Procedures for Testing Color Vision: Report of Working Group 41

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WORKING GROUP 41

JOEL POKORNY (Chair), Eye Research Laboratories, University of Chicago
BILL COLLINS, Civil Aeromedical Institute, Aeronautical Center, Federal Aviation Administration
GERALD HOWETT, National Bureau of Standards
ROMUALD LAKOWSKI, Department of Psychology, University of British Columbia
MARK LEWIS, Civil Aeromedical Institute, Aeronautical Center, Federal Aviation Administration
JACK MORELAND, University of Bradford, England
HELEN PAULSON, Naval Submarine Medical Research Laboratory, Groton, Connecticut
VIVIANNE C. SMITH, Eye Research Laboratories, University of Chicago
STEVEN SHEVELL, Statistical Advisor, Department of Behavioral Sciences, University of Chicago

COMMITTEE ON VISION

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PREFACE

Color vision tests are used in selecting personnel for certain occupations that require the use of color vision. These tests are also used clinically to identify and differentiate congenital and acquired disorders involving color vision. Several basic techniques are used for testing color vision and many different devices are available commercially. It is extremely important that color vision testing devices be validated before being adopted for screening; this requires demonstration that a test actually does identify and discriminate among color vision deficiencies as required for a particular occupational task. Some, but not all, commercially available tests have been adequately validated. This information, however, has not been available from any single source, making it difficult for users to decide what tests are most appropriate for their needs.

Working Group 41 was established by the Committee on Vision to assemble information on existing color vision tests and to assess their utility and the extent to which they have been adequately validated. This report, which is derived from deliberations of the working group, describes the administration, scoring, and interpretation of various color vision tests and evaluates validation studies that have been performed on these tests. Additional material is included to make this report a self-contained reference source on procedures for testing color vision. Characterization of color vision and the classification of color vision defects are described. An appendix on the principles of test design is included for nonspecialists. Recommendations are made for the appropriate use of color vision tests in occupational screening. The report includes information on most of the more commonly used tests, but it was not possible to obtain complete descriptions of all tests. Readers are welcome to send to the study director of the Committee any supplementary information that might be used if this report were to be updated in the future.

Members of Working Group 41 brought to this project great expertise in such areas as the nature of color vision defects, colorimetry, test design, and occupational uses of color vision tests. Individual members of the group contributed material, which was drafted by Joel Pokorny and Vivianne Smith into manuscript form and reviewed by the entire group. Preparation of the report was supported in part by grants EY 01876 (Smith) and EY 00901 (Pokorny) from the United States

Public Health Service and the National Eye Institute. Mary Jo Nissen provided technical editing. Several members of the Committee on Vision staff contributed to the preparation of this report: William Benson, Barbara Brown, Key Dismukes, Michelle Eabon, Llyn Ellison, and Luis Proenza. Robert M. Boynton, Ronald Everson, Dorothea Jameson, and Whitman Richards also encouraged this work and commented helpfully on the manuscript. Some of the information herein is based on material prepared for Congenital and Acquired Color Vision Defects (Pokorny et al., 1979).

CHAPTER 1

INTRODUCTION

Color vision tests are used for a wide variety of purposes. Some of these include the rapid screening of congenital red-green defects in industry, transportation, and the military. The classification of discrimination ability within the population of congenital red-green defects is used for job assignment purposes. Another use for screening involves the recognition and diagnosis of congenital disorders for psychophysical or genetic study. In the the clinic, screening is used for the recognition and differentiation of congenital and acquired disorders, for the classification of acquired disorders in patients with eye disease, and, in some cases, for the assessment of treatment or for tracking recovery from disease or trauma. Finally, in education and industry, screening for both color vision defects and color aptitudes is used for vocational guidance in occupations or professions that require color judgments.

The two major problems faced by those who use color vision tests are (1) to know the color vision requirements of a given task and (2) to select appropriate color vision tests.

COLOR VISION REQUIREMENTS IN DIFFERENT OCCUPATIONS

It is essential for the benefit of both employer and employee that the color vision requirements of a job be adequately described. On the basis of these professional requirements and observer capabilities a decision can be made about whether an individual's color vision is suitable for performing the particular duties encountered in daily work situations. Such practical assessment of the relevant color qualifications helps to prevent the inappropriate allotment of manpower. A major difficulty in this regard is the lack of precise checklists of color vision requirements for different jobs; there are no guidelines to help employers establish color requirements for a given job. Broadly speaking, however, many occupations can be divided into three categories (e.g., Lakowski, 1968) depending on the quality of color vision required:

1. Those excluding major color defective observers;
2. Those requiring representative color vision;
3. Those requiring good color discrimination.

Occupations Excluding Major Color Vision Defects

There are many activities and occupations in which defective color vision is either undesirable or unacceptable. Generally observers with severe color defects should not be expected to work in any industrial situation in which a premium is placed on the recognition and/or classification of color surfaces, lights, or objects. Abnormal color vision is therefore a serious handicap in all those areas of electronics and telecommunications that involve the identification, coding, and wiring of electrical equipment. The exclusion of major color-defective observers is also essential in transportation industries (railway, marine, or aviation) in which confusion of signal lights can endanger public safety. On the other hand, not all professions that validly exclude major color defective observers require normal color vision. Individuals with mild impairments can perform many operations involving color discrimination without any special risk to their own or to public safety.

Occupations Requiring Representative Color Vision

There are a vast number of occupations in which the mere exclusion of color-defective observers is an inappropriate policy for selecting personnel. In industry, especially, it seems more important to discover whether a person is fit for a particular job than to classify him or her as either normal or color defective. What is required in most situations is to establish whether the employee has the necessary skill to deal with a particular color task or to satisfy some criteria acceptable to the employer. In such areas as color research, commercial painting, color photography, chemistry, papermaking, paint mixing, the graphic arts, lithography, cartography, and textile dyeing, it is especially important that those who must make color matches have color vision that is representative of the majority of consumers. It is well known that color-matching ability may vary considerably from one observer to another; those observers who fall at the extremes of the distribution of normals may be considered to have an atypical form of normal color vision. Usually such deviations from the mean are not diagnosed by routine testing, yet they may constitute serious practical color vision problems by reducing the individual's effective job performance.

Occupations Requiring Good Color Discrimination

In many professions, individuals are chosen for their ability to make fine or difficult decisions in color discrimination. Here the exclusion of color-defective observers is not the prime consideration. Rather, people are selectively chosen for their precision in matching sample colors to standards or in classifying colors that differ only very subtly. In addition, in some occupations the recognition of color at twilight levels of illumination is required. Only individuals with

good color discrimination or specific aptitudes can perform these types of jobs with facility and accuracy.

SELECTING COLOR VISION TESTS

It is possible to design appropriate task-specific field tests in order to establish the color vision requirements of different jobs, but such a job-by-job analysis would be inefficient and expensive. On the other hand, selecting an available clinical color vision test for a particular application is not simple. First, information concerning the merits of these tests relative to each other and to various job requirements has not been readily available. Second, clinical color vision tests are not designed for the scaling of performance or for multiple cutoff criteria; the scoring standard for most clinical tests is stated in terms of a single pass/fail score. Third, the classification of color discrimination ability by clinical tests might not predict performance in a real-life situation (Kinney et al., 1979). Many experts feel that to generalize from a clinical test to a job requirement is inappropriate at best and meaningless at worst. Fourth, the determinants of performance on each test are sufficiently complex, ranging from colorimetric design to motivational factors, that no test can be considered to provide a single metric of color vision.

In the absence of good population studies that relate job performance measures to test scores in batteries of color vision tests, these problems might be essentially insolvable. However, an understanding of the existing color vision tests may help an employer who is familiar with the job requirements to decide whether to use a clinical test or to have field tests designed to his specifications. This report surveys the existing clinical tests of color vision and gives some general indications as to their design and use.

