EFFECTS OF LIGHTING AND BACKGROUND WITH COMMON
SIGNAL LIGHTS ON HUMAN PERIPHERAL
COLOR VISION

by

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A THESIS

IN

INDUSTRIAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Technological College
in Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

Approved

Accepted

June, 1987

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ACKNOWLEDGMENTS

I am deeply indebted to Dr. Richard A. Dudek for his direction of this thesis and to the other members of my committee, Drs. Mohammed Ayoub and Monty Davenport, for their helpful criticism. Thanks also goes to Dr. Paschal Strong for his aid in direction of the study and helpful criticism. A special appreciation is offered to my wife, Angela Colton, for her fortitude and help in every way to attain my goal.

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CHAPTER I

INTRODUCTION

Purpose

The importance of color vision and peripheral vision has long been recognized in industry. There has been a large amount of research conducted primarily by optometrists and psychologists, to explain the physiological and psychological aspects of color vision. Many tests, some successful and others unsatisfactory, have been devised to measure and examine the degree of color discrimination among humans and animals.

A study of available literature indicates that most of the work to date has been concerned with color vision in the fovea. No material was available concerning the relationships of peripheral color vision to an industrial situation.

This research study was designed to investigate two aspects of binocular peripheral color vision. The first purpose was to study the relative position of the fields for red, yellow, green and blue test lights, hereafter referred to as the relative color field study. This is in effect determining the point at which a true color is recognized by an observer. The second purpose was the investigation of the apparent color change of the test lights as they were moved inward from a position outside of the subject's field of vision and before the true color was recognized. For the remainder of this thesis this will be termed the "false color" study.

History

The interest in investigating peripheral color vision and its industrial applications was first generated by an experiment conducted by members of the Advanced Work Measurement Class of the Industrial Engineering Department, at Texas Technological College. (See Appendix I.) Prior to the start of the experiment an attempt was made to find reference work on peripheral color vision and its industrial applications. Since no references were available which mentioned uses or applications pertinent to industry, it was concluded that this field was relatively unexplored.

During the experiment the subjects commented on an apparent color change in the test objects as they were moved into the subject's field of vision. This phenomenon was of considerable interest to the group conducting the experiment. Attempts to explain the appearance of the false colors were unsuccessful.

At this time the optometrist at Reese Air Force Base, Texas, was consulted and was unable to explain this appearance of false colors. He stated that he did not know of very much research that had been conducted in the area of peripheral color vision. At his suggestion, books by Dr. Joshua Zukerman (1) and Dr. W. D. Zoethout (2) were obtained.

Neither Zukerman nor Zoethout discussed at length the apparent color change of test objects as they are moved from a point outside of the field towards the point of fixation.

Zukerman (1; page 82) states:

If colored test objects of sufficiently large size are used

they can be seen even at the extreme periphery, i.e. where normally form (white) is visible. A small colored test object which is invisible at the periphery of the field of vision presents several changes as it approaches the point of fixation before it is identified as its true color. For example, a green test object appears first as yellow, then as yellow-green and finally as green, red appears yellowish, yellowish orange, orange-red, and finally as red.

Zoethout (2; page 204) states:

Some colors in passing from the fovea to the periphery undergo a series of changes in their hue before they finally lose all color; other colors, known as the stable or invariable colors, do not change in hue but become more and more unsaturated until they finally fade into a colorless gray. The stable colors are given variously by different investigators; according to Hess they are 574 mu (yellow), 495 (green), 471 (blue), and a purplish red. For this reason these colors are sometimes spoken of as being physiologically pure. In passing from the fovea to the peripheral regions, the colors having wave lengths longer than 549 mu pass through a yellow stage before they appear colorless; those of shorter wave lengths pass through blue.

During the Advanced Work Measurement Class experimentation, data were not recorded for the false colors; however, it was noted that this phenomenon does exist. The information given by Zukerman and Zoethout is not in sufficient detail to be of much possible benefit to industry. They were not concerned specifically with common industrial panel lights, nor did they consider the effect of the color of the background or the level of the environmental light.

It was felt that the investigation of false colors would be a fruitful field for further research. Errors committed by a worker because he mistook the color of a signal light are intolerable. The rising cost of production in industry requires that no avenue be left unexplored in an attempt to cut expenses.

It is believed that incorrect feedback of information from a worker's peripheral vision can and has caused accidents and errors in judgement. A typical situation could be: a worker is intent upon his

job and suddenly he sees a light in his peripheral vision. The worker thinks the light is green, indicating the end of a process, so he stops the process. He then turns his head toward the light and realizes it is actually a yellow light indicating that the process has entered the second stage and everything is operating normally. Since he stopped the process before time, the work that was being performed was ruined and had to be discarded. Even if he began to turn his head toward the light as soon as it was noticed, there is a possibility that his reflex action at the thought of a green light would have been dominant and he would have thrown the switch anyway.

A person's brain is rather "mule-headed" and dislikes to admit that it was wrong and change a decision already made. Even though the worker had finally turned his head far enough to recognize the light, there would have been a lag while the brain was convinced to change its decision. Reflex patterns are faster than those requiring a decision (3; page 32). Thus, even though the color of light is finally recognized, the reflex action has probably already been completed before the brain can take hold and keep the worker from throwing the switch.

When the means for the peripheral color fields obtained by the Advanced Work Measurement Class were plotted, it was noted that these were not in complete accord with the color fields given by Zukerman and Zoethout.

Zukerman states:

The isopters for colored test objects should be of normal average extent and position. Normally, they increase in size successively in the following order: green, red, blue and yellow. (1; page 134) (See Figure 1.)

Fig. 1.--Average normal isopters for colors. Color isopters presented in successively increasing order of size, obtained at the perimeter, with 5/330 green, red, blue and yellow test objects, respectively

Normally the color fields are those for green, red, blue and yellow, in increasing size. If this order is disturbed, inversion is present. (1; page 32)

In a similar vain Dr. Zoethout (2; page 204) says:

In a similar manner the retina shows a varying sensitivity to colors. As usually investigated by the perimeter, with a constant size of test object of colored papers the retina is seen to have five somewhat concentric fields. As the test papers of green, red, yellow and blue are moved from the center outward the green color is seen last, its field not extending much beyond 20; red is next to lose its color, to be followed by blue and yellow, successively. Outside of the area sensitive to yellow, lies a field in which no color, but white or gray can be perceived; this outlying area is therefore said to be totally color-blind.

These fields are not always completely distinct from each other; interlacing may take place, as shown in Figure 99 (See Figure 2). By some the blue field is said to be more extensive than the yellow and that violet has the most circumscribed field of all the colors.

It is apparent that there is some difference in opinion between Zukerman and Zoethout. They offer no indications as to how, when, or where the boundaries of the peripheral color fields were obtained. They do not indicate if statistical methods were used to determine if there is a difference between the color fields. They agree as to the order of the color fields, but not as to the shape of the field.

It must be recognized that the Advanced Work Measurement Class experiment was not conducted under the most ideal scientific conditions. The five subjects that were used were not tested for color blindness, but were only asked if they had any color defects of which they were aware. There were no tests used to determine if all of the subjects had approximately the same peripheral vision for a white test object.

There are four important factors that affect the recognition of hue and the peripheral angle at which a color is recognized.

Fig. 2.--A map of the visual field of the right eye (Krapart)

Zoethout (2; page 204) states:

The extent of the retina through whose stimulation by various ether vibrations we can become conscious of color sensations depends upon several factors among which we may list: 1. condition of the retina as to light adaptation, 2. the nature of the stimulus with respect to the wave length saturation and intensity, 3. the size of the test-object, 4. the condition of the field surrounding the test-object.

1. Condition of the retina - It goes without saying that to determine the sensitivity of the retina to colors, the eye must be in the light adapted state. As any part of the retina adapts itself very speedily to any form of stimulation (see Chapter XX), the test-object should not be allowed to remain on a certain area for any considerable length of time.

2. Intensity of the light - The greater the intensity of the light, the larger is the retinal field for any color. It is claimed that with sufficient illumination, the field for every color is coextensive with that of colorless (White) light. The achromatic field is thus reduced to a very narrow strip or disappears entirely. The peripheral portions of sensitivity to certain wave lengths is less than that of the fovea and with stronger illumination they respond in a manner similar to that of the fovea. Ferree & Rand state that the above is not true for green colors, these have a somewhat restricted area.

When test papers are used, it should not be forgotten that the illumination of a pigment by white light decreases its saturation and hereby decreases the power of the individual to recognize the color. It is, for this reason, that the spectral colors, where luminosity can be very largely increased without sacrificing saturation, are far superior to pigment colors.

3. Size of test-object - The test-object subtending a visual angle of 5 degrees may be readily perceived at a certain peripheral portion of the retina where an object of 1 degree would only evoke a sensation, of gray. This may therefore be a source of error in color field mapping. It is stated that a color test-object of 5 degrees is recognized over the whole retina, no matter what the color may be.

When radiometric units of intensity are used, that is, when the various colors exhibited have the same energy content, the hue sensitivity is greatest at the fovea and decreases progressively towards the periphery. The greatest area of sensitivity is for yellow, next blue and green and least for red.

It will be seen from the above discussion that in photopic vision the various parts of the retina differ quantitatively and not qualitatively. There is merely a variation in the sensitivity both as to the appreciation of light intensity and hue; there is no difference in kind, such as exist between photopic and scotopic vision. The periphery instead of being achromatic should more properly be spoken of as being dyschromatic.

