) task. In general, the results of the study indicate that peripheral lights elicit slower responses as their displacement from the center of the visual field is increased, and that performance is worse when lights are mounted above the line of sight. Unfortunately, the authors did not discuss the effects that peripheral viewing had on the central tracking tasks, and did not compare their results with those obtained in the typical "unloaded" warning light experiments.

Apparently, until about 1958, little attention was given to any other type of peripheral vision display. At this time, a requirement for displays presenting continuous information (e. g., continuous tracking functions) in the periphery arose out of practical problems involving the failure of traditional instruments to provide adequate flight control information. The earliest work, specifically devoted to these problems, was apparently carried out in England by Majendie, and later by Chorley and Lowe at S. Smith and Sons, Ltd. Majendie (1960) pointed out that traditional instruments consistently failed to solve three problems:

"(a) The difficulty of transition from instrument to visual flight conditions at the final stages of an instrument approach to land in bad weather.

"(b) The preservation of instrument control when the pilot's attention is, for any reason, directed away from the appropriate instruments. Preoccupation with other duties, lack of concentration due to fatigue, keeping a look-out for other aircraft, &c., are examples of situations when the maintenance of accurate flight control may be lost.

"(c) The effective monitoring of the accuracy and precision with which an automatic pilot is achieving its selected function. Admittedly, this can be achieved by the pilot continuously watching his appropriate primary instruments, but this tends to be extremely monotonous, and to a considerable extent reduces the advantages to be derived from effective automatic control. This particular problem reaches its peak under high altitude, high-speed conditions of cruise of a jet transport, and in the final stages of an automatic approach, automatic flare, or automatic landing, on any type of aircraft."

He proposed to use peripheral vision displays to "provide flight intelligence to the pilot without distracting his attention from other tasks, without preventing him from looking freely about, either through the windscreen or within the cockpit, so that he can take appropriate corrective action from the information provided without serious interruption to his other tasks." Majendie's objection to projective systems (heads-up displays) for solving these problems was quoted earlier in the first section of this report.

The results of these efforts was the Para-Visual Director shown in Figures 34 and 35. It consists of three "barber pole" type displays located: one in front and the other two on either side of the pilot; all three in a horizontal plane below the line of sight. Each display consists of a servo cylinder with a black and white helix inscribed on its surface as illustrated in Figure 35. Rotation of the cylinder creates the illusion of longitudinal motion along its axis. The display in front of the pilot provides bank angle information while the other two side displays, slaved together, provide pitch. When the bank display shows motion to the right, the pilot banks to the right until the motion ceases. When the pitch displays show forward motion, the pilot pushes his control column forward until motion ceases. Majendie (1960) states "considerable flight experience with a wide cross-section of pilots has shown that this type of display is as nearly instinctively natural as one could possibly hope for." The display unit is also provided with integral lighting and a shutter which closes when malfunctions occur or when power is "off." The relationship between display speed and altitude demand is non-linear and a rate limiting signal is employed in the fully developed system. Subject to this, the system can be used for all phases of flight when a conventional flight director would normally be used.

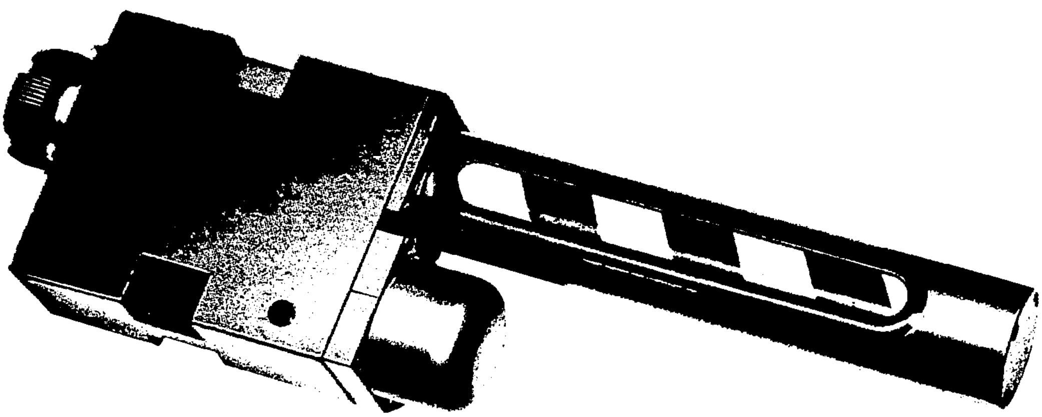


Figure 34. Smiths PVD--Typical Display Unit

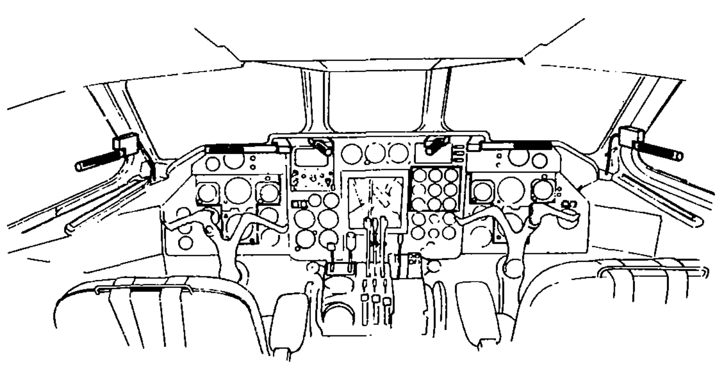


Figure 35. Smiths PVD--Typical Installation

"Under the conventional circumstances of a manual instrument approach, it has been found possible to fly accurately close-coupled to localizer and glide path with the pilot free to look out of the windows, or around the cockpit, over a surprisingly wide angle. Complete approaches have been flown with the pilot deliberately looking out at an angle of more than 45° from dead ahead, and yet close-coupled instrument flight has been maintained to within the presence of the ground. Under genuine transition conditions, both day and night, it has been found possible to maintain accurate manual instrument control while looking out for the approach lights; and when they come into view, it has been found easily possible to combine the PVD instrument intelligence with that derived from the external world. In other words, instrument and visual flying are made to overlap naturally, and the problem of transition, as such, has disappeared.

"It is particularly significant to report how easy it has been found to combine PVD glide path control signals with visual approach light guidance in azimuth. The problem of elevation guidance from visual aid patterns in reduced visibility is well known, and the significance of this particular combination will be immediately obvious to all with experience of low-minima approach problems. The PVD can undoubtedly be a powerful tool for safety in this particular context.

"So much for the application of the PVD to the direct problem of transition. It will be obvious that it is also capable of solving the general problem of retaining accurate instrument control, when the pilot's attention is temporarily directed elsewhere than his conventional instruments. The freedom to look around when flying instruments using PVD is a completely new experience, and one that has to be tried in actual practice to appreciate fully its significance.

"Similarly as a monitor of autopilot control the PVD is extremely effective. Under conditions of correct operation, the display units are all sensibly at rest, but as soon as a malfunction develops, a highly dynamic pattern is immediately generated, and obtrudes itself compellingly on the pilot's attention. The signal provided is not only a warning, but a clear and positive indication of the corrective action required. This is particularly valuable during an automatic approach, or as a continuous monitor in high-speed jet cruising conditions.

