THE MEASUREMENT OF VISUAL SEARCH

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INTRODUCTION

There are many reasons for recording eye movements; hence, there are many different types of eye movement data. In the measurement of visual search as I will discuss it today, the data of interest are accurate records of the sequence of eye fixation locations with respect to the contents of the visual field. In other words, where was an observer looking at any given point in time and what was the order in which he fixated different locations? Recording accuracy is defined in terms of how well eye fixation records coincide with where a subject actually fixated.

There are a number of areas where visual search data are extremely useful. For example, they can:

- Provide unique information in display evaluation efforts
- Serve as a basis for display design specifications
- Provide guidelines for the specifications of parameters for visual world simulators.

And, of course, these data are indispensable to the development of meaningful programs in visual search training.

As background for the discussion of the use of eye movement data, let me review three of the more widely used techniques for obtaining such data. I will refer to them as the electro-oculograph recording technique, the motion picture recording technique, and the corneal reflection recording technique.

MEASUREMENT TECHNIQUES

Electro-Oculograph

The basic components of apparatus used in the electro-oculograph recording technique include:

- Electrodes
- Amplification system
- Recording medium - x-y chart, CRT/film

The electrode arrangement is shown in Figure 99. The electro-oculograph operates on the fact that the retina of the eye is a polarized layer with the positive side towards the lens system and cornea. This makes the cornea electrically positive and the back of the eyeball electrically negative. When electrodes are affixed to the skin as shown in Figure 99, any given electrode will become electrically positive as the cornea rotates to reduce the distance to that electrode. The changes in polarity are amplified and either recorded in x and y coordinates, as shown in Figure 100, or used to drive a CRT display in two dimensions. The display format is recorded on film for a permanent record.

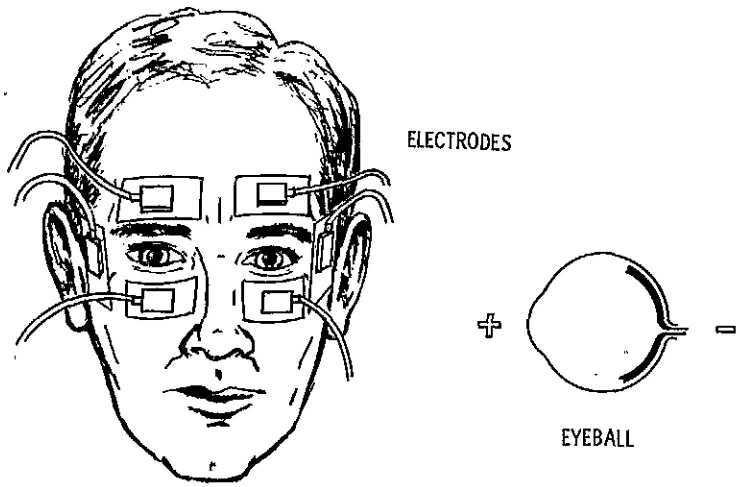

Figure 99. Basic Components of Electro-Oculograph Recording Technique

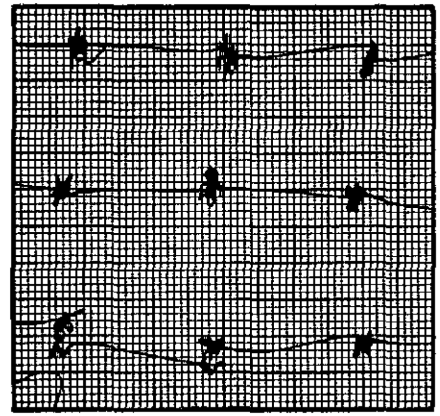

Figure 100. Enlargement of Portion of X-Y Chart Recorder Printout Showing Matrix of Eye Fixations