4. The nature of the surrounds - Whether a color can be recognized at a certain part of the retina also depends upon the nature of the field surrounding the test-object. The color field is the largest when the light intensity of the surrounds and of the test-object are equal. Placing the test paper in a dark holder therefore reduces the retinal color field.

It would be appropriate to compare the conditions under which the Advanced Work Measurement Class experiment was conducted to these which Zoethout says are important. Taking these factors one at a time and relating them to the experiment, it is seen that:

1. Condition of retina: The eyes of all subjects were adapted to the level of environmental light in the room in which the experiment was conducted. As much as it was possible moving the test objects by hand, a constant velocity of movement was used. Consequently the stimulus did not remain on the same area of the retina for any period of time.

2. Intensity of light: The intensity of light for all colors of test objects, color of background and subject was virtually the same, though not measured.

3. Size of test object: The effective size of the test object did not remain constant as the object was moved from the outer edge of the test board to the center. The board was a flat surface and at any location other than the exact center only an oblique view of the test object was presented to the subject. The subtended visual angle increased from $1^{\circ} 21'$ at the ninety position to $12^{\circ} 40'$ at the exact center position.

4. Nature of surrounds: The experiment was conducted with both white and black backgrounds against which the test papers were viewed.

It is not intended to compare the angles of peripheral color

vision found during the Advanced Work Measurement Class experiment to those presented by Zukerman and Zoethout. This would be presumptuous as several factors that affected the size of the fields cannot be compared.

Any differences caused by the condition of the retina, intensity of light, size of test object, and background would be the same for all of the colors of test objects. It would, therefore, appear that the relative positions of the color fields obtained by the experiment and those given by Zukerman and Zoethout should be comparable. Assuming comparability, it was noticed that the positions of the fields as given by Zukerman and Zoethout were not the same as those obtained by experiment. The most notable divergence was a reversal of the yellow and blue fields over most of the field of vision.

On the black background, the color blue was seen at a greater distance than the other colors, except for a small area around 330 degrees and also between 90 degrees and 123 degrees. On the white background red tended to be seen at a greater distance than green over most of the field.

Industrial Considerations

The scarcity of reference materials plus the tendency for there to be some areas of disagreement between Zukerman and Zoethout led to the conclusion that further research, primarily concerned with an industrial viewpoint, would be fruitful. The research was to include variables such as colors of background and levels of environmental light that would be found in industry. In addition binocular instead of monocular vision would be emphasized.

The main purpose of the study of relative positions of fields for color was to determine which colors of the specific panel lights used would give the largest field of recognition. At the present time it appears that red and green lights are the most frequently used colors on industrial control panels. This assumption is based on personal observation and interviews with distributors of panel light assemblies. This is possibly because most lights have been used merely for the purpose of giving dichotomous information. That is, red color would be used for a dangerous or stop signal and green for a satisfactory or go situation.

With increased automation and complexity of equipment it is quite likely that more colors of indicator lights will be required. Even if more colors of lights are not required, consoles are increasing in size to the extent that peripheral vision is becoming more and more important.

By determining which colors are seen the easiest, industry could attempt to locate lights of these colors where peripheral vision is most likely to be required. Also, in conjunction with design, if the color of background or the level of environmental light has an overall effect or an effect on any particular colors, the combination of color of panel light, color of background, and level of environmental light that gives the largest relative field of peripheral color vision could be used. Likewise, given a fixed color, background or environmental light level the other variables could be planned for maximization in the given situation.

The possibility of a worker misinterpreting the color of a signal light is also of importance. Colored test lights are thought to undergo an apparent change in color as they are moved into the visual

field of the eye. The false color study was designed to determine if these apparent color changes follow a random process, or if any particular test color is repeatedly thought to be of some other color before the test color is identified. As in the study of the relative color fields it was considered that the background and level of environmental light could have an effect on these color changes (i.e. false colors).

It would be of considerable importance if a definite relationship could be shown to exist between the relative color field study and the false color study. That is, it would be important to know that the colors which are recognized first in the periphery were also those least likely to undergo an apparent color change, or vice versa. While this study is primarily concerned with studying signal lights on control panels, it may be possible that industry would be able to utilize the data resulting from the experimentation in designing the workplace layout for assembly operations. The electronics industry uses color coded wires, resistors and other components in manufacturing electrical assemblies. The work station may be laid out so that the worker is primarily directing his attention to holding a soldering iron on a piece of work; this, then causes him to primarily identify the wire or component he is reaching for through peripheral vision. The workplace could be laid out so that components displaying colors recognized at the greatest distance in the periphery are located in more nearly optimum areas.

If, as it is expected, some colors are falsely identified as another color (outside the field of vision where they are always recognized) it would be well for industry to recognize this phenomenon. Suppose that it is shown that yellow is often thought to be green.

The workplace would then be designed so that components displaying these two colors would not be located close to one another. Consequently, if the components happened to be located outside the field of recognition for yellow, the worker would not pick up a yellow component thinking that it was green. He would know that a green component was not located any place near where he thought that he saw it and therefore would turn his head or eyes to correctly identify the color.

After consideration of the pilot study and the small amount of historical reference material available the possible experimental design, procedures, and equipment required to be used were developed. All of these had to be integrated into an overall concept that would produce a useful result and also fit within the allotment of time, materials, and facilities available. The logical order of consideration was to first determine the variables that would yield the most useful information and yet stay within limitations of equipment, time and facilities.

The variables, experimental design, equipment and experimental procedure will be discussed in the indicated order in Chapter II. The results obtained by using the above will be presented in Chapter III. In Chapter IV conclusions will be drawn from the results, and recommendations for future research will be presented.

CHAPTER II

EXPERIMENTAL DESIGN AND EQUIPMENT

This chapter will be devoted to the discussion of the experimental design and the test equipment used in the experiment. The discussion will include the variables used and the experimental procedure. This will involve an explanation of why the variables were chosen, how they were used, and the importance of each. The construction and use of the equipment will be explained.

The consideration of the experimental design and the selection and construction of the test equipment were of necessity interrelated. The practicality of obtaining or building equipment that would be required for the variables included in the experimental design placed constraints on the type, number and levels of the variables.

No attempt was made to design an experiment that determines the absolute field of peripheral color vision. That is, the investigation was not designed to determine if red is recognized at 70 degrees, or any other particular angle, from the central angle of the eye when viewed in the horizontal temporal position. The absolute field of color vision depends upon too many variables. The size and intensity of the test object are primary factors that affect the field. The larger and more intense a test object is the farther in the periphery the object will be recognized. The distance that the worker/subject is from the test object will of course change its apparent size. Another factor considered was that most industrial control panels or work stations are flat surfaces.

Hence, the farther the worker is from the location of the object (e. g. an indicating light), not only will the apparent size of the object be smaller, but the actual area of the object will be smaller as viewed by the eyes of the worker.

The study of false colors was conducted in conjunction with the study of the relative positions of color fields. The variables and conditions were consequently the same and applicable to both portions of the study. The discussion of experimental variables is logically broken into two categories: the dependent variables and the independent variables.

Dependent Variables

To map the relative positions of the binocular visual fields for colored test lights it was necessary to determine either the distance or the angle from the center at which the test light was seen. Angles could only be determined as a function of distance from the center of the test panel and the subject's distance from the panel; therefore, it was decided that distance in inches should be the dependent variable for the binocular visual color field portion of the study.

The false color portion of the study required information about whether or not a false color was named, and if so, what the false color was named. The datum for whether or not a false color was named was simply a yes or no. It was therefore decided that the dependent variable for false colors would be a one or a zero, indicating the naming or the failure to name a false color. This type of datum could be used by the analysis of variance technique that was used for the analysis of the resulting data.

Independent Variables

The criterion used to choose the independent variables for the

experiment was that of giving information that would be of value in an industrial environment. Four of the variables used, namely color of background, level of environmental light, test position, and the color of the test lights, were chosen to meet this criterion. The other two variables, trials and subjects, were chosen to facilitate the experimental design.

Color of Background

The variable, color of background, was further broken into three levels: black, a medium shade of gray, and white. Black and medium shades of gray are the most commonly used colors for display and control panels, and were chosen for this reason. The third color of background, white, was chosen for two reasons. First it was desired to use a color that would give results for the other extreme, that is, opposite of black. Data were gathered for the extremes of black and white, and the intermediate zone of gray was also covered. The second reason for considering white as the third level of the background variable for study was Zoethout's statement that placing the test paper in a dark holder reduces the retinal color field. This statement implies that a light background is best. If the white background was to give the largest field of retinal color vision, industry could consider using white backgrounds; however, the pilot study (Appendix I) raised doubts as to whether black or white were the best backgrounds. Examination of the data resulting from the pilot study revealed that over a large portion of the monocular visual field colors were recognized at a greater distance when viewed against the black background. As they were in disagreement with Zoethout it was deemed that the white background should be

included in a more rigidly controlled experiment and comparisons made again.

It was not expected that these three levels would allow postulation of linearity or non-linearity in the relationship of background and the relative positions of the visual color fields; however, by using three levels of the background variable the relationships of the extreme cases and the medium shade can be explored and extrapolations and general conclusions made from these.

Environmental Light

Many different types of lighting conditions are found in work situations. These depend mainly upon the type of work that is being accomplished. A missile/satellite control center for the Air Force would have to use entirely different lighting levels than an assembly station in a manufacturing concern. In the control room, lighting levels would be low in order that the room lights would not interfere with radar screens, television monitors and other displays. On the other hand, light levels in work areas where very small components are assembled would of necessity be high in order so that the extremely small parts could more easily be seen. High light levels would cause the pupils of the eye to contract. This would cause less light from the signal lights to enter the worker's eyes and thereby possibly reduce the distance at which he could recognize the signal light.