CHAPTER 2

CLASSIFICATION OF COLOR VISION DEFECTS

This section describes how an individual's color vision is characterized on the basis of color-matching performance and chromatic discrimination capacity. The characterization of normal color vision, which occurs in about 90 percent of men and 99 percent of women, is described first.

NORMAL COLOR VISION

Colorimetric Definition

There are many ways of producing a given hue sensation.* For example, a “yellow” can be produced by a monochromatic radiation (589 nm) or by the additive mixture of a yellow-green (545 nm) and a yellow-red (670 nm). White is produced by a continuous source containing radiations of all visible wavelengths, such as the sun, or it may be produced by a mixture of as few as two wavelengths, for example, 475 nm (blue) and 575 nm (yellow). When we look at a yellow or white object, or at any color field at all, we have no way of knowing the spectral composition of the physical stimulus.

The Color-Matching Experiment

In a typical example of a color-matching experiment, the observer sees a circular field formed by two semicircular half-fields (Figure 2-1). The half-fields contain different isolated spectral bands. In the particular example we have chosen, the upper half-field contains a narrow spectral band centered at 545 nm (yellow-green light) and a

*A discussion of the facts of colorimetry is beyond the scope of this report. Information that is necessary for an understanding of the design of color vision tests is described in the appendix. Readers interested in a more complete discussion of colorimetry may find it in Bouma (1972), Boynton (1979), Graham (1965), LeGrand (1965), Pokorny et al. (1979), Wright (1946, 1972), and Wyszecki and Stiles (1967).

narrow spectral band centered at 670 nm (yellow-red light). The lower half-field contains a narrow spectral band centered at 589 nm (reddish yellow light). By appropriate adjustment of the quantities of 545 nm and 670 nm lights, an observer can make the whole field appear to be the same color. The halves of the split field contain dissimilar spectral radiations and yet are seen as the same by the observer. Pairs of such stimuli are known as metamers.

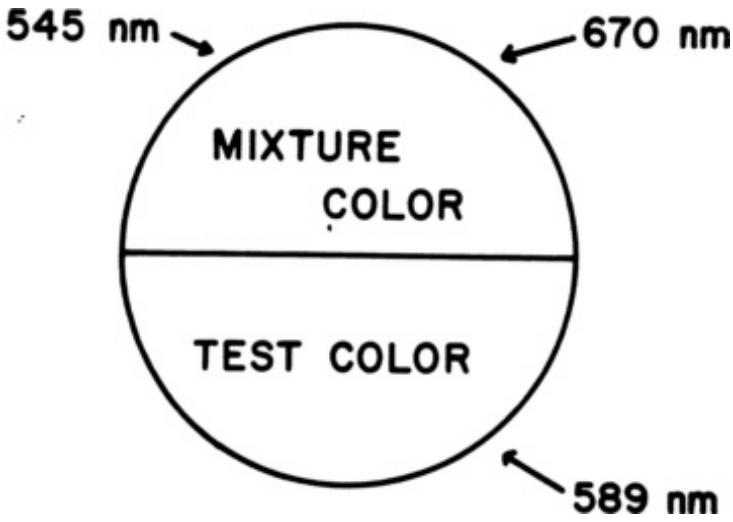

FIGURE 2-1 View of the field as seen by the observer, who sees a circle with a black dividing line. The top half of the field appears red, orange, yellow, yellow-green, or green depending on the relative amount of 670 nm and 545 nm light. The bottom half appears yellow.

Normal observers can match all hues by the appropriate mixture of three colored lights. Hence, normal observers are known as trichromats (tri=three, chroma=color). The match usually requires that one of the three mixture primaries, as they are called, be subtracted from rather than added to the mixture field. Because light cannot be physically subtracted, the third primary is added to the test field; the task thus requires matching the mixture of the test color and one mixture primary to the mixture of the remaining two primaries. Different normal trichromats will use slightly different amounts of the primaries to match various hues, but it is the general similarities among normal observers rather than the comparatively small differences that allow us to classify an observer, whose color vision we are evaluating, as either normal or abnormal.

Some Special Matches

In order to define normal trichromacy and diagnose color defect, we have available some special color matches that make use of only two primaries. These matches are relatively quick and easy to perform,

compared with full spectrum color matching. Instruments that allow us to evaluate these special matches in the population are called anomaloscopes. Historically there have been three such special matches used to test color defect: the Rayleigh match or equation, the Pickford-Lakowski match or equation, and the Engelking-Trendelenburg match or equation. Of these matches, the Rayleigh match and Pickford-Lakowski match are the most frequently used today.

Rayleigh Equation. The Rayleigh equation differentiates normal trichromats from observers with congenital red-green color defect and allows classification of these defects. The Rayleigh equation is a special type of color match that involves matching a spectral light near 589 nm to a mixture of spectral or nearly spectral lights near 670 nm and 545 nm, as shown in Figure 2-1. (The exact wavelengths have differed in various instruments. Wavelengths given here are for the Nagel Model 1 anomaloscope in current production). When the 670 nm and 545 nm mixture primaries are added together, normal trichromats see a full range of hues from yellow-green, yellow, orange, to yellow-red, depending on the proportion of 670 nm to 545 nm primary in the mixture. The observer's task is to adjust this proportion so that the mixture field exactly matches the 589 nm field. The observer may also adjust the luminance of the 589 nm field to achieve an exact match. A normal trichromat can make the match quickly and reliably; there is a unique proportion of 670 nm and 545 nm, which is matched to 589 nm.

Two statistics are taken on the primary mixture: the range and the midpoint of the matches. The matching range includes all of the ratios of 670 nm and 545 nm that a given observer can match to the 589 nm. Usually little change can be made in the mixture ratio without upsetting the color match, and the matching range is termed narrow. The midpoint of the matching range is the 670 to 545 nm ratio, which lies in the center of the range.

In population studies of normal trichromats, the distribution of match midpoints describes a bell-shaped or normal curve including only a rather narrow group of settings. An observer who has a unique match that falls within this range can be excluded from the most frequent categories of color defective vision--the congenital red-green color defects. We can, however, statistically define two subtypes of normal trichromats whose color vision may make them unsuitable for jobs in color-sensitive industries (Figure 2-2). The deviant color normal observer is the normal trichromat whose Rayleigh equation lies within normal range but with the midpoint displaced more than ± 2 standard deviations from the mean of average observers. Deviant color normal observers comprise 4 percent of the normal population. The weak color normal observer is one whose Rayleigh equation midpoint is within normal range but whose matching range is more than twice the most frequent range (modal value) for the population. Color-weak observers comprise 20 percent of the normal population.

The Pickford-Lakowski Equation. A special match that is available in some anomaloscopes is the match of a white light (from a tungsten source) to a mixture of 470 nm and 585 nm lights. The match was

designed to evaluate the effect of aging (Pickford, 1968) and has also proved important in evaluating color defects acquired in eye diseases (Lakowski, 1972).