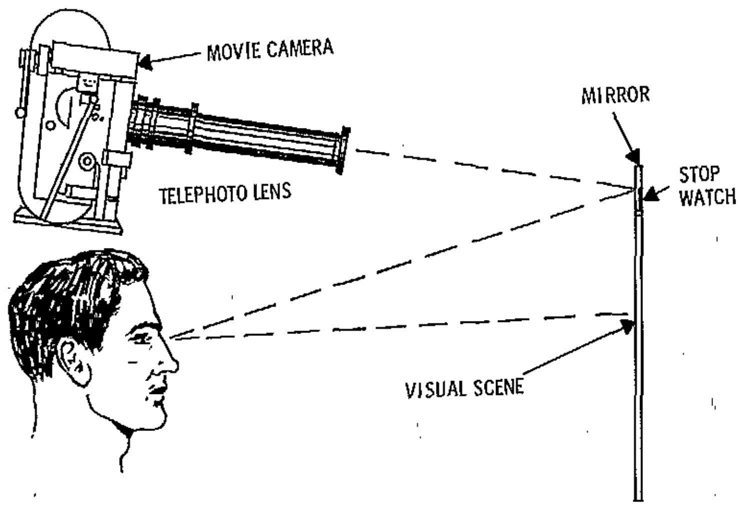

Figure 101. Basic Components of Motion Picture Recording Technique

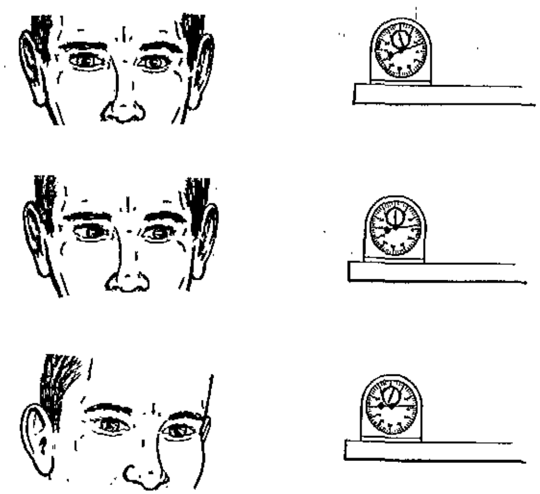

Figure 102. Film Record Obtained With Motion Picture Recording Technique

Advantages of this approach include:

- Accuracy between 1° - 2° visual angle (va)
- Vision with both eyes unimpaired
- Not subject to corneal configuration or refraction errors

Disadvantages include:

- Head movement relative to the apparatus introduces error
- Manual data reduction laborious
- Difficult to maintain satisfactory signal-to-noise ratio

Motion Picture

A second method for recording eye movements is the motion picture recording technique. The basic arrangement of components used in this approach is shown in Figure 101. The components include:

- Movie camera
- Mirror
- Timer

An example of the type of data obtained is shown in Figure 102. Each face/timer combination represents a frame of film. By comparing the direction of gaze with known location of objects in the visual field the location and sequence of fixations are determined. The time record permits determination of fixation duration and rate.

Advantages of the technique may be summarized as follows:

- Permits head movement
- Convenient to use
- Useful field of view is large

Disadvantages include:

- Laborious data reduction procedures
- High susceptibility to scoring errors
- Low accuracy

Corneal Reflection

The corneal reflection recording technique is feasible because the radius of curvature of the cornea is smaller than that of the eye. Thus the center of curvature of the cornea is displaced relative to the center of rotation of the eye. This is illustrated with the outline of the eyeball shown in Figure 99. The cornea, like the convex surface of a lens, reflects part of the light falling on its surface as the corneal reflex (the sparkle of the eyes). Because the center of rotation of the eye and the center of curvature of the cornea do not coincide, the angle at which a stationary source of light is reflected in the cornea changes during a movement of the eye so that the corneal reflex moves when the eye moves.