To study the effects of environmental light, three levels of indirect illumination were used. The high light level was 35 foot candles. The effective brightness of lights as viewed by a subject is a power function (4). The light levels used do form a power series although

each level is not twice the brightness of the previous level. Each level of the environmental light will appear to the subject to be proportionally higher than the previous level. These proportions will allow postulation as to the linearity of the effect that environmental light levels had on the recognition distance of true color. These levels were obtained using a direct reading foot candle meter facing the test board at the same distance and location at which the subject's eyes would be located. To insure that the light level was the same over all portions of the test the readings were made at the outer edges, the center and points between.

An industrial plant would not be expected to normally be able to adjust lighting levels so that the same amount of light was reflected from each color of background. Lighting fixtures are normally designed and installed to cover large areas and the color of backgrounds could vary over this area. It was desired to study how the recognition distance of color was affected by the color of background when the output of the environmental light source remains the same.

The readings were the result of reflected light from the white background. It is to be recognized that the light being reflected from the gray background would be less than that from the white background, and that reflected light from the black background even less. Each background would still reflect the high, medium and low light levels in the same proportions as the white background, 35:7:1.4. Similarly, the medium level of light reflected from the black background was one fifth of the high level, and the low level one fifth of the medium level. It would have been impractical to have attempted to hold the light levels the same for all backgrounds. Twenty-five hundred watts produced by photo

flood lights were required to produce the 35 foot candle light level for the white background. It is not known how many watts would have been required to produce the same level reflected from the black background. The lighting of the backgrounds was indirect as the flood lights were situated so that the direct beams of light did not strike the test board.

Test Position

The third variable considered was that of test position. The test position variable was quite important in that it was the factor which established the number of points to be plotted for the binocular visual color field on a two dimensional surface facing the subject. If too many levels of test position were used, for example, increments of 5 degrees, the study would become unwieldy because of the mass of data required. On the other hand if the test positions were too far apart, extrapolation between points becomes excessive. The data gathered in the pilot study indicated that using test positions 30 degrees apart would be reasonable, as only twelve positions are required and it is fairly easy to extrapolate between these points because the data were smooth and a pattern could be developed. Hence, twelve levels of test positions were used. The first position was at 0 degrees, the upper vertical position, the second position at 30 degrees clockwise as an observer faces the panel, and so on to position twelve being at the 330 degree angle.

Color of Test Light

The fourth variable considered to be of concern to industry was the color of test lights to be used. The selection of colors would in turn ~~determine the number~~ of test lights to be used. This variable is

the factor of primary interest as the other factors have been considered on the basis of the possible effect that they would have on the naming of the correct color of test light. There were a large number of colors and types of light sources available. Limitations had to be placed on the size, type and number of light sources considered to keep the size and complexity of the experimental equipment within reasonable bounds. Further consideration was that the light assemblies should be of a common industrial type.

Investigation into the type of assemblies available showed that the Drake, Type 100 was a commonly used assembly and could readily be adapted for use with the envisioned experimental equipment. The next consideration was the number of assemblies and colors of lens to use. Reference material from Zoethout and Zukerman had only four colors, red, blue, green, and yellow, that could be used for comparison. The pilot study had used six colors: red, orange, yellow, green, blue, and violet. Also considered was the fact that red, green, and blue are normally considered to be the additive primary colors and red, yellow, and blue the primary subtractive colors. Further consideration was given to the assumption that red and green are the most commonly used colors in industry while yellow and blue are also frequently used.

The final conclusion was that using the four colors, red, green, yellow, and blue, would yield the most significant results. Use of four levels of the color of light variable would also simplify and expedite the building of the experimental equipment.

The assemblies were fitted with jeweled lenses of the desired color. These were selected as the test object because they were of the same type commonly used for industrial applications. The lights were not selected

because they would necessarily be the best to use under conditions where peripheral color vision is necessary; however, it was considered that data obtained using one of the most commonly utilized lights would be best. It may be possible to use these particular data to make extrapolations and general conclusions about the relative positions of color fields and the apparent color changes of test objects.

The four variables of primary interest have already been discussed. Subjects used during experimentation added a fifth variable, subjects. A sixth variable, trials, was added to provide an error term for use in the analysis of variance.

Experimental Design

The experiment was designed so that the resulting data could be analyzed by use of the ANOV 6.0.090 program for the IBM computer. The experimental variables (factor) and levels of each are summarized in Table 1. Figure 3 shows the breakdown of the design diagrammatically.

The design was modeled after example 10.1 in Hicks (5; page 156) and the analysis was performed in the illustrated manner. The trials factor and interaction terms involving trials were used as the error term. This factor was chosen for two reasons. First the variances that it contained were within subjects. It was not expected that there would be any significant results by observing the behavior of this variable because the subjects had been trained and were not expected to show a learning curve.

Two analyses were required. The first analysis was made using the dependent variable of distance from the center of the test board that a light was correctly identified as to color.

TABLE 1
EXPERIMENTAL FACTORS

Factor	Type	Levels	Identification
Subjects	Between-random	1. Subject no. 1 2. Subject no. 2 3. Subject no. 3 4. Subject no. 4	A
Color of test light	Within-fixed	1. Red 2. Blue 3. Green 4. Yellow	F
Test position	Within-fixed	1. 0/360 degrees 2. 30 degrees 3. 60 degrees 4. 90 degrees 5. 120 degrees 6. 150 degrees 7. 180 degrees 8. 210 degrees 9. 240 degrees 10. 270 degrees 11. 300 degrees 12. 330 degrees	E
Color of background	Within-fixed	1. White 2. Black 3. Gray	C
Environmental light level	Within-fixed	1. 35 foot candle 2. 7 foot candle 3. 1.4 foot candle	D
Trials	Within-random	1. Trial no. 1 2. Trial no. 2	B

Fig. 3.--Diagrammatic presentation of experimental design

of experimental design

The second analysis was identical to the first except that the dependent variable was whether or not a color was named incorrectly as the test light was moved into the subject's field of vision. In this case, if the subject saw a false color a one was placed into the data column, and if he did not indicate a false color a zero was placed in this column.

In determining the experimental design it was decided that four male subjects having normal color and peripheral vision would be used. The four subjects were obtained from a larger group of volunteers in the Air Force Institute of Technology program at Texas Technological College. Each potential subject was given tests for color vision and peripheral vision by the optometrist at Reese Air Force Base. The potential subjects were tested for peripheral vision using a Perimeter, and four subjects were selected having peripheral vision within $\pm 2^\circ$ of each other. Peripheral vision could have been statistically controlled while performing the analysis of variance, but it was a better procedure to experimentally control this potential variable by having all subjects with approximately the same peripheral vision.

Each subject was tested for the four colors of light at each of the twelve test positions on each color of background used in combination with each environmental light level. In addition each subject was tested two times (trials) for each of the forty-eight color of light - test position combinations for each environmental light level on each color of background.

To prevent expectancy, the order of angle (test position) and color of test light for that position were determined by a random process. To

do this each of the forty-eight possible color of test light - test position combinations was written on a piece of paper and placed in a container. The papers were drawn from the container to determine the sequence in which each combination was to be given to each subject.

A partial counterbalancing was used to remove confounding of the order of test position and color of test light. This was accomplished by starting the second subject at slot number two in the table of forty-eight test position - color of test light combinations. Subject number three was started at the third slot and subject number four at the fourth slot of the pre-determined square. It was not possible to use complete counterbalancing as there were forty-eight starting positions and only four subjects.

Experimental Equipment

Equipment and facilities had to be provided that would enable the accumulation of the type and amount of data required. To meet this criterion it was decided that all four of the test lights should be mounted on one chassis. This light assembly would be built so that it would move on a track attached to a radial arm pivoted at the center of the test panel. The radial arm could be moved to any of the twelve test positions.

The size of the test panel and radial arm was dependent upon the size and intensity of test lights and also the distance that the subject was seated from the test panel. It was desired to have the subject seated a distance from the test panel that would approximate an industrial condition. This plan was discarded, however, and the size of the test panel was set to be eight feet square.

The eight foot dimension was chosen because it was the size of

readily available construction materials and also was as large as it was practicable to construct. The capability had to exist to change the color of background against which the test lights were viewed, to change the level of environmental light and to place the test lights at a given test position with a minimum of effort. The test lights had to be mounted on the equipment in such a way that they could be moved from the outer edge to the center at a constant velocity. The distance that the subject sat from the test panel was determined by experiment; the criterion was that the distance was to be such that the subject would not be able to see a light at the outer edge of the panel.

The completed test panel, as seen in Figure 4, is eight feet by eight feet and supported ten inches off the floor. The facing of the panel was one-eighth inch fiberboard bolted to a framework of one and one-half inch angle iron. Three-quarter inch slots were cut only from within four inches of the outer edges to within three inches of the center to prevent excessive weakening of the board. When the slots were out in the fiberboard it weakened it so much that a flat surface could not be maintained.

The assembly was strengthened by cutting an eighteen inch square out of the center of the fiberboard panel and replacing it with the same size piece of aluminum. Electrical conduit was bolted to the aluminum between the slots (Figure 5) and also attached by sheet metal screws to the fiberboard sections between the slots. This construction gave a test panel that was sufficiently rigid to withstand the many hours of testing required.

A most complex and time consuming problem was encountered when

Fig. 4.--Front view of completed test panel. Note that numbers have been placed by slots to indicate test position numbers. Panel is eight feet square and supported on ten inch legs.