"It will be realized that the Smiths PVD does, in fact, provide an effective solution to all the problems posed at the beginning of this report. Experimental units have also been supplied for test purposes as part of the instrument display for helicopters, and a number of other direct applications of the principle can be foreseen.

"Finally and not least in importance a direct application of the Smiths PVD to the problem of providing instrumental guidance during landing flare must be reported. It was stated above that an experimental installation has been made in an aircraft fitted with a fully automatic landing system. The installation was arranged so that the signals from the automatic landing coupling unit could be fed either to the autopilot, to the PVD, or to both. Highly successful manual instrument control of the flare-out to touch-down has been achieved using PVD, with the pilot able to monitor his own performance by looking freely ahead through the windscreen. Under these conditions, the azimuth control in the final stages has generally been by direct visual means, so that flight control has been on instruments in pitch, and visually in roll and yaw. However, a number of completely blind touch-downs have been carried out using the bank PVD display for azimuth guidance. Owing to the problems of kicking-off drift in the final stages, this technique is not acceptable under cross-wind conditions.

"Objective recording of flare control using PVD has shown a remarkably consistent agreement with similar results obtained under fully automatic conditions, and the scatter of vertical velocity at impact has been consistently close about the design figure. Also, using PVD as a monitor of fully automatic landings, many take-overs from autopilot to PVD have been accomplished without difficulty during all stages of the approach, and including the flare maneuver itself."

Hopkin, at the Institute of Aviation Medicine, in Farnborough, was also concerned with the development of peripheral vision displays for aircraft use, but did not possess the same enthusiasm for them that Majendie did. Hopkin (1959) completed an excellent review of the literature dealing with peripheral vision and its relation to the design of peripheral vision displays, concluding: "Attempts to use other visual methods besides peripheral vision to convey additional information to the pilot have met with little success. The use of peripheral vision instead of scanning inside the cockpit is most unpromising." He also recommended that considerable caution be used in the application of peripheral vision because of the lack of definite knowledge about it and its liability to spells of very poor acuity. Hopkin emphasized the need "a) to measure peripheral vision adequately; b) to find out what the capabilities of peripheral vision are; c) to discover methods of improving peripheral vision performance; and d) to explore possible uses and applications of peripheral vision."

Also in England, Brown, Holmquist, and Woodhouse (1961), at the Applied Psychology Research Unit, were interested in peripheral vision and its capabilities for presenting information to pilots during final approach to landing under poor visibility conditions. In a series of laboratory experiments, they compared tracking performance using four flight-direction displays, three of which were peripheral vision displays--Majendie's Para-Visual Director as well as displays consisting of "streaming lights" and "flashing lights." The fourth instrument was a conventional ILS indicator.

The streaming light display system consisted of two 53.34 cm rows of 45 neon lamps, spaced at equal intervals. One row was oriented horizontally at a visual angle of 25° below a central display. This row was used to indicate errors in heading. The second row, oriented vertically at a visual angle of 30° to the left or right of the central display, was used to provide altitude error. Eight lamps in each row were illuminated at any instant to produce an apparent streaming movement of lamps. The direction of the streaming movement indicated the control movement required and the rate of streaming indicated the size of required movement. The tracking task, here, as well as with the other displays studied, was compensatory with zero time lag.

The flashing light display system consisted of four neon lamps. Two lamps, displaying errors in altitude, were placed 25° vertically above and below the central display. The other two lamps were placed horizontally to the left and right of the central display, at a visual angle of 30°. A flashing light to the left indicated a requirement for movement to the left and a flashing light above indicated a movement towards the operator of an aircraft type control. The rate of flashing indicated the size of the control movement required. When the system was balanced, the lamps were off. The flashing light system was also studied with the lights attached directly to the visor of the operator's helmet.

The Para-Visual Director (barber's pole) system used in these experiments was described earlier. Here, the central display presented changes in bearing and the two sister displays presented changes in altitude even though they were mounted horizontally. In one case, only one (right) display was used.

The ILS meter was located at the right and slightly above the center display at a visual angle of 6°. The horizontal pointer displayed altitude and the vertical pointer bearing. When the horizontal pointer moved up the correct control movement was towards the operator. When the vertical pointer moved left, the required control movement was to the left. The target area on the meter was represented by a white circle (7.95 cm in diameter). Tracking with the ILS meter was also examined when it was located 10° directly below the central display.

All displays were attached to a 76.2 cm diameter hemisphere at the displacement angles indicated above. The central display consisted of a 15.24 cm diameter ground glass screen located at the center of the curved surface of the hemisphere. Three spots of light were projected on the screen in a pre-arranged order. (A second "central display," 70° to the right of the center of the hemisphere, was used in the portion of the experimental program dealing with the effects of head rotation and of combining two display systems.) The operator's basic tasks were to fixate the central display, to press a switch as quickly as possible whenever the pattern of spots changed, and to track at the same time with the flight-director display system.

The results of the study indicated that during "continuous tracking, the time off target with Flashing Lights or the ILS meter was about a quarter of the time off target with either the Streaming Lights or the Barber's Poles. In correcting sudden errors, Flashing Lights on the Helmet gave quicker responses than any other display which was investigated. This was presumed to be the result of the high attention-getting value and the immediate directional indication of the signals. The weakness of Flashing Lights on the Helmet, which also applied to the Barber's Poles and Streaming Lights, was in presenting information on the size of errors. The ILS meter was the best display in this respect, although it did not always attract the man's attention as soon as it indicated an error. The combination of Flashing Lights on the Helmet and the ILS meter produced the quickest corrections recorded during the experiments.

"Reaction time to signals presented on a central display increased about 40% when attention had to be paid to any of the flight-director displays. The size of the increase was about the same whether simulated control of the aircraft was carried out or not while performing the central task." They concluded that: "It was the need to attend to the additional channel of information, rather than simultaneous demands for action, which interfered with the central task.

"Performance with Flashing Lights on the Helmet and Streaming Lights showed only a small and not statistically significant adverse effect from occasional rotation of the head and eyes of 70°.

"Sideways movement of the head altered the angle subtended at the subject's eye by the Barber's Poles mounted horizontally fore and aft to display information on altitude. This changed the apparent rate of movement of the display and the apparent display-to-control ratio, and thus caused the subject to miss small errors occasionally, or make control movements of the wrong size. In addition, with the Barber's Poles the display-control directional relationships changed as attention was directed from one end of the azimuth display to the other. This could occur in an aircraft when the pilot rotated his head and eyes, and might be dangerous." This last conclusion made by the authors is inconsistent with the normal interpretation of display-control relationships in that they have interpreted the area of intersection of two displays as an additional source of information to which the operator can attend in addition to the two basic input sources comprising it. If such confusion was a real problem, physical separation of the two displays and/or training should minimize this effect.