The basic components of apparatus used in the corneal reflection recording technique as shown in Figure 103 include:

- Light source - infrared or white light
- Beam splitter - half-silvered mirror to reflect eye spot
- Lens system - to focus eye spot
- Signal transport system - fiber optic bundle or electrically-transduced signals
- Recording medium - film, video tape, or x-y chart printout

Three systems represent present equipment design concepts using this technique. They are:

- Oculometer - developed by Mr. John Merchant at the Honeywell Radiation Center in Lexington, Mass.
- The Mackworth System - developed originally by Dr. Norman Mackworth, now at Stanford University
- Honeywell visual search apparatus - a research tool developed by Dr. Leon Williams at the Honeywell Systems and Research Center, Minneapolis

An example of the eye fixation data obtained with the Honeywell visual search apparatus is shown in Figure 104. The scoring technique is illustrated with an overlay viewgraph presentation. This represents eye fixations in a real world night vision search task. Note that the location of each fixation and the path of movement is clearly visible. The double spot is produced by a second light source triggered by the observer to indicate he has found the target.

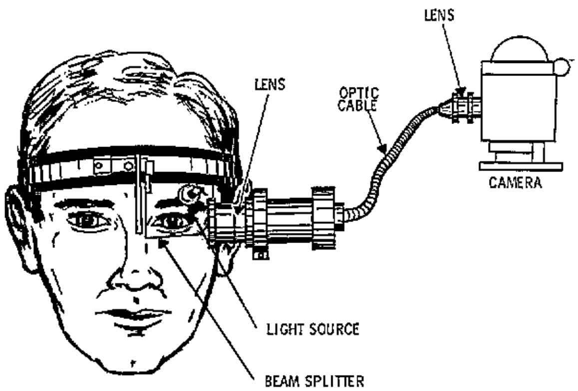

Figure 103. Basic Components of Corneal Reflection Recording Technique

Figure 104. Eye Fixation Record Taken in a Night Vision Search Task

Figure 100 illustrates a portion of an x-y chart recorder printout showing a matrix of eye fixations. This type of data is currently available from the Oculometer.

Eye fixations records obtained with a Mackworth camera resemble those obtained with the Honeywell visual search apparatus. However, no saccade traces are visible because of the type of light source and film used. The eye spot movement and visual scene are integrated optically before being recorded on motion picture film. In an alternate technique, the integration is accomplished electronically and displayed on a TV screen.

The three variations on the corneal reflection technique have similarities and important differences in their advantages and disadvantages. These are summarized in Table 3.

Table 3. Advantages and Disadvantages of Variations on Corneal Reflection Recording Technique

Characteristic	Honeywell Visual Search Apparatus	Oculometer	Mackworth System
Advantages:			
Accurate to 1° va or less	X		
Accurate to 1° -2° va			X
Vision in both eyes unimpaired	X		
Good Film resolution of eye spot and saccade track	X		
Light source not visible	X		
Can tolerate some head movement		X	
Can be head-mounted for mobility			X
Manual data reduction relatively easy			X
Can be used in a closed-loop system with a computer	X	X	X
Disadvantages:			
Manual data reduction laborious*	X	X	
Even slight head movement introduces error	X		X
Vision in one eye reduced by beam splitter		X	X
Useful field of recording 30° -40° va	X	X	X
Light source quite visible			X
Parallax errors become a problem when viewing close objects		X	X

* A digital eye fixation incremental recording system is being developed for the Honeywell visual search apparatus which will provide automatic data reduction.

Other Techniques

Of course, other techniques for measuring search behavior are used. These include purely optical systems such as those using mirrors mounted on suction cups which are attached to the cornea. Mirrors are also attached to contact lenses. The suction cup devices were developed by Yarbus (1967). This technique produces highly accurate data, but the devices are very difficult to fabricate and can only be used for a few minutes at a time on the anesthetized cornea. Contact lenses arrangements suffer from errors introduced through slippage of the lenses.