Fig. 5.--Rear view of test panel showing radial arm attached and in test position number ten.

building the radial arm and the test light chassis. This radial arm had to hold the chassis rigid so that the test lights would run true in the slots cut into the test panel. The radial arm also had to support the motive power to drive the chassis inward and outward along the radial arm. The chassis was to provide a means of holding the light assemblies so that only one light assembly would be visible at a time.

The light chassis shown in Figures 6 and 7 was constructed first. Each light assembly was screwed into a section of aluminum tubing that was supported in an aluminum block. The inside of the chassis was drilled larger than the diameter of the tubing so that springs could be placed around each tube. The springs were used to hold the light assemblies in an extended position during testing as shown in Figure 8. Each assembly could also be locked into a retracted position.

The next problem to be solved was construction of the radial arm with a source motive power and tracks for the chassis. After trying several unsuccessful arrangements this was solved by constructing the radial arm of two pieces of commercial grade drapery traverse rod. The traverse rod was sufficiently rigid to support the chassis with no movement even at the mid-point. In addition the traverse rod provided a track and guide for the chassis. The chassis was guided by two machined, slotted rollers that were bolted to each side of the chassis, and rolled in the traverse rod as shown in Figure 9.

The motive power to move the chassis from one end of the radial arm to the other was provided by a reversible DC motor located at the center end of the radial arm. It was desired that the inward movement of the chassis be at one inch per second. The speed of the motor had

Fig. 6.--Partially disassembled light chassis.

Fig. 7.--Completed light chassis.

Fig. 8.--Light chassis on radial arm with one light assembly in the extended position for testing.

Fig. 9.--End view of radial arm showing how rollers on chassis fit into arm.

to be reduced to provide this speed. To provide for decreased RPM of the drive pulley and also give increased torque the speed was lowered through two reducing gears.

When the completed radial arm assembly was attached to the test panel, as shown in Figure 5 (page 28), it was discovered that the velocity of inward movement was not the same at all test positions. This occurred because the torque of the DC motor was not sufficient to be unaffected by having to pull the chassis vertically upward in test position number seven and also hold it as it tended to fall in position number one. The resulting velocity in position number one was much greater than that in position number seven.

This problem was resolved by setting up the voltage to the DC motor required to produce a one inch per second inward velocity in position seven. To get the voltage necessary to drive the chassis at one inch per second in the other positions, resistors were used to drop from the voltage used in the number seven position. The voltage did not have to be dropped for each position as they could be paired as follows: two and twelve, three and eleven, four and ten, five and nine, six and eight. This gave a total of seven voltages required.

The electrical distribution system shown in Figure 10 enabled selection of the required motor speed to drive the chassis at one inch per second. In addition the voltage dropping resistors could be bypassed by using the double pole double throw switch. Hence, the chassis could be returned to the starting position at a higher speed, thus conserving time during the experimentation.

The radial arm was supported at the outer end by a bolt placed

Fig. 10.--Electrical distribution system

at the end of each test slot. Stop nuts were located on the bolts so that the jeweled lenses on the light assembly would be flush with the front of the test panel.

Cloth tape measures were glued beside each slot on the rear of the test panel. These tapes were used to note the distance when a subject stated he saw a color.

A means had to be provided to insure that each subject's eyes were exactly eighteen inches from the center of the test panel. This was accomplished by building a device against which the subject could rest his forehead. The forehead rest, seen in Figure 11, in no way interfered with the subject's vision.

The three colors of background were achieved by painting the test panel with flat paint. The paint for the gray background was mixed using flat black and flat white. The light chassis was painted the same color as the background. The area behind the panel was covered in material the same color as the test panel was painted, to reduce variation in background as viewed through the slots.

The environmental light levels were produced by using photo flood lamps placed at various distances from the test panel. To get an even dispersion of the light over the test panel the flood lights were pointed at the floor, ceiling and walls; light reflected from these surfaces illuminated the test panel. This gave a very even distribution of indirect lighting on the test panel.

Experimental Procedure

Four male subjects having normal color vision and similar peripheral vision were used for the study. Prior to the start of testing,

Fig. 11.--Subject sitting
in testing position using forehead
rest.

each subject was given a training period in which he was to learn to recognize and pick the spectral colors. Learning was also controlled by this training period.

The testing was broken into eighteen testing periods for each subject. Each testing period consisted of showing the subjects each color of light at each test position on one color of background under one level of environmental light. Each subject was tested twice, trial one and trial two, at each level of environmental light on one background before proceeding to the next background. This was because the color of background could not be changed as readily as the environmental light levels. The backgrounds were used in the order: white, black, and gray.

Prior to beginning the tests the data sheets were prepared for all subjects. Each data sheet contained all the required tests to be given a subject during one testing period. The first three subjects were each started at a different environmental light level on each background and the fourth subject at the same level as the first. Each subject was tested on all three light levels on trial number one prior to starting trial two.

Time limitations did not allow all of the subjects to be tested at approximately the same time of day. The testing periods had to be scheduled as the subjects were available over a three week period. A ground rule was established that no subject would choose two consecutive testing periods, to control and reduce any effect of fatigue. Because each testing period required approximately fifty minutes, each subject was given a five minute rest break after one-half of the tests during

each period. This break was given to reduce eye fatigue resulting from the prolonged testing.

The subject was seated in front of the test panel so that the point halfway between his eyes was exactly centered on, and level with, the center of the panel. A forehead rest was provided and fastened to the chair in which the subject was seated. This rest was adjustable so that the subject's eyes were eighteen inches from the center of the test panel.

During the time that the forehead rest was being adjusted the subject's eyes were becoming adjusted to the lighting conditions. After the chair had been adjusted to height and the forehead rest adjusted, the subject was allowed to relax in the chair until a total of ten minutes had elapsed to allow his eyes to adjust to the experimental light condition. The subject could stand if he wanted, but he had to stand near the test panel and keep his eyes in that general direction.

After the ten minute adjusting period the subject was seated and the testing begun. The subject was instructed that when he was asked if he was ready, he was to focus his eyes on the head of the bolt in the center of the test panel. He was to maintain this focus until he was told that he could relax. When told to relax he was permitted to move his eyes.

Prior to asking the subject if he was ready the radial arm was moved to the desired test position, and the correct motor speed and the test light selected. When the subject replied "ready" the test light and motor were simultaneously turned on. As the test light moved toward the center of the test panel the subject named a color when he thought

that he knew what color of light was turned on. A chalk mark was made by the tape measure on the back of the panel at the location where the specific test light was at the time the subject named a color. The light chassis continued its movement toward the center of the panel. If the subject again named a color this distance was also marked. This procedure was repeated until the chassis reached the center of the panel. The distance at which the correct color was named was recorded on the data sheet. Also recorded were any false colors named along with the distance at which these false colors were named. The radial arm was moved to the next test position and the process repeated.

There were some cases of a subject's naming the color of test light correctly, then changing his mind and naming a false color, and finally naming the color correctly. In these cases the distance of the final correct call was recorded as the true distance and the other two were recorded as false colors.

The test light was always moved to the center of the panel. This insured that consistent test procedures were always used. If the test light was stopped at the position where a color was recognized, and not stopped when an incorrect color was named, the subject would know that he had named an incorrect color. He would then be warned to name another color.

After each testing period the subjects were asked for any comments they had on the testing. Many comments were made at this time as to the sensations that the subjects had as the test light was being moved into their field of vision. The subjects were not told if they were recognizing colors at a greater distance or lesser distance than any other

subject. The reason for this was an attempt to prohibit the testing from becoming a competitive effort between subjects.

The findings and interpretations resulting from the use of the procedure will be presented in Chapter III.

CHAPTER III

FINDINGS AND INTERPRETATION

Introduction

The data resulting from the experimentation were reduced and analysed by the method of analysis of variance. The significant effects will be presented and discussed in this chapter for both the distance at which a color was recognized and the percentage of errors made prior to recognizing a color.

The IBM program 6.0.090, completely generalized ANOV, was used to obtain the mean squares for all main factors and interactions in the experiment with the exceptions of the main effect trials and all interactions containing trials (4). Trials and its interactions were obtained as a total in the residual and used as the error term. The F-test statistic was then hand computed, following the method of example 10.1 presented by Hicks (3; page 156). When the significant effects had been determined, the means were obtained by a second usage of IBM program 6.0.090.

The data for distance at which a correct color was named and for the false color study were handled in the same manner, but in separate computer runs. Presentation and discussion of the findings will be presented in two parts. The first part will be concerned with the dependent variable, recognition distance of true color. The second part will present the false color portion of the study.

Recognition Distance of True Color

The results of the analysis of the distance at which a color was correctly recognized are presented in Table 2. The significant effects are shown in Table 3 along with the level of significance and the figure and page number for the plots of the means of these effects.

There were five main effects, nine first order interactions, seven second order interactions and two third order interactions significant. This large number of interactions necessarily involves a considerable amount of discussion related to several of them simultaneously. For this reason it was felt that it would be best to present the significant effects in a manner the writer feels will give the maximum continuity to the discussion.

Figure 12, the plot of subjects main effect, shows that there was considerable difference among the four subjects; as the main effect of subjects is of little interest alone, further discussion will be delayed until interactions involving subjects are discussed.

The average distance at which green, red, yellow, and blue test lights can be recognized is noted in the plot of main effect of Color of Test Light (F), Figure 13, to be considerably different. A blue light was recognized at the greatest distance, followed by yellow, green, and red with no essential difference between the green and red lights. This main effect is the averaged results of each background and environmental light level and will be examined further when interactions involving the color of test light are discussed.