In the United States, Collins Radio Corporation, as early as 1961, was also interested in the possibility of using peripheral vision displays in the aircraft cockpit, and developed the "Peripheral Vision Command Indicator" as shown in Figure 36. (Fenwick, 1963), against a background of actual flying experience and laboratory simulation. This development effort was undertaken because of increased pressures for lower aircraft landing minimums under adverse weather conditions.

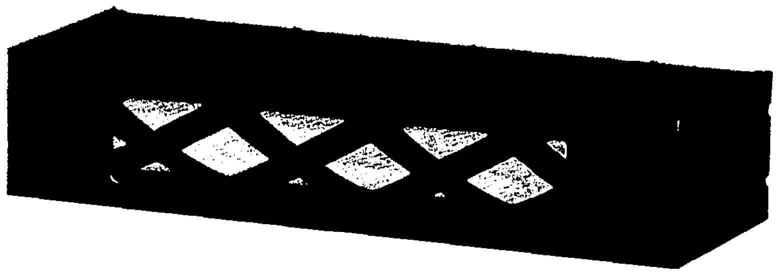


Figure 36. Collins' Peripheral Command Indicator

Collins' peripheral command indicator translates pitch and bank steering information into a rate of movement of a single, black and white display pattern. With appropriate inputs to the device, which consists of a helix on each of two concentric cylinders, the black and white pattern moves in any desired direction (up, down, left, right, and any vector between these) at any desired rate within a wide range. In practice, movement of the pattern has been controlled by quickened flight director signals so that the display presents the pilot with a continuous, two-dimensional, compensatory tracking task. Fly-to-sensing is employed so that, for example, if movement is perceived in the direction 15° to the right of vertical, the pilot pitches up and steers slightly to the right until the display is nulled, that is, until movement ceases. The rate of movement represents the magnitude of error to be corrected (Fenwick, 1963).

Early tests with the instrument indicated that sensitive commands in two axes could be perceived and followed even when the pilot was attending to other instruments in the cockpit or scanning the windscreen. Simulator tests were used to determine the usefulness of the peripheral command indicator as a supplement to conventional displays. Laboratory experiments were also conducted to assess the "effects and interactions" of various display variables in an effort to optimize the display. With the best combination of display variables, Fenwick (1963) states that "direction of motion could be perceived with considerable accuracy when the display was located as far as 35° from the subject's line of regard."

Keston, Doxtades, and Massa (1964), at the Laboratory for Electronics, were concerned with the possibility of using a peripheral artificial horizon as an aid to pilots during night carrier landings. They conducted a laboratory study to determine the feasibility of using such an aid. The artificial horizon consisted of a thin luminous line presented in a horizontal plane at eye level; the central 10° visual angle of which was removed resulting in a "peripheral" display. The operator's task was to judge the vertical position with respect to his line of sight. No central tracking or loading task was used. The authors reported a "dramatic enhancement of reliability and accuracy" with the use of the artificial horizon. Variability and errors were reported to be far greater when no horizon was present in the periphery.

Holden (1964) at the Queens University in Belfast, Ireland, investigated the use of horizon "side bars" to create the illusion of a stationary horizon in the pilots' periphery during blind flying. The side bar display system consisted of two instruments in the periphery. A horizontal line on each instrument moved up or down as the aircraft banked. In 1963, Holden conducted a simulator study of this system. The side bars were located to form a plane about a foot below the line of sight on either side of the head. The side bars were geared so that they formed an extension of a central artificial horizon display which was situated directly in front of the pilot. The results of the study indicated that small changes in bank angle were detected more quickly with the use of side bars; however, even with modifications the illusion of a stationary horizon was not achieved. Nevertheless, a 22% improvement in performance was found with the side bars in tests which required the pilot to track in roll and pitch simultaneously. Here, the bars were modified to move "in sympathy" with aircraft pitch. Holden concluded that the major advantage of the side bar system appears to be in its ability to reduce the amount of concentration required of the pilot.

In discussing other instruments for blind flying, Holden stated that "director instruments (integrated displays) can become exceedingly complex. . . and such a complex instrument may offer only marginal advantages over the conventional display." With regard to Smith's Para-Visual Director, he also pointed out that "in any case reliance, in a primary instrument, on peripheral vision is open to severe criticism since medical evidence indicates that it would be quite easy to miss peripheral clues at a crucial stage when under strain. Relegated to a secondary instrument the system still appears to have many merits, the pilot flying the aircraft with normal instruments using the PVD display to help ease the task by reducing the concentration required."

In the 1964 summer issue of the Journal of the Institute of Navigation, and again in the 1965 summer issue of the same journal, Massa and Keston revealed a "new display concept--The Minimum Attention Display." Keston (1964) states: "The Minimum Attention Display Concept attempts to provide highly specific and veridical guidance information that would augment and clarify direct visual contact through visual codes compatible with the required control responses. The display has minimum attention requirements; that is, it does not compete for the attention of the pilot to the detriment of both the display and direct visual contact. The pilot is not required to look directly at the display; instead, he can look through the windscreen and maintain direct visual contact. This is usually accomplished by transmitting information through the visual periphery by means of non-specific (low acuity) visual parameters (color, motion, flash rate, brightness, etc.).

"The use of this unique display concept allows continuous maintenance of direct visual contact, while simultaneously providing supplemental guidance information. The time scale required for information transmission is thus compressed, resulting in more rapid performance of critical control maneuvers.

"The Minimum Attention Display Concept is proposed as one form of solution to several display problems (delineated above) inherent in both manual and automatic systems."

Massa and Kenton (1965) wrote: "We conclude that a distinct possibility exists for the utilization of peripheral phenomena in information transmission in a minimum attention visual display." They considered the following stimulus dimensions to be the most promising: "flicker frequency, color discrimination, relative size discrimination, relative position discrimination, relative velocity discrimination, and relative shape discrimination." No further comment will be made by this author with regard to their work except that they appear to be unaware of the work performed in England by Majendie, et al., and in the United States by Collins Radio on peripheral vision displays even though they quoted (with credit) Hopkin's excellent review of peripheral vision described above.

Before concluding, some mention should be made about the work completed by Howell and Briggs (1959) and Moss (1964a, b). Howell and Briggs found deterioration in a two-dimensional positional control task when one dimension of the task was moved into the periphery. Performance decreased as a function of the degree of separation between the two dimensions. Moss compared tracking performances using a positional display and a differential brightness display as they were moved into the periphery (15°, 30°, and 45° eccentricity). Performance with the positional display was superior when it was situated in the center of the field of view. However, as the displays were moved into the periphery, the differential brightness display proved to be the better of the two. These results emphasize the importance of selecting the appropriate stimulus dimensions for use in the design of displays for peripheral viewing.