The point is that there are many techniques for measuring visual search behavior. There is no one technique available as yet which is best undal all circumstances. Thus, the goals of any research where eye fixation data are to be taken must be considered carefully and a technique chosen which has the most relevant advantages and the least debilitating disadvantages for the research at hand.

VISUAL SEARCH

A program of research on visual search behavior has been under way at the Honeywell Systems and Research Center for over five years. A major objective of this effort is the development of models of visual search which can be used to predict search times.

The conceptual background for this work may be described as follows. When an observer searches for a target, his eyes fixate one point after another in the field. If it were possible to predict the average number of eye fixations for a given search task, then the average search time would follow directly. The basic assumption is that the number of fixations depends upon the observer's ability to perceive objects in peripheral vision and that this ability can be predicted from two factors - his knowledge about the target and the composition of the search field. When the observer seeks a given target, he is more likely to fixate some objects than others. The likelihood of his looking at the given object depends on its similarity in peripheral vision to the target as he conceives of it. This can be estimated by studying eye fixations of observers during search.

Ordinarily the search task is regarded as involving an observer who searches for a target in a background. Then one attempts to relate the target's characteristics to search time. However, it is much more realistic and useful to consider that there are two "targets" - the target as it appears in the display and the target as the observer conceives of it. The target as it appears has specific size, shape, brightness, orientation, position, relationship to other objects, etc. The target as conceived is what the observer knows about it and, consequently, what he is looking for. He may know its size and shape, for example, but not its color and orientation. In the general case, he has only probability information about its characteristics.

Two generations of equipment have been used to obtain data on search behavior at the Systems and Research Center. During the early phases of the program, equipment such as is illustrated in Figure 103 was used. The stimulus materials were abstract fields containing objects which differed on such dimensions as color, size, shape, and contrast.

The equipment now used is shown in Figure 105. Note that the beam splitter/fiber optics components have been replaced by a mirror/telephoto lens arrangement. The mirror serves the dual purpose of providing the eye spot reflection for the camera and the visual scene for the observer. The visual scene is projected on a four-foot portion of a glass rear-projection screen. This arrangement provides much better resolution of the eye spot and saccade traces than can be obtained through fiber optics and leaves the view through both eyes unobstructed by a beam splitter. Also, the observer does not have distractions created by uncomfortable gear worn on the head.

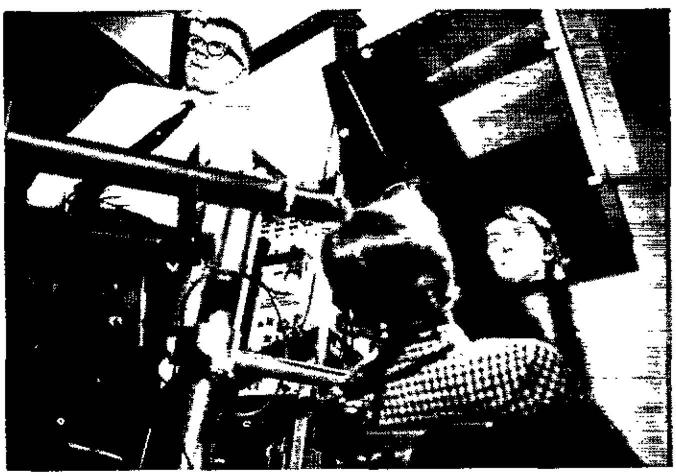

Figure 105. Recording Eye Movement Data With the Honeywell Visual Search Apparatus

A large data base has been established over the past five years through the program of research on visual search behavior. The effects of color, size and shape on search behavior have been studied (Williams, 1966a). Color was found to be the most effective way of coding information location. That is, the question of where to look next is answered most efficiently when the searcher has information about target color on which to base the decision. Size was next in order of effectiveness. Shape information was of little help. This latter finding is not too surprising considering the relatively low acuity of peripheral vision. Also, shape is a multidimensional characteristic. The amount of information available in shape probably cannot be processed effectively in peripheral vision within the time constraints of the duration of a fixation. Another explanation might be that color and size can be organized into or encoded as figure/ground relationships and the search strategy based upon these relationships rather than on the appearance of individual objects. The shape-variable does not lend itself to this kind of organization.