The main effect, background (C), shown in Figure 14, indicates that for an average of all other conditions a test light's color was recognized

TABLE 2

RECOGNITION DISTANCE OF TRUE COLOR
ANALYSIS OF VARIANCE TABLE

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	"F" Ratio
Subjects (A)	3	14508.3769	4836.12	177.759
Background (C)	2	18810.8694	9405.43	15.5326
AC	6	3633.1501	605.525	22.257
Environmental light level (D)	2	2661.6537	10330.8	121.6599
AD	6	509.4929	84.9154	3.1212
CD	4	258.8919	64.7227	.7654
ACD	12	1349.6187	112.468	4.1339
Test position (E)	11	82737.4864	7521.58	35.838
AE	33	6925.7810	209.872	7.7141
CE	22	5561.7565	252.8070	4.1607
ACE	66	4010.1265	60.7594	2.2333
DE	22	2431.6859	110.531	.9403
ADE	66	2050.6284	31.0701	1.142
CDE	44	1481.4972	33.6703	1.1179
ACDE	132	3975.4206	30.1168	1.1069
Color of test light (F)	3	124462.9708	41487.6	19.8049
AF	9	18853.3406	2094.81	76.9980
CF	6	3860.9577	643.492	2.3796
ACF	18	4867.4092	270.411	9.9393
DF	6	1767.2475	294.541	2.651
ADF	18	1999.8707	111.103	4.0837
CDF	12	1078.0098	89.8341	2.111
ACDF	36	1531.6241	42.5451	1.5638
EF	33	18324.8379	555.298	6.402
AEF	99	8586.7455	86.7348	3.1880
CEF	66	5304.8712	80.3768	1.7501
ACEF	198	9093.0499	45.9244	1.6880
DEF	66	2788.9895	42.2574	1.5254
ADEF	198	6741.3914	34.0474	1.117
CDEF	132	4185.2490	31.7069	1.1654
ACDEF	396	12070.2905	30.4804	1.1203
Error (composed of all terms involving trials)	1728	47011.9682	27.2061	
Total	3455	441436.0651		

TABLE 3
SIGNIFICANT EFFECTS FOR RECOGNITION
DISTANCE OF TRUE COLOR

Significant Effects		Level of Significance	Fig. No.	Page Number
<u>Main Effects</u>				
Subjects	(A)	.001	12	44
Background	(C)	.001	14	45
Environmental Light Level	(D)	.001	15	45
Test Position	(E)	.001	25	58
Color of Test Light	(F)	.001	13	44
<u>First-Order-Interactions</u>				
Subjects X Background	(AC)	.001	20	50
Subjects X Light Level	(AD)	.005	21	52
Subjects X Test Position	(AE)	.001	28	62
Subjects X Test Light	(AF)	.001	19	50
Background X Test Position	(CE)	.001	27	60
Background X Test Light	(CF)	.05	16	47
Light Level X Test Light	(DF)	.025	17	47
Test Position X Test Light	(EF)	.001	26	59
<u>Second-Order-Interactions</u>				
Subject X Background X Light Level	(ACD)	.001	22	53
Subject X Background X Test Position	(ACE)	.001	31	70
Subject X Background X Test Light	(ACF)	.001	23	54
Subject X Test Position X Test Light	(AEF)	.001	32	73
Background X Light Level X Test Light	(CDF)	.025	18	49
Background X Test Position X Test Light	(CEF)	.001	30	67
Light Level X Test Position X Test Light	(DEF)	.01	29	63
Subject X Light Level X Test Light	(ADF)	.001	24	56
<u>Third-Order-Interactions</u>				
Subject X Background X Light Level X Test Light	(ACDF)	.025	42	115
Subject X Background X Test Position X Test Light	(ACEF)	.001	43	118

Fig. 12.--Plot of subjects means.

Fig. 13.--Plot of color of test light means

Fig. 14.--Plot of background means

Fig. 15.--Plot of light level means

at the greatest distance against the gray background. Discussion of the background X color of test light interaction and the background X environmental light level X color of test light interaction will further the understanding of this effect.

The effect of environmental light level (D), Figure 15, showed that the lower the light level, the greater the average distance at which a color was recognized. The plotted data indicate that the increase in distance for lower light level closely approximates a linear function.

The color of background X color of test light interaction (CF), shown in Figure 16, indicates that the primary difference between the gray and black backgrounds was caused by recognition of the yellow test light at a greater distance on the gray background. It is also noted that as the three backgrounds were made darker, the difference in distance at which the yellow compared to blue lights were recognized increased. The white background was the only one on which the average distance for red was not equal to or greater than that for green.

Figure 17 shows the environmental light level X color of test light interaction (DF). The 35 foot candle level is the only one in which green is recognized at a greater distance than red. For decreases below the 35 foot candle level, the means for red increased more rapidly than for green. It is noted that for each decrease in light level most of the increase in the yellow and blue means occurred for the change from 35.0 to 7.0 foot candles. Apart from these noted differences, the trends noted in the main effects of light level and color of test light are maintained.

Fig. 16.--Plot of background X test light means (CF)

Fig. 17.--Plot of color of test light X light level means (DF)

The background X environmental light level X color of test light interaction (CDF) is shown in Figure 18. Note that the green test light was recognized at a greater distance than red at the 35 foot candle level on each background. The trend of the recognition distance for blue to increase less on the darker backgrounds as the light level was decreased from 7.0 to 1.4 foot candles was maintained. Also in the DF interaction it was noted that the means for red tended to increase more rapidly than the means for green as the environmental light level was reduced. It is now shown that this did not hold true on the white background, but did hold true on the gray and black backgrounds. It is also important to note that with the two exceptions there is little difference between the gray and black backgrounds light level effect or test light means. One exception is that the means for the yellow test light are higher on the gray background. The second exception is that the mean for the blue test light on the black background was not increased by reducing the light level from 7.0 to 1.4 foot candles, but was actually decreased. This is an important deviation from the established pattern and will be discussed further in Chapter IV.

It is interesting to observe that the subject X color of test light interaction (AF), Figure 19, shows that subject four had a marked ability to recognize the yellow test light at the greatest distance. This is particularly noteworthy as subject four recognized red, green, and blue at a lesser distance than subject three or one. Even with this high sensitivity to yellow, subject four had only the third highest overall average as was noted in the main effect for subjects. Otherwise each color maintained its respective position as noted in the

Fig. 18.--Plot of background X light level X test light means (CDF)

Fig. 19.--Plot of subject X test light means (AF)

Fig. 20.--Plot of subject X background means (AC)

main effect for color of test lights.

The graph of the subject X background interaction (AC), Figure 20 (page 50), indicates that there was no difference in the average distance that subject one could recognize color on the gray and black backgrounds. Subject three's greater perception on the gray background was the reason that this background showed a slight superiority to the black background. The subject X background X color of test light interaction will further clarify this point. Subject four was able to recognize color at a greater distance on the black background. Otherwise the trend for subject three followed by subjects one, four, and two, in that order, to recognize color at the greatest distance was maintained.

The subject X environmental light level interaction (AD), shown in Figure 21, indicates that there was only a slight difference in the 7.0 and 1.4 candle levels for subject one.

In Figure 22, the subject X background X environmental light level interaction (ACD), it is shown that on the gray and black backgrounds the means for subject one are very nearly equal for the 7.0 and 1.4 foot candle light levels. At the 35 foot candle light level on the black background subjects one and four did not follow the pattern of maintaining the second and third best mean scores respectively; the mean for subject one was the highest and for subject four the second highest.

The subject X background X color of test light interaction (ACF) is plotted in Figure 23. For yellow, subject three had the third highest mean on the white background, the second highest mean on black and the highest mean on the gray background. In the (AC) interaction it was noted that subject three had the highest mean on the gray

Fig. 21.--Plot of subjects X' light level means (AD)

Fig. 22.--Plot of subjects X background X light level means (ACD)

Fig. 23.---Plot of subject X background X light level means (ACF)

background. This can be accounted for by his unexpected sensitivity to the yellow test light as viewed against the gray background. Subject three is primarily responsible for the superiority, shown in the (CF) interaction, of the gray to black background for the yellow test light. Also on the gray background, subject two did not maintain the pattern of having the lowest mean scores, but was able to recognize the green test light at the second greatest distance. Subject four had the highest mean for yellow on the white and black backgrounds and was slightly lower than subject three on the gray background. Subject one was able to recognize the blue light at a slightly greater distance than subject three on all backgrounds. On the gray background subject two was able to recognize green at the second greatest distance.

Subject four continued to recognize the yellow test light at the greatest distance, as is shown in subject X environmental light level X color of test light (ADF) plotted in Figure 24. At the 1.4 foot candle level, subject four also recognized blue at a greater distance than the other subjects. Also for blue at the 1.4 foot candle light level there was less difference between subjects for the other light levels or for the other colors for all light levels. There was less difference between subjects for the other light levels or for the other colors for all light levels. There was less difference between subjects three and four for the distance that yellow was recognized at the 35 foot candle light level than the other light levels. In the (DF) interaction it was indicated that there was a more rapid increase for the red means than the green means as the light level was decreased. It can now be observed that this can be attributed to subject three.

Fig. 24.--Plot of subject X light level X test light means (ADF)

The test position effect, shown in Figure 25, indicates that color can be recognized at the greatest distances in the lower portion of the visual field. The major contribution of the figure is that it indicates how the geometry of the eyes as they are set in the face affects binocular vision.