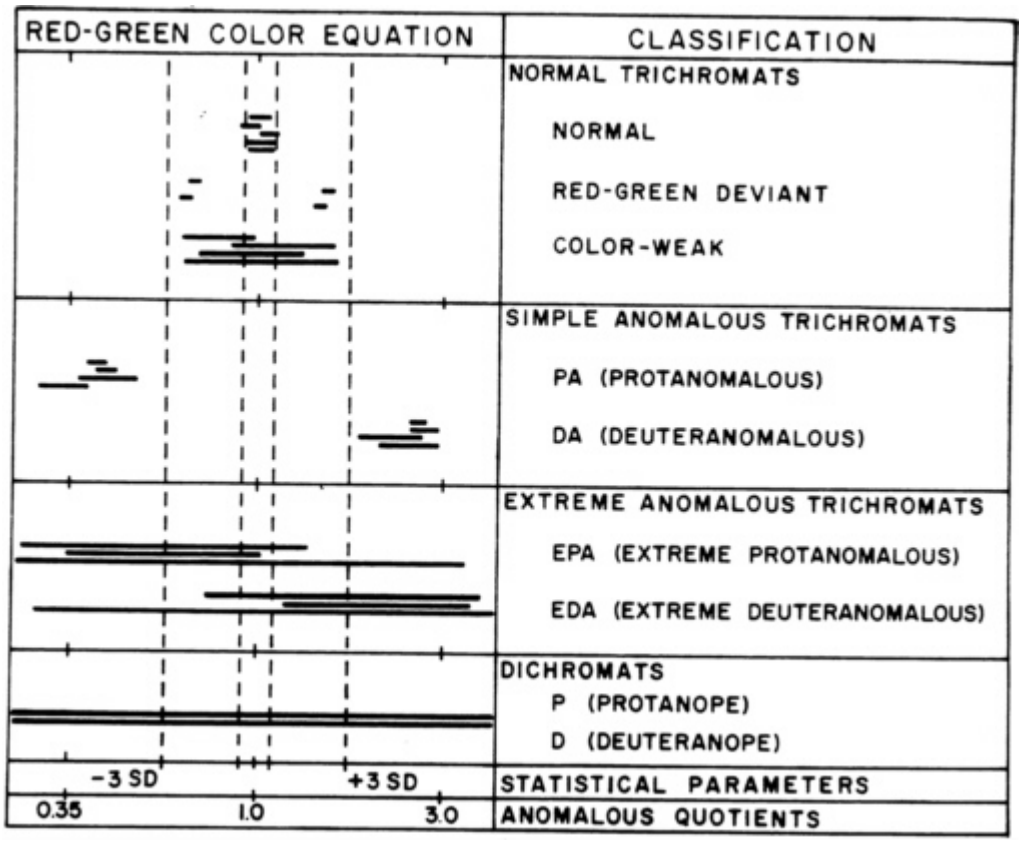

FIGURE 2-2 Characteristic red-green matches made by normal trichromats and observers with congenital red-green defects.
Adapted from Lakowski (1969).

Engelking Trendelenburg Equation. This equation involves the match of 490 nm to a mixture of 470 nm and 517 nm. This match was designed by Engelking and modified by Trendelenburg in order to evaluate congenital blue-yellow color defects (Engelking, 1925; Trendelenburg, 1941). Other investigators have used different wavelengths. As for the Rayleigh match, the normal trichromat makes a unique match. The match may be strongly affected, however, by the inert pigments of the eye. These inert pigments are the lens and a pigment that occurs in the back of the eye called the macular pigment. The lens and macular pigment absorb short-wavelength light (400-500 nm). Different indi

viduals show great variability in the amount of light absorbed by these pigments. One result of this variability is that the Engelking-Trendelenburg equation shows a wide distribution of match midpoints in the normal population, thereby decreasing the utility of the match as a test for the abnormal color vision.

Chromatic Discriminative Ability

There is considerable variability among color-normal observers in their ability to discriminate small differences in hue or saturation. This fact may be demonstrated in a number of ways. In color match performances, different observers have different matching ranges. Observers with good color discrimination tolerate little change in the mixture ratio and have narrow matching ranges. Observers with poor color discrimination have wide matching ranges. A clinical method of estimating chromatic discrimination is the Farnsworth-Munsell 100-hue test.

CONGENITAL SEX-LINKED COLOR VISION DEFECTS

Observers with congenital red-green color defects comprise about 10 percent of the U.S. male population, thus 4 percent to 5 percent of the U.S. general population (Paulson, 1973). These observers are of concern to the armed forces and transportation industries, because their defects may inhibit their ability to function appropriately.

Red-green defects have X-chromosome-linked recessive inheritance. This term refers to traits carried on the sex chromosomes. The female has two X chromosomes, one inherited from the mother and one from the father; the male has one X chromosome from the mother and one Y chromosome from the father. X-chromosome-linked recessive inheritance is specific to genes occurring at a locus on the X chromosome for which no corresponding gene occurs on the Y chromosome. Thus, in X-chromosome-linked recessive inheritance, the male who inherits a defective gene from his mother will always show the defect because he has no normal gene to oppose expression of the defect. The female, however, must inherit a defective gene from both parents to show the defect. Females who have one defective gene are called carriers. The affected male who gives an X chromosome to daughters and a Y chromosome to sons will pass the defective gene to all of his daughters and to none of his sons. Assuming that the mother has two normal X chromosomes, the daughters will be carriers. The offspring of marriages between color-defective males and color-defective females will have higher incidences of color-defective males, color defective females, and carrier females. Comprehensive reviews of the genetic aspects of red-green defects are given by Bell (1926), Francois and Verriest (1961), Waardenburg (1963), Kalmus (1965), Jaeger (1972), and Franceschetti et al. (1974).

Color matching using the Rayleigh match, allows us to differentiate the various red-green color defects. There are two major subdivisions

of color defect observers according to the severity of the defect; anomalous trichromats and dichromats. Within each of these classes we find two qualitatively different types of red-green defect, the protan defects and the deutan defects. The classification given below is that of Franceschetti (1928).

Anomalous Trichromats

These observers comprise about 7 percent of the U.S. male population.

Color-Matching Classification

Anomalous trichromats, like normal trichromats, need three primaries for color mixture to match the spectrum, but their matches differ from those of normal trichromats. According to Franceschetti (1928) there are four subcategories of anomalous trichromats. Each subcategory is defined by use of the anomaloscope.

Simple Protanomalous Trichromats. The simple protanomalous trichromat is given the designation PA. This term refers to a presumed genetic entity. The observers who comprise 1 to 2 percent of the U.S. male population need a higher ratio of red to green primary than normal trichromats in the Rayleigh equation (see Figure 2-2). The mixture half-field that the protanomalous trichromat accepts as a color match to the yellow test field would appear orange to the normal trichromat. In addition, long-wavelength (red) spectral lights appear dim; we say that protanomalous trichromats have a "long-wavelength luminosity loss."

Simple Deuteranomalous Trichromats (Genetic Entity DA). These observers comprise about 4 to 5 percent of the U.S. male population; they need a higher ratio of green to red primary than normal trichromats in the Rayleigh equation (Figure 2-2). The mixture half-field that the deuteranomalous trichromat accepts as a color match to the yellow test field would appear greenish yellow to a normal trichromat.

In addition to the deviation of the match midpoint, the ranges of the matches made by simple protanomalous and simple deuteranomalous trichromats are often wider than for normal trichromats (see Figure 2-2). Although a given anomalous trichromat may have as narrow a matching range as that of a normal trichromat (Hurvich, 1972; Alpern and Moeller, 1977), it is more usual to find that the matching ranges are two to three times wider than those of normal trichromats (Willis and Farnsworth, 1952; Helve, 1972).

Extreme Protanomalous Trichromats (Genetic Entity EPA). This group accepts a wide range of red-green ratios, usually including the ratio accepted by normal trichromats and perhaps one of the primaries (usually red). The extreme protanomalous trichromat also shows reduced sensitivity to long-wavelength spectral light.

Extreme Deuteranomalous Trichromats (Genetic Entity EDA). These observers also accept a wide range of red-green ratios, including the normal match and perhaps one of the primaries (usually green).

Extreme protanomalous trichromats and extreme deuteranomalous trichromats differ from the corresponding simple anomalous trichromats in the width of the matching range (see Figure 2-2). Extreme anomalous trichromats always have a wide matching range that usually includes the normal match.