D. Future Research

The Phase I experimentation demonstrated clearly that peripheral displays are effective in improving man's performance in a complex tracking task when visual switching is an essential part of that task. The next logical step would be to maximize the effectiveness of peripheral displays. This is the objective of Phase II of the research program. To accomplish this objective, display concepts must be developed in accordance with the known capacities of peripheral vision, the state-of-the-art in display techniques, and the requirements of anticipated operational environment, e. g., concepts not readily implemented in an aircraft cockpit or space capsule should have low priority while concepts already implemented or readily developed should be investigated early. The relative merits of these concepts must then be tested and verified for their information transfer capacity in the context of a complex control task. This can best be accomplished by means of careful experimentation under controlled conditions in the laboratory. The purpose of the Phase II experimentation, therefore, is to provide a test bed in which the various display concepts can be quickly evaluated and compared as they are developed. Final evaluation, of course, can only be accomplished under the more realistic conditions possible with flight simulators or with actual flight vehicles. This is the goal of the Phase III program.

1. Display Concepts

At the present time, a number of display concepts appear worthwhile investigating during Phase II. These concepts may be divided into two broad categories. One category contains displays which attempt to simulate the peripheral motion cues associated with the maintenance of body equilibrium, e. g., the streaming light and barber pole displays developed by Majendie, Chorley and Lowe in England (Chorley, 1961). The other category contains displays that do not attempt to create such an illusion but are designed only to be compatible with the perceptual capabilities of the periphery. The Collins Peripheral Command Indicator, incorporating omni-directional movement of a moiré pattern, would fall into this latter category as well as the differential brightness displays successfully used during the Phase I experimentation discussed above. Displays falling into this latter category are, therefore, not limited to those incorporating motion (apparent or real) as is the case with the first category of displays. Other stimulus dimensions such as changes in size, color, or flicker rate could be used as the predominant encoding parameter depending on their discriminability in the periphery and their compatibility with anticipated operational environments. For example, the effectiveness of displays utilizing color, brightness, and flicker would be influenced by the level of ambient illumination in the cockpits of aircraft and space vehicles. Displays requiring shape and pattern recognition would suffer more from accelerative forces than those providing motion or brightness cues. Other factors, which must also be considered, include the availability of space for mounting, structural shape of the operator's workspace, power conservation, and weight. In view of these considerations, displays which rely on their spatial positioning in the operator's visual field to convey information are not considered promising since four instruments would be required to present information on two control dimensions, viz, two pairs of displays would be required to present directional information, one above and one below the operator's line of sight for "upness" or "downness" and a second pair on either side of the operator for "leftness" or "rightness." Certainly a single peripheral display, capable of providing this same information with no deleterious effects on control performance, would be more desirable than a multi-display configuration.

In view of the above considerations, displays incorporating changes in the rate of motion as their primary cue appear to hold the greatest promise. The perceived motion, however, must be smooth, otherwise it may tend to distract or annoy the operator (Chorley, 1961). For this reason, the smooth moving barber pole displays have been generally accepted as the best means developed thus far for presenting tracking information in the form of visual balancing cues. Research indicates that these cues can be utilized to provide flight director information during aircraft landing under poor visibility conditions (Chorley, 1961). Motion cues are also considered promising because they can provide quickened tracking information, viz, a conventional display in the center of the visual field for presenting positional information (error) and the peripheral display(s) for presenting a combination of error and error rate (or higher derivatives depending on the dynamics of the system controlled). Flicker displays could also be used in this manner; however, they may suffer from the same limitations as found with streaming light displays (Chorley, 1961), i.e., they may distract and annoy the operator even though they can provide useful control information. Displays incorporating changes in brightness or size could not be effectively used to provide quickened information. In addition, display concepts utilizing other than motion as the predominant stimulus dimension must also depend on their location in the operator's visual field for directional cues which require an undesirable multi-display configuration as explained previously. This limitation, of course, does not preclude the use of flicker, brightness or other stimuli to enhance the signal value of motion displays. For example, brightness might be used to present redundant information, i.e., the background brightness of the motion display might increase to bring the operator's attention to gross tracking errors requiring immediate action.

Brightness, flicker or other stimuli might also be used to enrich the information content of a motion display by providing supplementary information such as airspeed, radar range or rate of descent. In this way, information on a third tracking dimension might be simultaneously presented to the operator.

Enriched displays may, of course, also be enhanced. For example, changes in the rate of motion would be utilized to present pitch and roll information; gross errors would be indicated by an increase in the rate of display motion as well as an increase in the overall intensity of the display background; and deviations from a preset optimum airspeed would be presented by a slow flicker meaning "too slow" and a fast flicker meaning "too fast." Here, the operator's task would be to adjust his controls so that no apparent motion or flicker could be perceived peripherally. His attention would be immediately directed to gross errors by an increase in the rate of motion as well as by an increase in the background brightness of the display. Concepts such as these should be investigated during Phase II to determine the feasibility of providing simultaneous information on three control dimensions entirely in the periphery. To evaluate this concept, it will be necessary to obtain base line data using conventional displays designed for central viewing. The control task, of course, will have to be difficult and involve visual switching in order to tax the operator to the limit of his information processing capacity. Depending on the results of this effort, it may be advantageous to examine the feasibility of using peripheral displays to present information on four or more control dimensions. Only careful laboratory experimentation will yield reliable answers to such questions.

In view of the above discussion, it appears desirable to investigate the following display concepts during the Phase II experimental program.

a. Rippling Light Display

The rippling light display consists of bands of light and dark areas which can be electronically controlled to move smoothly along the longitudinal axis of the display unit as shown in Figure 37. The viewing aperture of display should be approximately 1 dm x 1 cm.

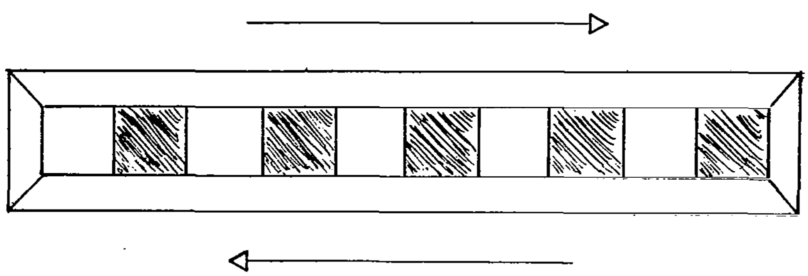


Figure 37. Rippling Light Display

Three displays should be configured in the visual field to simulate peripheral balancing cues as illustrated in Figure 38.