Figure 26, the test position X color of test light interaction (EF), shows the average (over all conditions) distance at which the four colors of lights can be recognized. Note that the means for red and green remain very close to each other for all test positions. It has previously been noted that this condition also holds true for different backgrounds, light levels and subjects. At those positions where colors are recognized at the least distance it is noted the distance differences between colors is least. All means are larger in the lower half of the plane than in the top half. There is a moderate tendency for the means to be larger on the right of the plane. The primary importance of Figure 26 is that this is the binocular field of vision for the colors of light used in the experiment. Chapter IV will contain further discussion.

It is observed in Figure 27, the background X test position interaction (CE), that the mean distance at which a color was recognized was greater in the lower half of the plane than the top half. The trend for the means on the black and gray backgrounds to be close to each other and separated distinctly from the white background is maintained. It is also noted that around test positions one, two, and twelve, where the mean distances are the least, there is also less difference between backgrounds. At test position seven the white background means do not show a marked decrease as do the means for the gray

Fig. 25.--Plot of test position means (E)

Fig. 26.---Plot of test position X test light means (EF)

Fig. 27.--Plot of background X test position means (CE)

and black backgrounds.

The subject X test position interaction (AE) is plotted in Figure 28. Note that the means for subject three are only the third largest at positions one, two, and twelve while in positions four through eleven, subject three's means are the largest. Subject two continues to recognize color at the least distance while the means for subjects one and four remain relatively close.

Figures 29A through 29C are the plots of the means for the environmental light level X test position X color of test light interaction (DEF). The DEF interaction is plotted with one environmental light level per figure because it is hoped that this manner of presentation will aid the reader in understanding the figures and also because each figure then becomes, for a given light level, the binocular visual field for the colors of test light used in the experiment. It is noted that the means for each color are less in the top half of the plane than the bottom half. There is less difference between the means of red and green in the top and bottom halves than there is for the means of yellow and blue in the top and bottom halves. As has been noted in previous figures, the means for red and green remain very close over all test positions. At all light levels the means for yellow show a marked decrease at test position seven. Blue at 1.4 foot candles is the only other color to show the marked decrease at this position. Means for green and red at the 35 foot candle level show an unaccountable decrease at test positions eight and nine. The means for red and green show a nearly uniform increase as the light level is decreased, while the means for yellow and blue make the biggest increase when the light level is decreased from

Subject 1
 Subject 2
 Subject 3
 Subject 4

Fig. 28.---Plot of subjects X test position means (AE)

Fig. 29A.--Plot of light level X test position X test light interaction (DEF) 35 ft. candles

Fig. 29F.--7 ft. candles (DEF)

Fig. 29C.--1.4 ft. candle level (DEF)

35.0 to 7.0 foot candles. It is noted that yellow or blue is always superior to green or red independent of the light level.

The background X test position X color of test light interaction (CEF) is shown in Figures 30A through 30C. The CEF interaction is plotted with one color of background per figure because it is hoped that this manner of presentation will aid the reader in understanding the figures and also because each figure then becomes for a given background the binocular visual field for the backgrounds used in the experiment. These indicate that for the red and green test lights most of the improvement in the field of vision lies in the change from the white to gray background. It is noted that for yellow and blue the gray background was the best, while for red and green there was essentially no difference between the gray and black backgrounds. It is interesting to note that there is a marked decrease in the distance at which a yellow light is seen at test position seven on the gray and black backgrounds, but not on the white background.

The subject X background X test position interaction (ACE) is plotted in Figures 31A through 31C. It is noted that subject three shows a more marked decrease in the distance at which a color can be recognized around test positions one, two, three, eleven, and twelve on the white and black backgrounds. On the gray background this decrease is noted only at positions one, two, and twelve. The most marked difference between subjects occurs on the gray background.

In Figures 32A through 32D the means for the subject X test position X color of test light are plotted. Subject two shows a marked reduction in the distance at which he was able to recognize the yellow test

Fig. 30A.--Plot of background X test position X color of test
light means (CEF) black background

FIG. 30E.--Gray background (CEF)

Fig. 30C.---White background (CEF)

Fig. 31A.--Plot of background X subject X test position (ACE) white background

Fig. 31B.--Gray background (ACE)

Fig. 31C.--Black background (ACE)

Fig. 32A.---Plot of subject X test position X test light interaction (AEF) subject 1

Fig. 32B.--(AEF) subject 2

Fig. 32C.--(AEF) subject 3

Fig. 32D.--(AEF) subject 4

light in test positions nine through twelve. It is possible that the subject had a slight yellow defect in his left eye. It is noted that subject three was able to recognize the green and red test lights at a much greater distance in comparison with the yellow and blue lights than were the other subjects. He still maintained the trend of recognizing blue at the greatest distance and yellow at the next greatest. Subject four was able to recognize the green and red lights at a lesser distance than the other subjects and recognized yellow at a greater distance than the blue light.

The subject X background X light level X color of test light interaction (ACDF) and the subject X background X test position X color of test light interaction (ACEF) will not be discussed in this chapter as they are extremely difficult to interpret and it is felt that the discussion would add little to the findings already presented. Since both (CDF) and (DEF) interactions have been discussed, it would seem that the two third order interactions would only yield further substantiation of subject differences. The plots of the means of these interactions can be found in Appendix II.

False Color Study

The data presented for the false color study are based on the percentage of times that a color of test light was incorrectly named. If a light was named a false color more than one time during any single test, while the light chassis was being moved to the center of the test panel, it was considered to have been named incorrectly only once.

The results of the analysis of variance for the false color study are presented in Table 4. The significant effects along with the level

TABLE 4

FALSE COLOR ANALYSIS OF VARIANCE TABLE

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	"F" Ratio
Subjects (A)	3	60.0440	20.0147	145.3190
Background (C)	2	10.6256	5.3128	2.8015
AC	6	11.3536	1.8923	13.7392
Environmental light level (D)	2	2.7159	1.3580	1.573
AD	6	5.1799	.8633	6.2681
CD	4	0.8362	.2091	.5843
ACD	12	5.4277	.4523	3.2839
Test position (E)	11	16.7523	1.5229	7.3040
AE	33	6.8797	.2085	1.5138
CE	22	2.5758	.1171	.3162
ACE	66	9.2227	.1397	1.0143
DE	22	2.1730	.0988	.4821
ADE	66	10.6256	.1610	1.689
CDE	44	11.2541	.2558	2.1157
ACDE	132	15.9543	.1209	.8460
Color of test light (F)	3	135.1227	45.0409	6.4638
AF	9	62.7130	6.9681	50.5928
CF	6	1.8443	.3074	.6942
ACF	18	11.8616	.6590	4.7847
DF	6	4.3165	.7194	3.3520
ADF	18	3.7506	.2080	1.5131
CDF	12	3.4300	.2058	1.7437
ACDF	36	5.8988	.1639	1.1900
EF	33	11.1343	.3374	1.5028
AEF	99	22.2244	.2245	1.6300
CEF	66	14.4821	.2194	1.2284
ACEF	198	35.3676	.1786	1.2967
DEF	66	10.4890	.1589	1.1415
ADEF	198	30.4162	.1536	1.1146
CDEF	132	15.6186	.1183	.9428
ACDEF	396	54.5803	.1378	1.0005
Error (composed of all terms involving trials)	1728	237.8456		
Total	3455	832.8704	.1377	

of significance, figure and page number for the plot of the means of these effects are given in Table 5.

There were three main effects, four first order interactions and two second order interactions significant. This large number of interactions necessarily involves a considerable amount of discussion related to several of them simultaneously. For this reason it was felt that it would be best to present the significant effects in a manner the writer feels will give the maximum continuity to the discussion.

The main effect, color of test light (F), is plotted in Figure 33. The blue test light, which was recognized at the greatest distance, is also the one that produces the fewest errors in initial recognition. This was followed by yellow, green and red in that order. Further discussion will be delayed until the CDF interaction is presented.

Figure 34, the background X color of test light interaction (CF), indicates that the blue test light produced the fewest errors on all backgrounds. The fewest errors were made when viewing the blue light against the black background. The number of errors in recognizing red varied only 0.07 percent between all backgrounds. Viewing the green light against the gray background caused the largest number of errors for the green light while the white and black were essentially equal.

The background X light level X color of test light (CDF) interaction is plotted in Figure 35. With the 7.0 foot candle light level the fewest errors were produced for the blue light on the black and gray

TABLE 5
SIGNIFICANT EFFECTS FOR FALSE COLOR

Significant Effects		Level of Significance	Fig. No.	Page Number
<u>Main Effects</u>				
Subjects	(A)	.001	36	84
Test Position	(E)	.001	39	88
Color of Test Light	(F)	.001	33	81
<u>Second-Order-Interactions</u>				
Subject X Background	(AC)	.001	37	86
Subject X Test Light	(AF)	.001	38	87
Background X Test Light	(CF)	.005	34	81
Test Position X Test Light	(EF)	.05	40	89
<u>Third-Order-Interactions</u>				
Background X Light Level X Test Position	(CDE)	.005	41	91
Background X Light Level X Test Light	(CDF)	.05	35	82

Fig. 33. ---Plot of color of test light means (F)

Fig. 34. ---Plot of Background X test light means (CF)

Fig. 35.--Plot of background X light level X test light means (CDF)

backgrounds while with the 1.4 foot candle level the fewest errors were made on the white background. There was very little difference for the yellow test light on the white background. For the green test light the best background was dependent on the light level. On the white background there was little difference between the 35.0 and 7.0 foot candle levels for the green test light, while on the black background the 7.0 foot candle level was best and on the gray background the 35.0 foot candle level was best.

It is notable that on the black background the fewest errors, with one exception, were made when using the 7.0 foot candle level of environment light. The exception was the yellow test light that was named incorrectly fewer times each time the light level was lowered. It is very evident that more errors were made in recognizing the green light against the gray background as the environmental light level was decreased; Conversely, for the red light fewer errors were made as the light level was decreased.