Chromatic Discriminative Ability

As indicated by the matching width, many anomalous trichromats show a loss of color discrimination compared with normal trichromats. There is, however, considerable variability among both protanomalous and deuteranomalous trichromats in the manifestation of such discrimination loss, with some of these observers showing no loss of color discrimination. Some anomalous trichromats may make more errors on the Farnsworth-Munsell (FM) 100-hue test than normal trichromats. Their errors do not occur randomly but occur for hues where their color discrimination is poorest. The Farnsworth-Munsell 100-hue test is discussed in detail in Chapter 3, Existing Tests.

Dichromats

Dichromats comprise 2 to 3 percent of the U.S. male population.

Color-Matching Classification

Dichromats require only two primaries to match spectral colors. They can match all spectral colors by a suitable mixture of two primaries located on either side of 500 nm; generally a red and a blue are used. Furthermore, when spectral colors and small fields are used, dichromats can match all wavelengths above 540 nm to a single wavelength. In the Rayleigh match they can match either the 545 nm primary, the 670 nm primary, or any mixture of these primaries to spectral yellow (see Figure 2-2). On the basis of the radiance at which they set the brightness of the yellow half-field in the Rayleigh match, dichromats can be differentiated into protanopes and deuteranopes.

Protanopes (Genetic Entity P). Protanopes comprise 1 percent of the U.S. male population and show loss of sensitivity to long wavelengths. On the Nagel Model 1 anomaloscope, protanopes match spectral red to very dim levels of spectral yellow; they match spectral green to brighter levels of spectral yellow. Protanopes confuse blues with purples, blue-greens with red-purples, and light greens with brown.

Deuteranopes (Genetic Entity D). Deuteranopes, who comprise 1 percent of the U.S. male population, possess a spectral sensitivity

similar to that of normal observers. On the Nagel Model 1 anomaloscope, they match spectral red and spectral green to approximately the same radiance of yellow. A deuteranope will confuse blues with blue-purples, blue-greens with purples and greens with reddish purples.

Chromatic Discriminative Ability

Dichromats have virtually no wavelength discrimination above 540 nm. They are thought to see the spectrum as shades of blues and yellows separated by a neutral region of grays in the spectral region around 495 to 500 nm. Dichromats usually make more errors on a color discrimination test such as the FM 100-hue test than a normal or anomalous trichromat. Their errors occur for those hues where their discrimination is poorest and show profiles similar to those of the corresponding anomalous trichromats (see Chapter 3).

AUTOSOMAL DOMINANT TRITAN DEFECT

In addition to the X-chromosomal-linked color defects, there are some very rare hereditary color defects. The tritan defect is one of these rare defects (minimum frequency estimated to be between 1/13,000 and 1/65,000 [Kalmus, 1965]). The defect shows autosomal dominant inheritance, a term which refers to traits carried on any but the sex chromosomes. In dominant inheritance the defect occurs if only one defective gene is inherited. Autosomal dominant inheritance is characterized by a high frequency of the defect (50%) in the male and female children of an affected parent. The severity of the defect can be quite variable from one family member to another.

The tritan defect is characterized by a lack of function of the mechanism that allows normal observers to discriminate colors that differ by the amount of violet or yellow they contain. The dichromatic state of the tritan defect is termed tritanopia. A tritanope can match all spectral colors to a mixture of two primaries, usually located on either side of 565 nm, and will have a wide matching range on the Engelking-Trendelenburg and Pickford-Lakowski equations. The tritanope, however, will have a reliable match on the Rayleigh equation, and the match will fall within the distribution of matches made by normal trichromats unless, of course, there is a concomitant red-green defect (Pokorny, Smith and Went, 1981).

It has proved difficult to demonstrate a defect comparable to anomalous trichromatism in observers with tritan defect, primarily because of the normal interobserver variability in the Engelking-Trendelenburg equation. There are, however, many cases of “incomplete tritanopia,” consistent with the typical variability observed in autosomal dominant inheritance. Specialized tests of color matching are required to differentiate the tritanope, incomplete tritan, and tritanomalous observer.

ACQUIRED COLOR VISION DEFECTS

Normal Color Vision Changes with Age

Test performance that depends on detection of small differences in color is at its best in young adults in their early twenties. Fewer observers above the age of 25 show excellent color discrimination. Color discrimination loss shows a characteristic pattern: discrimination on the blue-yellow axis is more affected than discrimination on the red-green axis. Thus, normal trichromats will show considerable widening of their matching ranges for the Engelking-Trendelenburg and Pickford-Lakowski matches as their age increases (Lakowski, 1958; Ohta and Kato, 1976) whereas the matching range for the Rayleigh equation shows little or no change with age. On the FM 100-hue test, more errors are made by older observers, who may show blue-yellow discrimination loss (Ohta, 1961; Lakowski, 1962; Verriest, 1963; Krill and Schneiderman, 1964).

The loss of discriminative ability with age is primarily but not solely attributable to the aging process in the lens of the eye (Lakowski, 1962). The lens gradually becomes denser and may accumulate screening pigments, which usually absorb short-wavelength light strongly (the lens may appear yellowish). As a consequence less light, especially short-wavelength light, reaches the retina.

These age effects are not trivial. The discriminative loss with age may be important in certain job situations.

Effect of Disease, Injury, and Drugs

Most individuals with defects in color perception have hereditary color defects that do not progress. However, color defects may occur secondary to disease or injuries. Such defects are termed acquired color defects. Acquired defects may be caused by disease or injury affecting the eye, the optic nerve, or the visual cortex. Some acquired defects result from primary hereditary retinal disorders and probably should be termed developmental color vision defects. Cataracts, too, may cause color defects. Drugs may cause toxic effects on the eye, with some loss of vision and color vision.

The acquired defects usually involve discrimination loss and may occur prior or secondary to loss in visual acuity. The common clinical methods of testing color vision are based on tests designed to evaluate the hereditary defects, using observers with normal visual acuity. The assessment of acquired color defects may be complicated by low visual acuity, presence of an undiagnosed congenital color defect, or other concomitant problems. However, the evaluation of color vision in eye disease can be diagnostically important and is common clinical practice in Europe. (Discussion of the measurement and etiology of acquired color vision defects is given in Grützner, 1972, and Pokorny et al., 1979).

It is helpful to summarize differences between acquired and congenital color defects (see Table 4-2). Congenital color defects usually involve both eyes. There is usually no visual complaint or

evidence of other abnormal visual function. The congenital defects are likely to involve red-green discrimination and to show X-chromosomal-linked inheritance. These observers may name many object colors correctly, since they were constrained in childhood to use the terminology of the color normal observer, and they tend to use whatever cues possible to do so (Jameson and Hurvich, 1978). In comparison, acquired or developmental color defects may differ in severity in the two eyes and are usually accompanied by decreased vision and other evidence of eye disease. These defects are more likely to involve discrimination loss on the blue-yellow axis.

PHYSICAL FACTORS AFFECTING COLOR VISION

Color vision is not static. Color appearance, color matches, and color discrimination are affected by changes in illumination and field of view.

Illumination

All color tests are designed to be administered at specific illuminations. Color discrimination is best at medium or moderate levels of illumination. At very high levels (glare), the apparent saturation of colors is decreased. Most observers find glare sources uncomfortable. At very low levels of illumination, discrimination deteriorates in a characteristic manner. If the FM 100-hue test is given at 1/100th of the recommended test illumination, observers may show increased errors, primarily on a blue-yellow axis.

Field Size

The size of the field of view is also important in color vision. The larger the field of view, the better the color discrimination. Normal trichromats show small but systematic changes in the Rayleigh match as field size is changed (Pokorny and Smith, 1976). Reduction in field size to one-quarter degree of visual angle (the size of a tip of a matchstick at arm's length) from the 1° to 2° (the size of a nickel at arm's length) of a typical anomaloscope will lead to decreased discrimination. Anomalous trichromats and dichromats show considerable improvement in discrimination as field size is enlarged. The wide matching ranges that occur with the usual anomaloscope field become narrower when a sufficiently large test field (8°) is used. Many dichromats will not accept a full matching range on an anomaloscope when the field is 8° (Smith and Pokorny, 1977).