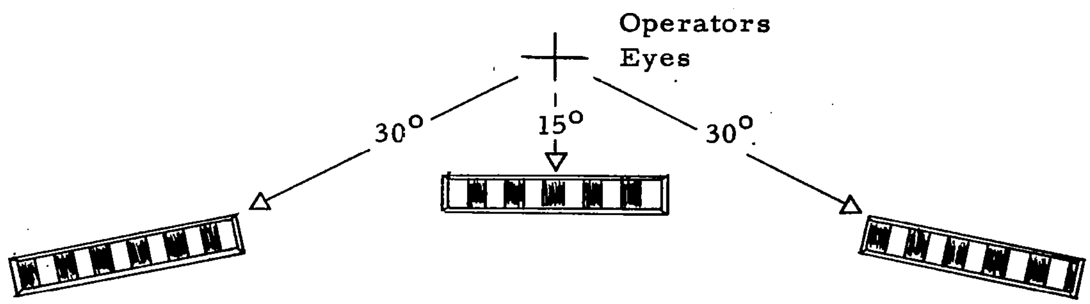


Figure 38. Location of Rippling Light Displays in Visual Field

This configuration is similar to that presently being used for barber pole displays. The center display should present roll information and the two side displays pitch. The control-display relationship should be inside-out, i.e., apparent movement to the left on the center display indicates a requirement to move the control to the left; forward movement on the two side displays indicates a requirement to push the stick forward; movement perceived in opposite directions, of course, requires reverse control movements. The rate of motion indicates the amount of correction required to attain zero error with the control system.

b. Barber Pole Displays

Conventional barber pole displays should also be investigated to obtain base line performance data for comparison with other display concepts. The barber poles should be used as supplied by their manufacturer and in accordance with their recommendations. Their location in the operator's visual field should be identical to that used for the rippling light displays. The operation of the display and the control display relationship should also be identical.

c. Moiré Display

The moiré display consists of a moiré pattern of interesting lines as illustrated in Figure 39.

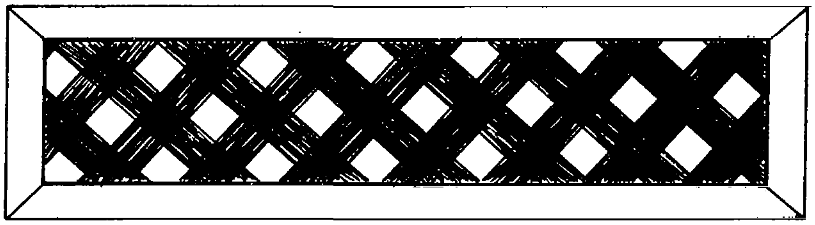


Figure 39. Moiré Display

The optimum number and width of lines and their angle of intersection are unspecified at the present time and, therefore, should be investigated during the experimental program. The overall size of the display and the techniques for mechanizing it should be similar to those for the rippling light display system. By translating the two sets of lines across the display surface at different relative speeds, it is possible to produce the appearance of motion in all directions, i. e., up, down, left, right, and any direction between these vectors. In this way, a single display can be used to provide both pitch and roll information. The rate of motion indicates the amount of control correction required to null the error in the system.

d. Collins Peripheral Command Indicator (PCI)

The PCI is similar to the moiré display but is mechanically driven. This display should be studied to obtain base line data for the purposes of evaluation and comparison. The PCI should be used as recommended by its manufacturer. Its location in the operator's visual field and information content should be identical to that of the moiré display, i. e., 15° below the operator's line of sight.

e. Concept of Enrichment

Enrichment refers to the addition of supplementary tracking information in the periphery such as airspeed or rate of closure which the operator would normally be forced to obtain from conventional displays designed for foveal viewing. This information might be presented in the form of changes in brightness or flicker rate superimposed on the primary display dimension. Here, the operator's task would be to control three tracking dimensions simultaneously (e.g., pitch, roll, and speed) using information presented entirely in his periphery. To evaluate this concept, it would first be necessary to obtain base line data on the operator's performance during conditions in which all three dimensions are presented centrally on conventional displays and during conditions in which only the third dimension (e.g., speed) is presented centrally and the other two (pitch and roll) are presented peripherally. In this way, it would be possible to determine if peripheral presentation of all three dimensions is feasible and does lead to improved performance.

f. Concept of Enhancement

In contrast to enrichment, where additional stimulus dimensions are used to provide supplementary information, enhancement refers to the use of additional dimensions (e.g., flicker or brightness changes) to provide redundant information in an effort to improve the discriminability of input signals. For enhancement to be effective, the primary encoding technique (e.g., changes in the rate of motion) must be less than adequate for conveying the information required by the operator to control the vehicle properly. Because of the perceptual limitations of the periphery, enhanced displays may be the only type which can be used to convey all the information required by the operator for efficient control of a vehicle. The effects of enhancement on performance, therefore, should be of primary interest during the experimental program.

2. Method

The program should be initiated by developing the display concepts into hardware which can be utilized in the laboratory for evaluation. This effort would consist of a reiterative process in which each concept is developed, tested, modified, and improved until optimum performance is judged to be attained and considered suitable for operational use. For example, the relationship between display velocity and input error must be selected on an empirical basis to ensure optimum performance. Such display parameters cannot be specified with certitude without first subjecting them to study under controlled laboratory conditions. The barber pole displays and the PVD should, of course, be used as supplied by their respective manufacturers and in accordance with their general recommendations.

Once the experimental displays are developed and considered operationally feasible, they should be compared with one another on the basis of performance on a two-dimensional compensatory tracking task. This task should normally involve a high level of visual switching. The same method should also be used to evaluate preliminary ideas and concepts during the initial development stage. The laboratory investigation of enrichment, involving the presentation of supplementary tracking information, will require, of course, a third tracking dimension, e.g., airspeed. Laboratory equipment, procedures, and techniques would be similar to that utilized during the Phase I program, discussed earlier in this report. The addition of a third tracking dimension would be, of course, a major sophistication in terms of equipment.

The operator's task would be to correct the errors in pitch and roll by means of compensatory tracking using a pressure stick hand control. Under the conditions involving a third tracking dimension, the operator might use a throttle type hand control for airspeed maintenance. Central displays for presenting pitch and roll would be the same as those utilized for Condition D of the Phase I experiment (see above). The central display for airspeed would also be of a conventional design and would be situated approximately 15° to the right of the lower central display. Under all conditions, peripheral displays should be located at a fixed distance near the operator as they would be in an aircraft cockpit or space vehicle. Peripheral displays for pitch and roll would present rate (quickened) information. Airspeed would be presented as an integral part of these displays and would consist of changes in flicker rate or brightness as the encoding parameter.

The difficulty level of the task and performance scoring might best be accomplished by utilizing self-adjusting techniques (Kelley, 1962). Instead of obtaining a variable score to represent the operator's performance in a task of fixed difficulty, as was the case during Phase I, a score representing the desired performance is fixed and the complexity of the task varied automatically to produce the fixed performance score. The average difficulty of the task achieved within a fixed time interval then becomes the performance index used to compare the various display concepts. For example, it might be found that the operator can control a much more difficult control task with enhanced displays then he can with unenhanced displays as explained above.

At least 10 subjects should be used as operators during the experiment. Eyesight should be tested using standard central and peripheral vision tests. Subjects who possess less than normal eyesight should not be permitted to participate in the experiment.

The display configurations should be presented to each operator in a different random order to alleviate any sequence effects due to fatigue or learning. In this way, it would also be possible to alleviate the effects of any uncontrolled variations in the experimental environment which might adversely influence the validity or reliability of the results. Standardized instructions should be given to the operators. They should contain an explanation of the overall purpose of the experiment, the tracking task and the operation of the various displays. Care must be taken not to bias the operator in any way; he should be allowed to use any source of information displayed in his visual field provided he does not fixate the peripheral displays. Each operator should be allowed to practice the tracking task with each display configuration for a period of five minutes prior to his experimental session. During each session, the experimenter should monitor the operator's eye movements to insure that he does not fixate any of the peripheral displays. This may be accomplished by watching the operator's eyes or by using simple monitoring equipment which does not obstruct the operator's visual field. Upon completion of each session, the experimenter should record any such instances of "peeking" together with the operator's performance index score. The experimenter should also note any comments made by the operator with regard to the various display configurations, e.g., annoyances, distractions, and eye fatigue. Once the experiment is completed, the performance scores should be analyzed using acceptable statistical techniques to test the differences between the mean performances of the various display systems. The scores should also be analyzed for any learning and sequence effects which might have influenced the results.