Subjects two, three, one, and four in that order made the fewest errors as an average over all conditions. The means for subjects are plotted in Figure 36, main effect for subjects (A). It was noted in the distance analysis that subject two recognized color at the least distance and now it is noted that the same subject made the fewest errors. The combined results tend to indicate that this subject was not naming the color when he first thought that he could recognize a color, but was waiting until he was sure of the color before naming it. Consequently he had the least means for distance and fewer errors. Subject three, who was able to recognize color at the greatest distance, also made the

Fig. 36.--Plot of subject means (A)

second highest number of errors.

The subject X background interaction (AC), shown in Figure 37, indicates that background had virtually no effect on the percentage of errors for subject one and very little effect for subject four. The black and gray backgrounds were virtually the same for subject two but more errors were made when using the white background. For subject three the gray background was the best, followed by black and then white.

Figure 38 shows the subject X colors of test light interaction (AF). Subject four had the most errors for each color of test light except yellow for which he had the fewest errors. In the distance analysis subject four was able to recognize yellow at the greatest distance. These results indicate that subject four is highly sensitive to the color yellow.

The main effect, test position (E), is plotted in Figure 39. Note that the fewest errors were made when using test positions four and ten. The fewest errors appear to have been made at the test positions where color was recognized at the greatest distance. There were more errors made in the upper position of the field.

The test position X color of test light interaction (EF), shown in Figure 40, indicates that the blue light produced the fewest errors, followed in order by the yellow, green and red test lights. At test position ten there were fewer errors for red than for green. The number of errors for yellow did not decrease as much at position ten as they did at position four.

Fig. 37.--Plot of subject X background means (AC)

Fig. 38.--Plot of subject X test light means (AF)

Fig. 39.--Plot of test position means (E)

Fig. 40.--Plot of test position x test light means (EF)

Figures 41A through 41C, the background X environmental light level X test position interaction (CDE), indicates that at test position four against the white background with the 1.4 foot candle level there was a notable increase in the percentage of error.

The conclusions evolving from these findings will be discussed in Chapter IV along with recommendations for further research.

Fig. 41A.--Plot of background X light level X test position interaction
 (CDE) white background

Fig. 41B.--Gray background (CDE)

Fig. 41C.--Black background (CDE)

CHAPTER IV

CONCLUSIONS AND FURTHER RESEARCH

The results of the false color study and the recognition distance of a true color study were presented in Chapter III. This chapter will contain the conclusions that were drawn from the findings and recommendations for further research.

Conclusions

The results of the experimentation presented in Chapter III indicated that the independent experimental variables selected for this study had a very definite effect on the distances at which a true color was recognized and on the number of errors made by the subjects prior to recognizing a color. In the recognition distance of a true color portion of the study, it was noted that the main effect of each variable was highly significant and that a large number of interaction terms involving test light were also highly significant.

Before attempting to make any conclusions concerning the color of panel lights that it would be best to use in an industrial situation, additional information is required. The experiment was designed so that the voltage to each test light was the same, as it would be in a normal usage environment. The lights were not controlled for brightness, luminance or total radiant energy. With a constant voltage the brightness and amount of light put out by each light would not be the same.

In actuality the yellow test light appeared to be the brightest and produced the most light. Some minor differences in results could have occurred due to differences in intensity.

The jeweled lenses that were used on the light assembly do not give a uniform scattering of light. They also have a slight tendency to vary from the central cone in directionality. This factor would average out over all test positions, but could have a minor effect at a given test position.

One of the most important aspects of the study was to determine which color of test lights could be recognized at the greatest distance and which would have the fewest errors associated with their recognition. It is very evident that the blue test light was the best in both instances. For any given condition of background or environmental light level the blue and yellow test lights maintained their respective positions for both criteria. The conclusion is that where distance or percentage of errors is important a blue light would be best and yellow next best.

Averaged over all conditions the green and red test lights were recognized at approximately the same distance; however, prior to recognition, the red test light was thought to be another color more often than the green test light.

The green and red test lights did not produce as consistent results as did the yellow and blue lights. While the plot of color of test light main effect means indicated that the distance at which each could be seen was approximately the same, the means varied significantly as the backgrounds and environmental light levels were changed.

In the false color portion of the study it was indicated that the blue light gave the fewest errors. Again though, it was seen in

the CDF interaction, Figure 35 (page 82), that the number of errors was dependent upon the background and light level used.

Consequently, a simple statement cannot be made as to whether green or red panel lights would be the best. This would depend upon the background, light level and whether distance of recognition or the number of errors was the most important.

The theory of Three-Pigment Color Vision presented by E. F. MacNichol (6) indicates that the sensitivity of the eye peaks for blue, green and yellow colors. The results of the experiment indicate that for the four subjects tested the yellow and blue lights were seen at a much greater distance than the green light. It would appear that on the basis of MacNichol's article the green light should have been recognized at a greater distance compared to red light. It is not within the scope of this thesis to investigate and explain the psychophysical aspects of color vision; the purpose is to report the findings and suggest industrial applications.

It was shown that the color of background had a very definite effect in the distance at which a color could be recognized and on the number of errors made when viewing a test light against the background. When using the white background, true color was recognized at the least distance and more errors were made. The average distances were greater when using the gray and black backgrounds with gray giving slightly better results; however, the primary difference in the two backgrounds was that yellow was recognized at a much greater distance against the gray background. Therefore, if it was not planned that yellow panel lights were to be used there would be essentially no difference in

choice between black and gray backgrounds if recognition distance was the only criterion. In the false color study the main effect for background was not significant. The CD and CDE interactions were significant, however.

The conclusion was reached that the choice to use the gray or the black backgrounds would have to be dependent upon whether distance or the number of errors was the most important. In addition the decision would also have to be based upon the required color of panel lights and environmental light level.

The main effect of environmental light level indicated that a decrease in the light level produced a proportional increase in the distance at which a color of test light was recognized. This result was anticipated as the test lights appeared brighter in reference to their surrounds as the illumination on the surrounds was reduced. In addition, as the light level was reduced the pupils of the subjects' eyes were dilated. The intensity of the test lights remained constant; therefore, as the pupils were dilated more light from the panel light sources entered the subjects' eyes.

The same theory could be applied to the results obtained from changing the color of background because the gray background reflected less environmental light than the white background into the subjects' eyes and the black background reflected less than the gray. It was noted that the background effect did not behave in the manner that would be predicted by use of the above theory.

The results of the CDF interaction, Figure 18 (page 49), suggest that there possibly exists an optimum combination of background and environmental light level for a given color of panel light. It was noted in

this interaction that the recognition distance of the blue test light was reduced when the environmental light level was changed from 7.0 to 1.4 foot candles. It was also noted in the CF interaction, Figure 16 (page 47), that the primary difference in recognition distance for the yellow test light was due to the background variable, namely, gray and black backgrounds.

The CDF interaction in the false color portion also suggested the existence of an optimum combination of background and environmental light levels. It was noted that a reduction in light level from 7.0 to 1.4 foot candles increased the percentage of errors for each color of test light except yellow, when viewed against the black background, and also for each color of light except red, when viewed against the gray background.

The plot of the means of the test position X color of test light interaction EF, shown in Figure 26 (page 59), is the map of the binocular visual field for the four colors of test lights used in the experiment. This map is not intended to present absolute distance or angle of peripheral vision; it is used to present the relative positions of the color fields over the entire binocular field of vision.

It was noted that the blue field is superior to the yellow field over the whole field of vision. The fact that the color fields are spread out more in the horizontal and lower portions of the visual field is most important. It was also noted in the CE (Figure 27, page 60) and DEF (Figure 29, page 63) interactions that the background and environmental light level curves diverged more in the same regions of the visual field.

This effect would be very useful in the design of industrial equipment. The color of panel lights or background would not have to be

controlled in those areas above the workers' eyes. In those areas where the greatest divergence of fields occurs the equipment could be designed so that the combinations of panel light color, background and environmental light level would be optimized.

In general it can be concluded that blue and yellow panel lights used on a gray background with a low level of environmental light level would give the best results for the recognition distance of color and number of errors made.

The subjects who were used in the experiment displayed a large difference in the distances at which they recognized colors and also in the percentage of errors that were made by them. The subjects were selected from a very small percentage of the normal population. Each of the subjects was a Captain in the United States Air Force. Subjects one and four were rated pilots. As was stated in Chapter II each subject was selected on the basis of nearly equal peripheral vision for a white test object as tested on a Perimeter and also their ability to pass the standard Air Force color vision test.

Even with these factors controlled the subjects differ quite markedly in results. The AF interaction in the recognition distance of true color study, Figure 19 (page 50), and in the false color study, Figure 38 (page 87), showed that subject four was quite sensitive to the yellow test light. He was able to recognize this light at a greater distance and made fewer errors prior to recognition. In addition subject four recognized the green and red lights at the least distance and made the most errors on these.

The structure of the cones in subject four's eyes was probably such that they caused him to be highly sensitive to the yellow light but

have less than normal sensitivity to the green and red lights. The lesser sensitivity to the green and red was not, however, as different from the other subjects as the high sensitivity to yellow.

On the average subject two recognized color at the least distance and also made the fewest errors. This subject was obviously waiting until he was sure of a color before naming it; this reduced the distance at which he named it and also kept him from making as many errors as the other subjects.

It is evident that subjects' differences are large even when controlled as they were for this experiment. These differences could be critical in an industrial situation when the distance at which a color is recognized or the number of errors that is made is important. It could be justified for an industrial concern to institute testing procedures to obtain workers that would meet the peripheral color vision requirements.