Population statistics are all based on the use of anomaloscope fields of 1° to 2°. Furthermore, most color screening tests depend for their success on discrimination loss in anomalous trichromats and dichromats. Such tests may be less effective if the observer is allowed to increase the field of view by bringing the samples closer. The ability to present a large field in an anomaloscope, however, may be useful in studying acquired color defects.

CHAPTER 3

COLOR VISION TESTS

HISTORICAL INTRODUCTION

One of the earliest methods used to test color vision was to compare the individual's color naming of everyday objects with that of a normal person. This was the method employed by Turberville (1684) and by several subsequent investigators. Dalton (1798) gave a detailed description of his own perceptions and those of his brother (both protanopes) and of some 20 other persons.

The next advance in testing was made by Seebeck (1837), who required the observer to choose from a wide range of colored samples those that matched or most closely resembled a selected test sample. The task was performed by inspection and without color naming. Variants of this test were devised by Holmgren (1877) using skeins of wool; by Abney (1906), Oliver (1902), and Edridge-Green (1920) using small beads or pellets; and by Fridenberg (1903) using small square pieces of colored cardboard. Holmgren's wool test is based on the principles of Helmholtz's theory of color vision. Helmholtz (1866) had tentatively proposed that color blindness could manifest itself in three forms--red, green, or violet blindness--depending on the missing type of color receptor (one for red, one for green, and one for violet). Although this position was subsequently abandoned by Helmholtz as erroneous, Holmgren adhered to it and selected three standard wool skeins (red, green, and purple) specifically to detect the three proposed types of color blindness. As a result, the Holmgren test is based on an erroneous and misleading set of color blindness categories and an unwise choice of test and match skeins.

Pseudoisochromatic plates were first introduced by Stilling (1873). The success of tests of this kind depends on the inability of color-defective observers to discriminate between certain colors. A symbol (number, letter, or geometric figure) composed of colored spots is set in a background of differently colored spots. The most frequently encountered design involves colors chosen so that the symbol is not seen by the color-defective observer (pseudo-isochromatic, falsely appearing of the same color). There are many modern variants of this kind of test.

Lord Rayleigh (1881), using his color mixing apparatus, which employed narrow spectral bands of red and green to match yellow,

discovered that a few observers made matches that were very different from those made by the majority of other observers. It is agreed that the anomaloscope is the only clinical method capable of classifying the color defects by their presumed genetic entities. The spectral colors used by Rayleigh were incorporated by Nagel (1899, 1900, 1907) in his anomaloscope.

In the lantern test, which was introduced by Williams (1903), colored signal lights were to be named by the observer. The advantage of such a test when applied vocationally is that the task can be made to simulate the real-life situation quite closely. Variants of the lantern test are still used today for testing transport workers and members of the armed forces of many countries.

Arrangement tests require the observer to arrange a set of colored samples in sequence. This kind of test was developed by Pierce (1934) and was first used in the National Institute of Industrial Psychology in London. All previously devised color vision tests were designed to separate color-defective observers from normal observers but did not indicate the wide range of color ability and aptitude that exists among normal observers. Pierce's solution was to develop a surface color test in which color ability could be measured by an observer's skill in arranging and matching color series. Applicants had two tasks to perform: to grade and then to match a series of nitrocellulose lacquer discs that varied in saturation and hue. In the grading test, 16 discs of one hue were presented in random order to the observer, who had to arrange them in a saturation series. In the matching test, prearranged series of discs of one color were presented to the observer who then had to select their match from a duplicate group of discs. Modern variants of arrangement tests involving hue discrimination were devised by Farnsworth (1943) in the FM 100-hue and the Panel D-15 tests. The Inter-Society Color Council of America (ISCC) employed colored plastics in the ISCC Color Aptitude Test, which involves saturation discrimination. Most recently, Lanthony (1974b, 1975b) has developed two arrangement tests (the Lanthony Desaturated Panel D-15 and the Lanthony New Color Test) for use in diagnosing acquired color vision defects.

GENERAL DESCRIPTION OF TYPES OF COLOR VISION TESTS

Anomaloscopes

Anomaloscopes are optical instruments in which the observer must manipulate stimulus control knobs to match two colored fields in color and brightness. The anomaloscope is the standard instrument for the diagnosis of color vision defects. When supplemented by information from other color vision tests, the results provided by this instrument permit the accurate classification of all color deficiencies. A variety of instruments were available in the past, but currently the Nagel, the Neitz, and the Pickford-Nicolson anomaloscopes are commercially available in the United States.

Of all of the color vision tests described here, anomaloscopes are the most difficult to use. Extensive training of examiners is necessary if anomaloscopes are to be used validly and efficiently; hence, these instruments are most often found in research settings. However, when used by a skilled examiner, the anomaloscope has advantages as a diagnostic instrument that far outweigh any inconveniences in training.

Plate Tests

In a plate test, the observer must identify a colored symbol embedded in a background (most pseudoisochromatic plates); identify which of four colors is most similar to a standard color, (City University Test); or identify which circle matches a gray rectangle (Sloan Achromatopsia Test).

There are many types of pseudoisochromatic tests (e.g., American Optical Hardy-Rand-Rittler, Ishihara, Dvorine, Tokyo Medical College). All provide efficient screening (90 to 95%) of congenital red-green defects. Basically these tests consist of a series of cards on which colored dots of discs of various sizes are printed to form a multicolored figure against a multicolored background. The figure is some easily identifiable letter, arabic numeral, or geometric configuration (e.g., a circle, triangle, or cross). The only systematic difference between the figure and background dots is in color: the figure is composed of dots of one or more colors, and the background is composed of dots of different color or colors. Variations in the size, lightness, and saturation of the dots may be employed so that identification of the intended figure by cues other than hue is less likely. Observers with normal color vision can detect the hue difference between figure and background and consequently can easily read the figures, but observers with defective color vision may fail to distinguish between figure and background colors and hence fail to read the figures. In this sense the colors of the plates appear isochromatic only to the defective observer.

Hardy, Rand, and Rittler (1945) characterized four types of pseudoisochromatic design: the vanishing design, the qualitatively diagnostic plate, the transformation plate, and the hidden defect design. The vanishing design contains a figure that is easily read by the normal trichromat but not by the color-defective observer. The qualitatively diagnostic plate is a vanishing plate that permits the differentiation of a protan from a deutan observer. In the transformation plate, two figures are embedded in the background: one figure with the appropriate color and lightness contrast to be read by the normal trichromat, and the other with the appropriate color and lightness contrast to be read by the color defective. In the hidden digit design, the plate is a vanishing plate for normal trichromats, but the figure is seen by the color-defective observer. Lakowski (1965b, 1966, 1969, 1976) has analyzed the colorimetric properties of several of the pseudoisochromatic plate tests.

The City University Test was designed to detect color confusions (i.e., colors that appear quite different to the normal observer but appear similar to the defective observer), and the Sloan Achromatopsia Test was designed to detect achromatopsia (i.e., the inability to differentiate any of the rainbow hues or their intermediaries other than on the basis of lightness).

There are certain advantages in the use of plate tests. They are rapidly and easily administered by inexperienced personnel; they are readily available; they are relatively inexpensive; and they can be used on naive subjects, illiterates, and children. There are, however, certain disadvantages. First, the spectral quality of the light source illuminating the plates affects the reading of the figures; the plates must be exhibited under the standard viewing conditions for which they were designed. Second, the success of the plates depends mainly on the careful selection of confusion colors. Often, for technical reasons, the best confusion colors for diagnostic purposes are not available. Third, even when a set of colors is chosen, individual variation in the eye lens and in coloration of the back of the eye means that a single choice of colors will not be optimal for all observers. Finally, no accurate scoring criteria for classifying defects on the basis of test performance are available; the number of errors on pseudoisochromatic tests tells us little about the type or extent of a color vision defect.