3. Summary and Conclusion

Having demonstrated the feasibility of using peripheral displays for improving complex control tasks, there remains the problem of how to maximize the effectiveness of such displays. As pointed out earlier in this report, the peripheral retina can be treated as an independent sensory input channel with its own set of characteristics. The problem of matching these characteristics to feasible display concepts is the primary objective of the Phase II experimental program. Due regard, however, must also be given to the operational environment in which they will be used. To be economical of time and effort, primary display concepts must be evaluated in the context of a difficult tracking task under as rigorous control as possible in the laboratory.

At the present time, the display concepts, discussed above, appear both feasible and worthwhile investigating during future research. However, it must be realized that, as in any research and development program, new problem areas and new solutions as well as alternative display concepts will be generated during the program effort. A good program is one which is versatile and flexible enough to accommodate new ideas and the uncertainties in this type of research.

APPENDIX A

REPLOT OF CONRAD'S RESULTS IN INFORMATION THEORY TERMS*

Conrad (1951) reported that increasing the load (i. e., number of information sources which must be "scanned" or attended to or both) had the effect of decreasing information processing or transfer rate. He concluded this because he was not really measuring information rate. Instead, he measured "signal" processing rate without establishing the quantity of information presented to the operator in a single signal in bits per signal or stimulus. This is the opposite of what researchers like Hake (1951) and Garner (1953) did in investigating stimulus dimensionality. They determined the quantity of information in bits per stimulus. Their experiments, however, did not present a continuous stream of stimuli to the subject, so that there was no rate involved. Conrad's report is one of the few which does justice to this problem.

Conrad (1951) investigated the combined effects of what he called "speed" and "load" upon human performance. These terms were used by him to denote:

> The overall rate (total of all signal sources) at which signals are presented to an operator (speed)
>
> The number of different signal sources to which the operator must attend (load)

His original results are shown in Figure A-1. They are replotted in Figure A-2 to indicate the decrease in correct responses per minute with increasing "load" (i. e., number of sources which must be attended to). At first, it would appear that this finding completely supports the hypothesis that information processing rate decreases when attending to multiple information sources. However, if "information" is precisely defined in information theoretic terms (see Shannon, 1948) then a totally new insight may be gained as to the meaning of Conrad's results.

In Figure A-3, Conrad's data have been transformed into information theory terms. The assumptions involved may be illustrated by the two-dial case. Each dial had six "target marks" on its periphery and a pointer which rotated at some nominal speed. The subject's task was to turn a knob (associated with each dial) whenever either pointer was coincident with any of the "target marks." Thus, signals would be "presented" to the subject from either of the two dials (sources), with a relative frequency of occurrence determined by pointer rotation speeds. It so happended that Conrad used gear ratios in the dial pointers such that the relative frequency of occurrence of signals from Dial #1 was:

*by J. Wohl, Dunlap and Associates, Inc., 1966.

$$\left[\frac{.75}{.75 + .90}\right] = .4545$$

and from Dial #2 was:

$$\left[\frac{.90}{.75 + .90}\right] = .5455.$$

In effect, the signals appeared to the subject to be coming "randomly" from the dial group because he could not predict in the short time available which dial would require the next response. Under these conditions, it is possible to determine the amount of information presented to the subject by each signal or stimulus (i. e., pointer/target mark coincidence).

The information per signal in the noise-free case is given by:

$$H = \sum_{i=1}^{N} \left[P_i \log_2 \left(\frac{i}{P_i}\right)\right]$$

where:

n = **number** of possible signal states
P_i = **probability** (or relative frequency) of occurrence of i^{th} **signal state.**

Substituting the gear ratio data for Conrad's two-dial case we obtain:

$$H = \sum_{i=1}^{z} \left[P_i \log_2 \left(\frac{i}{P_i}\right)\right]$$

$$= (.4545) \log_2 \left(\frac{1}{.4545}\right) + (.5455) \log_2 \left(\frac{1}{.5455}\right)$$

$$= 0.994 \text{ bits per signal}$$

For the three cases investigated by Conrad (2, 3, and 4 dials) the information content of the signals is summarized as follows:

	Number of Dials		
	2	3	4
Information content of signals in bits per signal	.994	1.56	1.97

These values may then be multiplied by the Conrad's signal presentation rate to get information presentation rate in bits per minute, and by the subjects' correct signal response rate to get information transmission rate in bits per minute.

These values are summarized in Table A-I and plotted in Figure A-3. It is clearly evident that there is no significant effect of "load" on human rate of transmission of information in bits per minute.

Table A-I. Summary of Conrad's Data in Information Theory Terms

		Transmitted bits per minute/Presented bits per minute				
Number of Dials (Attention Sources)	4	148.8 / 236.2	147.0 / 197.0	127.8 / 157.5	108.4 / 118.0	76.0 / 78.8
	3	138.1 / 187.2	131.2 / 156.0	112.0 / 124.8	90.7 / 93.5	61.8 / 62.4
	2	106.5 / 119.2	94.9 / 99.4	77.7 / 79.5	59.1 / 59.6	39.8 / 39.8
Transmitted Signals per Minute		120	100	80	60	40

Stated in another way, it means that regardless of the number of information sources being attended to (2, 3, or 4 in Conrad's experiment), the total information processing rate of the subjects remained constant. Adding more sources neither increased nor decreased their information processing rate.