Contrast has been studied as a factor affecting search behavior (Williams 1966b) as have the dimensions of color-hue, saturation and lightness (Williams, 1967). The orderliness of the relations established have made it possible to derive a model of search behavior which can be used to predict search time as a function of target characteristics and the composition of the search field.

APPLICATION OF EYE MOVEMENT DATA

Display Design and Evaluation

As I mentioned in my opening remarks, visual search data can provide unique inputs to display design and/or evaluation. A study surrently under way at Honeywell's Systems and Research Center will serve to illustrate a design input.

It has been accepted generally that one should not use more than seven to ten colors in a color coding scheme. This is generally true if each color must identify or represent a unique combination of information. However, it became evident from the work with color (Williams, 1967) that if color were used to code only the location of information one could be a great deal more flexible in the number of colors used. A systematic determination of the similarity among colors differing on the dimensions of hue, saturation, and lightness was carried out. From these data, a large number of objectively different colors could be identified.

The current study is testing the effectiveness of color-coding the location of potential checkpoints on aeronautical charts. As many as 28 different classes of checkpoints, and hence 28 different colors, are used on some maps. An example of such a map is shown in Figure 106.

The implications for use of color coding for information location on displays are great enough to warrant a good deal more research. The similarity values for color are affected by factors such as types and intensity of illumination and type of materials used to generate color (Munsell paper, phosphorous, filters, etc.). Thus, similarity values would have to be determined for specific situations.

Visual World Simulators

In developing visual world simulators, we must determine how much of the visual world we need to simulate and with what fidelity. Visual search experiments can help provide the answers. Providing complete, high-fidelity visual world stimuli in a flight simulator is a costly proposition. The question of how much of this information and context is really necessary to provide the optimal simulator training environment is an important one. Visual search data can produce valuable insights in answering this question.

Figure 106. Portion of Aeronautical Chart Color-Coded to Facilitate Information Location

Another question vital to optimum simulator and display design is whether information is overlooked or whether it is not processed. The implications for designs are different. The only way to answer this question is with eye fixation data.

Visual Search Training

Efforts have been made in the past to train effective visual search, and the characteristics of effective search behavior have been proposed. By and large, however, these efforts have been ineffective. The reason for this ineffectiveness is that the conclusions and recommendations have been based upon inappropriate or inadequate data.

For example, fixed-pattern scanning techniques have been suggested, such as a reading format scan pattern. It is obvious from Williams' (1966a, 1966b, 1967) data that fixed-pattern scanning would be appropriate only if the observer had no information about the target which could be used by the peripheral vision system to structure the search pattern. Even then, there is serious doubt that it would be any more effective than the so-called random-search pattern.

A number of techniques for measuring visual search behavior are now available which can produce the kind of data which is needed. We need to be able to quantify the behavioral differences between "good" and "poor" searchers. To do this, we must determine what dimensions are appropriate. Likely candidates are length of fixation, length of saccade, spatial characteristics of the search patterns, and information processing efficiency. We must also look beyond the eye movement records.

As I mentioned earlier, the searcher looks for his concept of the target. Therefore, we must include consideration of factors affecting short-term and long-term memory as a means of increasing the communality between actual and conceived target characteristics. Performance aids must also be considered for relevance to maintaining adequate "target concepts."

Closed-loop systems which integrate eye movement recording devices and computers offer challenging capabilities for the study of visual search behavior. Such facilities can double as research tools and training devices. The Oculometer has already been tested in a closed-loop system at MIT. Work is nearing completion on a closed-loop system incorporating the Honeywell visual search apparatus developed by Williams. The latter system will have extensive data processing capabilities as well as the eye-movement-driven display features.

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