Pseudoisochromatic tests should be used primarily as screening tests to divide people into normal and color-defective populations; their diagnostic value is limited. Caution should be used in extracting more detailed information about color discrimination from them. At present it is always better to look on information from pseudoisochromtic plate tests as providing a probable but not certain diagnosis.

Arrangement Tests

In arrangement tests, the observer is required to arrange color samples by similarity in a sequential color series. Usually the colors are mounted in caps, which are numbered on the back and can be moved about freely during performance. Arrangement tests may be designed for evaluation of fine hue discrimination (FM 100-hue test); for evaluation of color confusion (Farnsworth Panel D-15, Lanthony Desaturated Panel, Lanthony New Color Test); for evaluation of neutral zones or colors seen as gray (Lanthony New Color Test); and for evaluation of saturation discrimination (Sahlgren Saturation Test, ISCC Color Aptitude Test).

Arrangement tests are easy to administer and can be used with naive subjects. Such tests require manual dexterity, patience, concentration, and the understanding of abstract ordering. Hence, they are less suitable for young children. The Farnsworth Panel D-15 and the Lanthony Desaturated Panel provide rapid tests of gross color confusions but are not designed for fine color screening. The FM 100-hue test is more time-consuming, but it is acknowledged to be a sensitive indicator of aptitude for hue discrimination. Both the Panel D-15 and the 100-hue tests differentiate among protan, deutan, and tritan defects by the axes along which confusions are made. The ISCC test takes 45 to 90

minutes to complete and does not provide specific information about color defects.

Disadvantages of arrangement tests include the fact that some manual dexterity is required. For tests using colored papers, the observer should wear a glove to avoid soiling the colored pigments. The specified illuminant must be used.

Lantern Tests

Lantern tests were designed as practical means for measuring the ability of seamen, railway personnel, and airline pilots to identify and discriminate navigational aids and signals. Accordingly these tests emphasize correct color recognition as the important testing variable. The design of lantern tests is straightforward, necessitating neither the construction of complex optical systems (as do anomaloscopes) nor the development of complicated color printing procedures (as for pseudoisochromatic plate tests). Lantern tests simply require that a system be developed for presenting colored lights (duplicating signal lights) to the observer for identification. Several different models of lanterns are available: Giles-Archer, Edridge-Green, Martins, Sloan Color Threshold Tester, and Farnsworth Lantern.

Lantern tests are easy to administer. Their value lies in their simulation of the working condition. Lantern tests do not specifically screen for color defect, although it is expected that color-defective observers will not perform as well as observers with normal color vision.

HOW TO EVALUATE A COLOR TEST

Reliability and Validity

Evaluation of a new color test requires knowledge of its reliability and its validity. The term reliability refers to whether the test measures the same property on each occasion. Reliability is assessed by administering the test on two separate occasions. Statistical procedures are then used to compare the two sets of results. The term validity refers to whether the test measures what it claims to measure. For a test designed to screen or detect color defect, the results may be compared to another standard test. The Nagel Model I anomaloscope is considered a standard test of red-green color vision.

In comparing two tests, a statistical measure of agreement is necessary. An appropriate measure is the $\hat{\kappa}$ statistic developed by Cohen (described by Bishop et al., 1975). Normally, $\hat{\kappa}$ will be between 0 and 1. A value of zero indicates that agreement is only at the level of chance; a value of 1 indicates perfect agreement. A negative $\hat{\kappa}$ may occur, although it is unlikely to be found with well-known tests of color vision, since such a value indicates that agreement is below chance. The statistic $\hat{\kappa}$ may be interpreted as the number of actual agreements divided by the total possible number of agreements, adjusted

to exclude the number of agreements expected by chance alone. Specifically

$$\hat{K} = \frac{\text{Percentage of observations for which there is agreement} - \text{Percentage of agreements expected by change alone}}{100\% - \text{Percentage of agreements expected by chance alone}}$$

For example, a computation formula for a two-by-two table would be as follows:

Test 1

		Pass	Fail	Total
	Pass	a	b	a + b
Test 2	Fail	c	d	c + d
	Total	a + c	b + d	N

$$\hat{K} = \frac{(a + d) - \frac{(a + c)(a + b)}{N} + \frac{(b + d)(c + d)}{N}}{N - \frac{(a + c)(a + b)}{N} + \frac{(b + d)(c + d)}{N}}$$

A conditional $\hat{K}$ is computed in the same way, except that the expected agreements are calculated only for a particular row or column (on which the statistic is conditional). Hypothesis tests have been developed for $\hat{K}$ (Bishop et al., 1975).

Specific Procedures for Calculating Different Types of Tests

Plate Tests

The appropriate procedure is to compare $\hat{K}$ coefficients for reliability and validity. Evaluation of reliability should compare test and retest data; evaluation of validity should compare plate test data and anomaloscope data. In many cases, plate tests have been compared with other plate tests of known high validity. This procedure is less desirable than comparison with a standard anomaloscope.

Arrangement Tests

Reliability and validity of arrangement tests with pass/fail criteria can be evaluated by the $\hat{\kappa}$ coefficient. For the FM 100-hue test, calculation of $\hat{\kappa}$ coefficients is possible only for comparisons of classification data. Other standard statistical procedures, including analyses of variance, may be used to compare error scores.

Anomaloscopes

If appropriate technique is used, reliability of anomaloscope data should be high. If necessary, reliability of match midpoint or matching range can be evaluated by means of a scatter plot. Instrument values for the anomaloscope on initial testing are plotted against values obtained on retest. Since match midpoints are usually distributed normally and symmetrically (Lakowski, 1971), a correlation coefficient can be computed.

In order to evaluate the validity of new anomaloscopes, the diagnostic categories obtained from the new anomaloscope (i.e., P, PA, EPA, D, DA, EDA; see pages 9-11) should be compared with those from the Nagel anomaloscope, which is accepted as a standard instrument, and the $\hat{\kappa}$ coefficient should be calculated. It is appropriate to use scatter-plot and correlational analyses to compare match midpoints and matching ranges of two anomaloscopes that have identical mixture primaries and test wavelengths. In order to compensate for scale differences, however, the data must either be converted to the comparable scale units devised by Willis and Farnsworth (1952) or expressed in anomalous quotients. (The anomalous quotient expresses an individual observer's match relative to the mean of many observers. See “Existing Tests,” in this chapter.) It is not appropriate to compare match midpoints, matching ranges, or anomalous quotients of two anomaloscopes that have different mixture primaries or test wavelengths.

Lantern Tests

The reliability of lantern tests may be assessed by $\hat{\kappa}$ coefficients. Since lantern tests are field tests, the assessment of validity is virtually impossible. Lantern tests, however, may be compared with other color vision tests to check their agreement.

ILLUMINANTS

The majority of the plate and arrangement tests (see “General Description,” in this chapter) were designed and standardized either for natural daylight or for an artificial illuminant called CIE (Commission Internationale d'Eclairage) Standard Illuminant C. Standard Illuminant C appears slightly bluish white. Natural daylight refers to afternoon northern sky light in the northern hemisphere. Standard

Illuminant C approximates the average spectral distribution of natural daylight. However, the level of illuminance and spectral composition of natural daylight are not as constant as can be obtained with an artificial illuminant. Standard Illuminant C can be realized physically by an incandescent tungsten lamp of appropriate wattage (called Standard Illuminant A) in conjunction with a specified liquid filter that changes the spectral distribution to that of Standard Illuminant C. There are several glass filters that closely approximate the liquid filter.