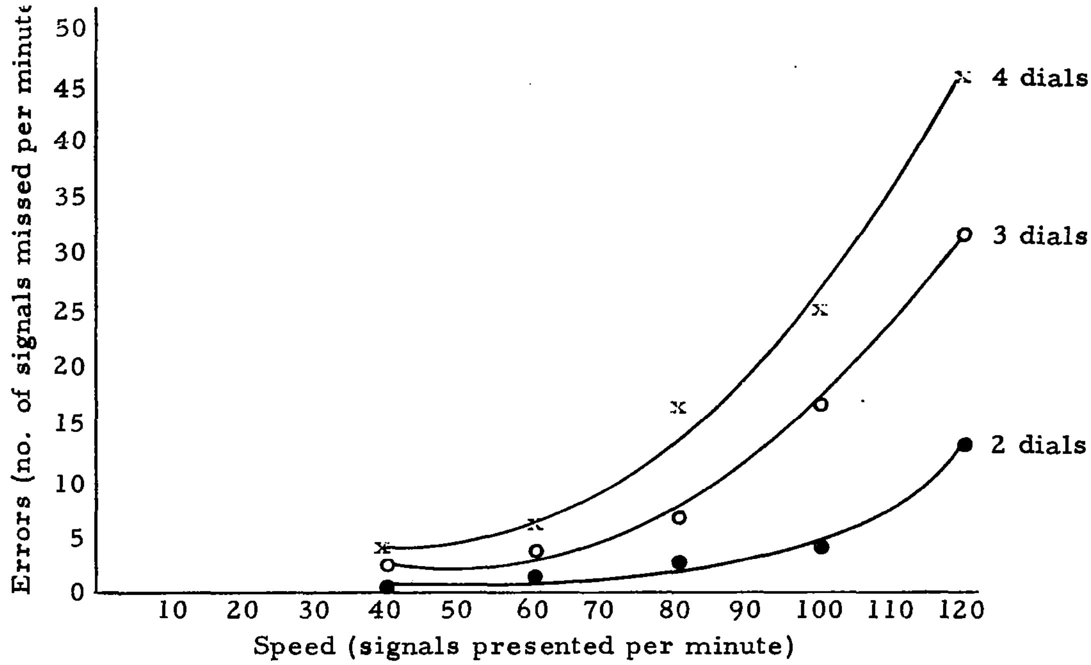


Figure A-1. Conrad's Original Data.

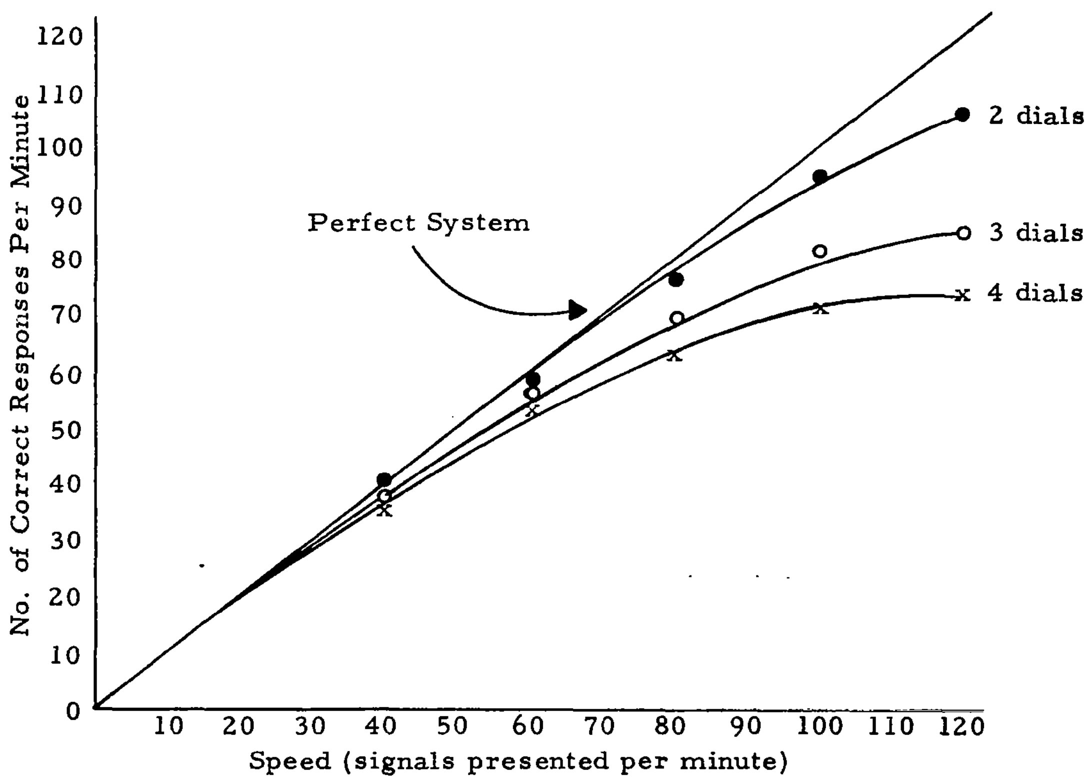


Figure A-2. Conrad's Data Simply Transformed to Show Correct Responses Instead of Errors.

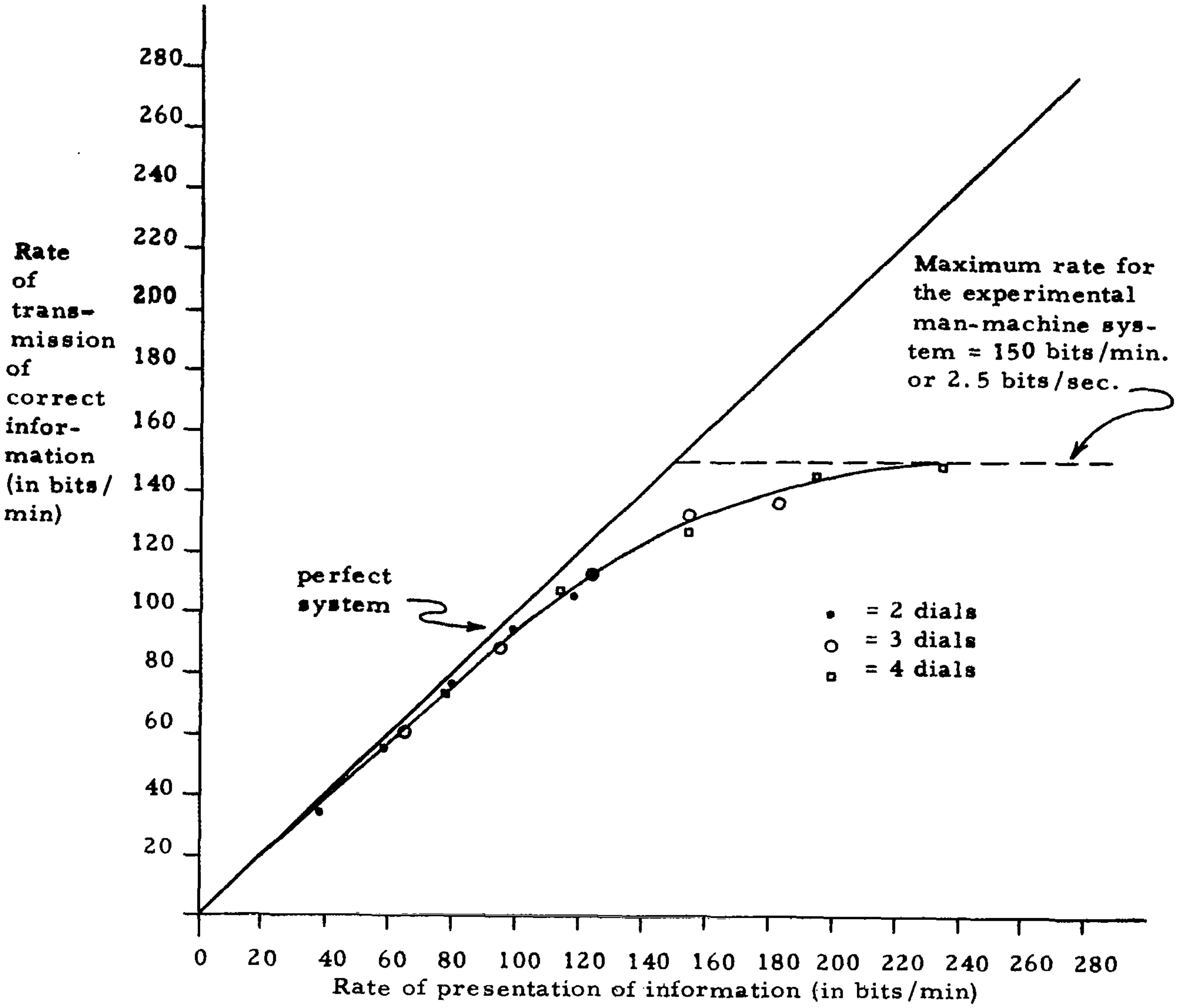


Figure A-3. Conrad's data transformed and replotted in terms of information theory (information in bits/signal is given by