Recommended Further Research

The results of the study indicate many areas in which further research would provide increased knowledge.

It would be advisable in further research to select subjects who do not display the differences observed in the subjects used in this experiment. This could be accomplished by selecting the subjects to be used on the basis of the average results obtained with a larger group of subjects in trial runs. A subgroup of subjects would be selected who were representative of the larger group but who did not display a large amount of differences among themselves.

The lenses that were used on the panel light assemblies could be changed. There are available ground glass lenses that do not exhibit the directionality and uneven dispersion characteristics of the jeweled lenses.

The writer feels that lenses of this type would enable the color of light to be recognized at a greater distance and also aid in reducing the number of errors that are made prior to recognizing the color. These lenses are made in a size that would fit the Drake, Type 100 panel light assemblies used in the experiment.

It has been suggested that a light assembly with a larger lens would give better experimental results. The writer does not feel that this is true, and the use of larger lenses would unduly complicate the equipment required. It is agreed, however, that the larger the panel light source, the farther in the periphery it will be recognized and that fewer errors most likely would be made.

In the experiment that has been presented, neither the brightness nor the intensity of the test lights was the same for each light. It is felt that it would be valuable to conduct an experiment in which the physical properties of the test lights are held constant.

It was noted that there possibly existed an optimum combination of the color of background and environmental light level at which color would be recognized at the greatest distance or for which the fewest errors would be made. Further research could be conducted to investigate the existence of this optimum combination. It has been shown that the white background and the 35 foot candle level of light do not give rise to the best results.

In further research the background could be varied from a light-medium shade of gray to a dark shade of gray. The environmental light levels could be varied in increments below 10 foot candles.

It would be of interest to compare some of the panel light lenses available on the market. This comparison should include the spectral

composition of the light passing through the lenses.

The use of different colors of environmental light would certainly add a valuable dimension to any future research. The Air Force would most certainly be interested in the effect that red environmental light would have on the recognition distance of color and on the number of errors committed in this environment. Pilots flying aircraft at night normally are in an environment of red light.

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APPENDIX I

A REPORT ON THE PERCEPTION OF COLOR IN THE PERIPHERAL AREA OF VISION

Submitted to:

Dr. E. Tichauer
January 22, 1964

By

Captain Raymond R. Medeiros

Introduction

This report represents a portion of an assigned laboratory project concerning various aspects of vision.

This particular experiment was selected, not for the conclusions that were drawn, but for the phenomena which were noted during the experiment, and the areas of possible future research that they could lead to.

Questions raised during the experiment, coupled with some research into the nature of the eye structure and various theories on vision have exposed an area which I believe could be very rewarding.

Because of the above observations, this report is divided into two areas:

1. The basic experiment and conclusions.
2. Further discussion and areas of possible research.

Although the report may appear critical of the experiment as it was conducted, I believe it proves the importance and advantages of a pilot study prior to embarking on an extensive research project and incurring excessive lost time and expenditure needlessly.

Basic Equipment

Purpose: To investigate the ability of a subject to differentiate hues in the peripheral area.

Experimental procedure: See Illustration D. A pasteboard background forty-eight inches by thirty inches was placed on a table perpendicular to the table top. This board was divided into thirty degree segments, the top being designated as zero-degrees. Each line was marked off in centimeters from the center outward. A small one-eighth inch hole was punched in the center of the board and a small incandescent

Illustration D.--Sketch of experimental set-up

light was placed to shine through the hole. This light was intended to give the subject a good focal point to assist in preventing the eye from wandering.

Four different test objects, colored disks, two inches in diameter, were mounted on the ends of twenty-two inch long pieces of wire. The colors approximated red, yellow, green, and blue. The subject viewed the disks against two colors of background, white and black.

An adjustable arm was attached to the top of the board to insure that the eye to board distance for each subject remained constant at nine inches throughout the experiment. The subject was seated on an adjustable seat to insure his line of sight was level with the center and perpendicular to the surface of the board. A white gauze bandage was taped over his left eye; all readings were for the right eye only at the nine inch distance.

A colored disk was placed parallel to the board on a selected angle and slowly moved inward towards the line of sight. The subject called out the color of the disk as soon as he recognized it. The disk was moved inward until the correct color was called. At that time the distance from the leading edge of the disk to the center of the board was recorded. The average score for the five subjects at each angle and for each color as viewed against each background was computed. These averages were plotted to give a visual interpretation of the results. (See Illustrations A, B, and C)

To insure random presentations of various colors at various angles, forty-eight poker chips were each marked with an angle and color. The drawing of a chip determined which color and angle would be used for each presentation.

Illustration A.--Fields of color vision for right eye
with test object on black background

Illustration B.---Fields of color vision for right eye with test object on white background

Illustration C.--The average distance at which color is recognized on a black background, dashed line; Compared to white background, solid line

Conclusions: For the stated conditions, various hues can be discriminated at varying angles and distances. The background (black or white) had an effect on the hue perceived and the distance at which the correct hue was recognized. Blue was the easiest hue to recognize for both backgrounds, yellow second, but red and green were reversed on the two backgrounds.

The most important conclusion for practical purposes was that color discrimination in the peripheral area was best in the region between 60 degrees and 150 degrees. This should be considered in the design of work stations, control panels, warning signals, and equipment in general.

General Discussion: This discussion will relate itself to the "duplicity theory" of vision.

This theory states, basically, that there are two types of receptors in the retina-rods and cones and they function differently. The cones are densely located in the area of the fovea, and are particularly sensitive to hues - the chromatic color. The rods are located sparsely in the area of the fovea and are denser as the distance to the fovea increases. The rods are not sensitive to hues, but are sensitive to brightness and the rods perceive colors as achromatics.

In bright daylight the cones dominate and hues are discriminated; however, in twilight and darkness the rods take over and hues appear as achromatics (blacks and grays). The above applies both to objects which are in the line of sight and those in the general area.

The small 110 volt light (foot candle power not known) which was placed in the center of the board could have affected the outcome of the

experiment. The distance of the light (and any object which would be focused on) from the eye could also have had an effect.

Assuming that the line of sight from the retina to the object is straight (a gross inaccuracy, but the same point can be made about actual conditions), the opening of the iris presents a limit to peripheral vision. As the light becomes brighter the iris closes, and the peripheral vision would be decreased.

The distance between an object focused on and the eye could also affect peripheral vision as the eye automatically focuses on objects close by the lens becomes thicker, more convex. This convexity of the lens could enable the eye to see further on the periphery. The results of this experiment are based on a distance of nine inches, and possibly do not lend themselves to a linear extrapolation for a hypothetical plane at some other distance. Further experimentation would be required to substantiate this point.

From the results of this experiment and accepting duplicity theory, it appears that the rods and cones are not located symmetrically about the fovea. If they were symmetrical the plots of illustrations A and B would appear as concentric circles with indentations in the areas of physical obstruction for the nose and eyebrow. The disks would have appeared as chromatics as soon as they passed these obstructions. During the experiment the disks appeared as achromatics.

On many presentations of disks the hues first perceived by the subject were not the correct color. The most frequent error was mistaking red or green for yellow. With the procedure used, the disk was kept moving toward the center until the correct hue was called. This

might be accomplished by mounting eyelid type drops similar to those on a telephone operator's switchboard.

This method would also help to eliminate or at least minimize unconscious eye movement towards the moving disk.

A source of errors and one which would make the duplication of this experiment impossible was the amount of saturation of the colors used. The disks were not highly saturated colors. If hypotheses are to be drawn concerning wave lengths and complementary colors it is necessary to have highly saturated colors.

Practical Applications: This study was accomplished for the right eye only; therefore, any conclusions drawn from the charts presented should be considered accordingly. If both eyes are used this would have an effect on the contours as drawn because both eyes would be focused on an object. Assuming the object is straight ahead, both eyes would be turned inward and the values on the charts between 0 degrees and 180 degrees would be reduced accordingly. Overlap of both eyes would render the readings between 180 degrees and 360 degrees of little value.

The design of work stations requiring peripheral hue discrimination should take into consideration the illumination in the area, the colors presented, the brightness of the colors, the angle at which the object is presented and the background.

Although I have strayed from the original purpose of the experiment, I believe I have recorded areas of interest which resulted from it. In this light our experiment can be considered a pilot study into an area which could be of considerable interest.

APPENDIX II

Figures 42 and 43 are presented
without discussion

Fig. 42A.--Plot of subject X background X environmental light level X color of test light means (ACDF) white background

— Green
 - - - Red
 - . - Yellow
 Blue

Fig. 42B.--Black background (ACDF)

— Green
 - - - Red
 — Yellow
 x x Blue

Fig. 42C.--Gray background (ACDF)

— Green
 - - - Red
 - . - Yellow
 Blue

Fig. 43A.--Plot of subject X background X test position X color of test light interaction means (ACEF) Subject 1, white background

Fig. 43E.--Subject 2, white background (ACEF)

Fig. 43C.--Subject 3, white background (ACEF)

Fig. 43D.--Subject 4, white background (ACEF)

Fig. 43E.--Subject 1, gray background (ACEF)

Fig. 43F.--Subject 2, gray background (ACEF)

Fig. 43G.--Subject 3, gray background (ACEF)

Fig. 43H.--Subject 4, gray background (ACEF)

Fig. 43I.--Subject 1, black background (ACEF)

Fig. 43J.--Subject 2, black background (ACEF)

Fig. 43K.--Subject 3, black background (ACEF)

Fig. 43L.--Subject 4, black background (ACEF)