To demonstrate the importance of using the correct illuminant, a number of investigators showed that if ordinary unfiltered tungsten lamps (which appear yellower than Standard Illuminant C) are used, deutan subjects make fewer errors in pseudoisochromatic plate tests, including the Ishihara, American Optical Co., and AO H-R-R tests (Reed, 1944; Hardy et al., 1946; Volk and Fry, 1947; Farnsworth, Reed, and Shilling, 1948; Schmidt, 1952; Katavisto, 1961; and Higgins et al., 1978).* Therefore, deuteranomalous observers (deutans) may pass a screening test that was administered under the wrong illuminant. With the wrong illuminant, deutans may also make fewer errors in an arrangement test, such as the FM 100-hue test or the Farnsworth Panel D-15. In addition, protans may show rotation of the error axis. Extreme protanomalous trichromats and protanopes may even show a deutan pirofile (Higgins et al., 1978). Thus, unfiltered tungsten lamps cannot be used as illuminants for these tests, since those lamps will not give correct results. Ordinary window light is too variable in both illuminance level and spectral composition to be an adequate source for color vision testing. The use of fluorescent tubes in color testing has been investigated, with variable results (Rowland, 1943; Katavisto, 1961). Ordinary commercially available fluorescent tubes are not generally appropriate for testing color vision.

In recent years, high-quality fluorescent lamps have been developed especially for use in color comparison work. Richards and colleagues (1971) compared two lamps manufactured in the United States--the GE Chroma 70 and the Verd-A-Ray Criticolor Fluorescent--with the Macbeth Easel Lamp, which was designed for use with screening plate tests. While the lamps gave similar screening data on the AO H-R-R and Panel D-15 tests, and similar total error scores on the FM 100-hue and ISCC tests, the classification data varied among the three illuminants. The authors suggested some caution in using these fluorescents for evaluation of color vision.

Very few tests specify the necessary level of illumination. The AO H-R-R should be viewed under 100 to 650 lux (Hardy et al., 1954a); the Farnsworth-Munsell 100-hue test and the Farnsworth Panel D-15 should be viewed under 270 lux. The City University Test is specified

*The Freeman Illuminant Stable Color Vision Test was designed as rapid-screening testing that would be valid under all illuminants (Freeman, 1948; Freeman and Zaccaria, 1948). The test did not prove to be a successful screening test (Farnsworth et al., undated); it is no longer in production.

for 600 lux. The majority of researchers would consider 100 lux to be a minimal level for screening purposes. Screening-test results are not affected by changes in level of illumination between approximately 100 and 1000 lux.

If the aim of research is evaluation of color discrimination, an illuminant that provides 2000 lux is preferable. Error scores on the FM-100 hue test vary with the level of illumination. Above 100 lux, increased illumination can improve the error scores of observers whose chromatic discrimination was below average at a lower level. These data make it clear that age norms are valid only at the level of illumination specified. The Verriest (1963) age norms (Table 3-2) are for 100 lux. Lower error scores would be expected with 2000 lux illumination. With reduction in illumination below 100 lux, error scores increase, showing first a blue-yellow confusion axis at an illumination of 15 lux, and, finally, a scotopic axis as illumination is reduced to a range of 0.04 to 0.20 lux.

Table 3-1 lists, describes, and names the supplier of some illuminants that are commercially available in the United States. The table includes three illuminants that use a tungsten source with filters, five fluorescent sources, and one xenon source. For some of the illuminants, correlated color temperature, color-rendering index, and approximate level of illumination are shown. The correlated color temperature specifies the spectral energy distribution of the source; Standard Illuminant C has a correlated color temperature of 6774 K. The color-rendering index expresses how closely a test source can reproduce color in comparison with a standard source. An index of 100 is perfect rendition (Wyszecki and Stiles, 1967).

The Macbeth Easel Lamp, designed for use with screening-plate tests, is a widely used illuminant in the United States. The lamp is mounted in a stand which allows source, plate test, and observer to be in correct spatial relationship. The daylight filters for the lamp vary slightly but are close to Standard Illuminant C. The Macbeth Daylight Executive consists of a metal light box that provides diffuse illumination. The various color tests placed in the box are viewed in correct spatial relationship to the observer. The color test glasses (Pokorny et al., 1977; Pokorny et al., 1978) are a pair of color-correcting glasses designed to be used with an ordinary 200-watt light bulb.

The color-rendering indices for the fluorescent lamps listed in Table 3-1 are almost as good as those for the filtered tungsten sources or for the one filtered xenon source. It should be noted that conventional commercially available fluorescent lamps do not have color-rendering properties equivalent to those of the special lamps listed in Table 3-1. For example, a conventional commercially available “daylight” fluorescent lamp has a correlated color temperature of 6673 K but a color-rendering index of only 76.

The observer, test material, and illuminant should be arranged to allow a comfortable position during test performance. The observer should be seated at a desk or table. The test material should be approximately perpendicular to the observer's line of regard to avoid glare or gloss. The illuminant should be mounted above the test

material and adjusted to provide even and direct illumination. The distance of the illuminant from the material determines the level of illuminance and the area of illumination. Plate tests should be presented at a distance of about 75 cm. Arrangement tests are presented at a distance comfortable for manipulation (about 50 cm).

TABLE 3-1 Some Commercially Available Illuminants *

Name and/or Description	Supplier	Correlated Color Temperature	Color-Rendering Index	Illumination
Tungsten Sources with Filters				
Macbeth Easel Lamp (with 100 W tungsten lamp and daylight filter	Macbeth, U.S.	c. 5500 K (value marked on the filter)	-	c. 100 lux
Macbeth Daylight Executive			-	1850 lux
Color test glasses (used with 200 W tungsten source)	House of Vision, U.S.	6800 K	96	385
Xenon Sources				
150 W Xenon Arc XBOF 6500 with one filter	Macbeth, U.S.	6580 K	97	-
Fluorescent Sources				
440 Luminaire (fluorescent) NL 6500	Macbeth, U.S.	6720 K	91	-
Fluorescent Macbeth NL 6500 - $F_{40}T_{12}$	Macbeth, U.S.	6710 K	90	-
Chroma 75 $F_{15}T8$ C75	General Electric U.S.	7500	94	-
Criticolor Fluorescent $F_{15}T8/CC$	Verd-A-Ray U.S.	5700 K	91	-
Verilux Daylight $F_{15}T8$ VLX	Verilux, U.S.	6200 K	94	-

*Data supplied by J.D. Moreland.

TABLE 3-2 Error Scores on FM 100-hue Test According to Age *

Age Group	N	Mean Score	Standard Deviation	Lowest	Highest	95 Percent
10-14	49	83.1	38.2	16	194	160
15-19	56	51.5	28.6	8	124	100
20-24	94	36.3	31.2	4	162	74
25-29	51	47.4	29.4	4	116	92
30-34	33	54.7	35.2	8	176	106
35-39	37	56.8	34.2	8	156	120
40-44	32	62.4	28.5	16	178	134
45-49	30	90.4	39.3	36	184	144
50-54	38	71.5	31.3	24	140	154
55-59	31	96.7	41.9	12	176	164
60-64	29	87.9	35.0	28	152	174

*Data from Verriest (1963).

EXISTING TESTS: AVAILABILITY, PRACTICALITY, AND PROCEDURES

Anomaloscopes

Nagel Model I

Made by Schmidt and Haensch, Berlin, Germany
Available in Canada from Imperial Optical Company, Ltd.
Available in United States from Alfred P. Poll, 40 West 55th Street, New York, NY 10019
Nagel Model II is out of production.