$$H = \sum_{i=1}^{n} P_i \log_2 \left(\frac{1}{P_i}\right) \quad \text{where} \quad \begin{cases} n = 2,\ 3,\ \text{or } 4 \text{ (no. of dials in use)} \\ P_i = \underline{\text{relative}} \text{ probability of occurrence of a signal on ith dial} \\ \text{(determined by dial generators)} \end{cases}$$

APPENDIX B

COMPARISON OF TASK DIFFICULTY

As mentioned earlier in this report, a high level of difficulty was selected for the operator's control task during the experiment. This was accomplished on an empirical basis by adjusting the amplitude of oscillations produced by the random function generators until an appropriate level was achieved for each tracking dimension. The resultant waveforms were considered sufficiently difficult to challenge even the well-practiced operator, i. e., close to perfect performance was considered impossible. In order to determine the effects of a less difficult control task on performance, a second experiment was conducted using the display configuation for Condition I, described previously.

1. Method

The general method was to compare the effects of the disturbance waveforms, used in the previous experiment, on performance with those of a much simplified and reduced nature. The latter waveform consisted of only half the amplitude of the slowest oscillator for both tracking dimensions. For the x-dimension of the vehicle, the input frequency was 0.066 Hz. with a peak-to-peak amplitude of 10 volts. For the y-dimension, the same frequency was used with a peak-to-peak amplitude of 7.5 volts. The same equipment and procedures, described above for the first experiment, were also used in this investigation. A staff member of Dunlap and Associates, Inc., served as a subject. He was found to possess average tracking ability on the control task.

2. Results and Conclusions

The results of the study are contained in the following table.

		DIFFICULT	EASY
TRIALS	1	1070	611
	2	1275	830
	3	1548	637
	M	1297	692

These data indicate that the average error score was reduced by approximately one half when the disturbance waveforms for both tracking dimensions contained only one half the amplitude of the slowest oscillator. The tracking task, therefore, may be considered only half as difficult. Elimination of the input disturbance would be expected to reduce the error close to zero for the trained operator.

Table C-I

Error Scores for the Experimental Conditions

CONDITIONS

SUBJECTS	A	B	C	D	E	F	G	H	I	J	K	Σ x	M
1	2047	1351	1426	1850	1741	1540	1234	3010	1373	1423	1071	18066	1642
2	1840	2839	2722	2767	1863	1200	2072	3854	1097	2813	1159	24226	2202
3	1217	1044	1233	2222	1482	1141	1990	3958	960	1489	1658	18394	1672
4	1900	1758	1786	2903	1850	1772	1473	2235	1545	2265	1916	21403	1946
5	1689	1637	1510	1899	1655	1740	2528	2484	1127	1685	1661	19615	1783
6	1687	1464	1720	2640	2092	1803	2189	4422	1482	2693	2761	24953	2268
7	1638	1580	1508	2505	2012	2001	1681	4437	1479	2362	2044	23247	2113
8	1265	1239	976	1541	1381	1412	1616	2435	545	1958	1387	15755	1432
Σ x	13283	12912	12881	18327	14076	12609	14783	26835	9608	16688	13657	165659	
M	1660	1614	1610	2291	1760	1576	1848	3354	1201	2086	1707		

Table C-II

Error Scores Arranged in Terms of the Sequence of Presentation

SEQUENCE OF TRIALS

SUBJECTS	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
1	1423	1741	1071	1540	1234	1850	3010	1373	1426	2047	1351
2	1863	1159	2072	1097	2813	3854	2767	2839	2722	1840	1200
3	3958	1233	1217	2222	1044	1482	1141	1489	960	1990	1658
4	1758	1545	1786	1900	1850	1473	1916	1772	2235	2265	2903
5	1689	2528	1637	1510	2484	1661	1655	1899	1685	1740	1127
6	1687	2189	1464	1720	4422	2761	2092	2640	2693	1803	1482
7	2505	2001	1681	2012	2044	2362	1638	1479	1508	4437	1580
8	545	1239	1541	1387	1265	1412	1958	976	1616	1381	2435
Σx	15428	13635	12469	13388	17156	16855	16177	14467	14845	17503	13736
M	1929	1704	1559	1674	2145	2107	2022	1808	1856	2188	1717

Table C-III

Summary of Analysis of Variance Comparing Mean Error Scores
for Conditions A, D, I, and J.

SOURCE	SS	df	MSS	F	P
Treatments	5605478	3	1868493	19.5	<0.001
Subjects	3055872	7	436553		
T x S	2009578	21	95694		
Total	10670928	31			

Table C-IV

Summary of Analysis of Variance Comparing Error Scores
for Conditions A, B, and C.

SOURCE	SS	df	MSS	F	P
Treatments	12508	2	6254	.09	N.S.
Subjects	3527746	7	503964		
T x S	1024555	14	73183		
Total	4564809	23			

Table C-V

Summary of Analysis of Variance Comparing Mean Error Scores for Conditions D, E, and F.

SOURCE	SS	df	MSS	F	P
Treatments	2204942	2	1102471	14.5	<0.001
Subjects	1702078	7	243154		
T x S	1063050	14	75932		
Total	4970070	23			

Table C-VI

Summary of Analysis of Variance Comparing Error Scores for Conditions E and F.

SOURCE	SS	df	MSS	F	P
Treatments	31240	1	312400	.28	N. S.
Subjects	885718	7	126531		
T x S	787383	7	112483		
Total	1724341	15			

Table C-VII

Summary of Analysis of Variance Comparing Mean Error Scores
for Conditions I, J, and K.

SOURCE	SS	df	MSS	F	P
Treatments	3154490	2	1577245	11.14	<0.01
Subjects	2884616	7	412088		
T x S	1982499	14	141607		
Total	8021605	23			

Table C-VIII

Summary of Analysis of Variance Comparing Error Scores
for Trials (Practice/Fatigue).

SOURCE	SS	df	MSS	F	P
Treatments	3582118	10	358212'	.73	N. S.
Subjects	6853410	7	979059		
T x S	34302540	70	490036		
Total	44738068	87			

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NASA-Langley, 1967 —— 5 CR-808