General Description. The Nagel Model I anomaloscope was designed to measure the Rayleigh equation in the general population using spectral lights. The instrument is designed to present a circular split field. In the lower half, a spectral yellow (589 nm) appears. The luminance of the yellow half can be continuously varied by turning a knob. When this knob is adjusted, the yellow half of the field varies from dark at scale zero to increasingly brighter yellow as the scale increases. The upper half of the field is filled with a mixture of spectral yellow-green (545 nm) and spectral red (670 nm). The relative proportions of green and red, from all green through any mixture to all red, can be continuously adjusted by a knob. At scale zero, the upper field appears yellow-green (only spectral yellow-green present). As the knob is adjusted to higher numbers (thereby increasing the proportion of red to green primary in the mixture), the upper field changes in appearance from yellow-green, to green-yellow, yellow, orange, and finally yellow-red at knob value 73 (only spectral red present). A normal observer can achieve a good color match between the two halves of the field by adjusting the red-green knob and the yellow luminance knob. The calibration is set at the factory; the normal match usually occurs between 40 to 50 units of red-green mixture and about 15 units of yellow. At the normal match, the field luminance is approximately 5 cd/m^2. The red and green primary lights have approximately equal luminance. The observer views the split field through a telescope tube. A focusing barrel on the telescope allows for minor adjustments, which are accompanied by a 10 percent variation in the field size. The field size in the currently available Nagel ranges from 1.8° to 2.0°. On the front panel below the telescope tube is a Trendelenburg adapting field for presentation of a uniform adapting field (Illuminant A). The test should be run in darkness or semidarkness.

Administration. Measurement requires a skilled and trained person. Instructions written by Linksz (1964) accompany the instrument, but no scoring sheets are available.

In the Linksz (1964) procedure, the examination starts with a three-minute preadaptation to the lighted Trendelenburg screen on the front panel of the Nagel Model I. The adaptation light is extinguished, and the observer is presented with a normal match prepared by the examiner in advance. If asked to comment on the color appearance, the normal observer and the dichromat will say that the colors look the same or appear as shades of the same color. The anomalous trichromat will usually say that the mixture field appears red (deuteranomalous trichromat) or green (protanomalous trichromat). At this point, some examiners allow the observer to use both red-green and yellow controls to adjust the two fields to equality.

If the normal match, or one close to it, is accepted the next step is to evaluate the range of acceptable red-green ratio values. For a normal observer this range will be small (between 0 and 5 scale units). The examiner turns the red-green mixture 5 scale units from the initial match. Then, alternatively setting the scale above and below the initial match, the examiner centers toward the match in

one-unit steps, asking "Is this a match?" on each trial. The observer is asked to adjust the yellow test knob to obtain a luminance match. In the Nagel Model I anomaloscope, the luminance of the primary lights is approximately equal for normal and deutan observers. The red-green knob changes only the hue of the mixture field, with little luminance effect. With minor luminance adjustments, the three or four scale units that constitute the usual normal range are quickly established for normal trichromats.

For a dichromat, a full range of red-green mixtures is acceptable; for an extreme anomalous trichromat, a very wide range is acceptable. For these observers the examiner turns the red-green mixture knob to zero, then to 73, and then alternates in 10 unit steps. The observer (or examiner) adjusts the yellow luminance knob. Deuteranopes usually make minimal adjustments with the yellow knob on the Nagel Model I anomaloscope, leaving it near the setting made by a normal observer (i.e., around 15). Protanopes set the yellow control to high numbers (35 to 40) at the green end (zero) of the mixture scale, and low numbers (0 to 5) at the red end (near 73). The extreme anomalous trichromat shows brightness matches similar to those of the corresponding dichromat. When testing observers with large ranges it is necessary for them to readapt to the Trendelenburg screen after each setting. All observers should be reminded not to stare at the field for more than a few seconds, and to check each match by a glance technique in order to avoid local color adaptation of the eye.

If a color match within the normal range is not accepted, the observer is an anomalous trichromat. Based on the color report at the initial normal match setting, the observer or examiner moves the red-green mixture into the appropriate range. The red-green matching range is then examined in a systematic way as described above. The obtained range of settings is the match range under neutral adaptation (Neutralstimmung).

Following this procedure, Linksz recommends the so-called tuning procedure, in which the observer stares at his own color match for 15 seconds (Umstimmung). The examiner then again examines the matching range asking, "Is this a match?" to establish a new "tuned" matching range (range under Umstimmung). Normal trichromats do not usually show a greatly widened range. The condition of those who do has been termed Farbenasthenopie in the German literature (Pokorny et al., 1979). Some simple anomalous trichromats show a minor amount of tuning. Extreme anomalous trichromats, as defined by Trendelenburg and Schmidt (1935), show a widened tuning range that may enlarge to include one or even both primaries.

The match midpoints of the range are calculated and may be converted to anomalous quotients or comparative scores. Many laboratories simply report the instrument scale units, including the usual normal range.

Scoring. The anomaloscope contains a red-green scale from which is read a number proportional to the primary ratio in the mixture field, and a Y scale from which is read a number proportional to the luminance of the test color. In testing an observer, the examiner writes down the scale values, which are then available for further transformation or comparison.

There are two statistics for the primary ratio: the range and the midpoint of the matches. In the case of the Rayleigh equation, the matching range comprises all of the scale values on the red-green mixture scale that a given observer says match the yellow test field. A third statistic is also noted: the scale value of the yellow scale. This scale value is used to evaluate relative luminosity losses of color-defective observers.

The anomalous quotient is a common method of presenting the midpoint of the red-green equation. The quotient was introduced by Trendelenburg (1929) as a technique for compensating for minor changes in line voltage and bulb aging. It involves calculating an individual observer's match relative to that of another observer or to the mean of many observers. The anomalous quotient for observer I relative to a group of normal observers is defined as:

$$\frac{\text{Amount 545 nm}}{\text{Amount 670 nm}} \text{ for observer I} \div \frac{\text{Amount 545 nm}}{\text{Amount 670 nm}} \text{ for the group}$$

In the Nagel anomalscope, for example, the mixture knob gives the amount of 670 nm light in the match. At zero the field is 545 nm and at 73 the field is 670 nm. Suppose that for a group of 50 normal trichromats the average match midpoint is 45 on the mixture scale. This means that 45 is the amount of 670 nm. To obtain the amount of 545 nm, subtract 45 from 73 and find 28 as the amount of 545 nm. The ratio 28/45 is the green-red ratio for the normal sample. Suppose a new observer comes in with a match midpoint of 43, giving a green-red ratio of 30/43. To find the anomalous quotient, we divide the observers green-red ratio by the green-red ratio for the normal sample, obtaining 30/43 divided by 28/45, or 1.12. Anomalous quotients for normal trichromats fall between about 0.74 and 1.33. Anomalous quotients may be used to compare data from different laboratories if the identical set of primaries is used in both laboratories.

Calculation of the anomalous quotient is meaningless when the matching range is large, as it is in many color-defective observers.

A slide rule for rapid calculation of anomalous quotients (anamal-quotientrechenschieber or AQ) is manufactured by Schmidt and Haensch. Halldén (1959) published a nomogram for easy calculation of the AQ.

An alternative calculation of the anomalous quotient is to convert the anomaloscope raw scale units to comparative scale units (Willis and Farnsworth, 1952). Comparative scale units (CSU) range from zero at the green primary to 100 at the red primary, with the normal match at 50. The equation to convert to comparative scale units is

$$\frac{\text{Raw score X correction factor}}{(\text{raw score X correction factor}) + (\text{maximum score} - \text{raw score})}$$

provided that the scale is adjusted to go from zero at green primary to maximum at the red primary. The correction factor is the ratio of raw score units of green to raw score units of red at the normal match.

Thus in the Nagel Model I anomaloscope with a range of 0 to 73 and normal match at 45, we take 45 as the amount of red and 73 to 45 or 28 as the amount of green, giving a correction factor of 28/45 or 0.62. A raw score of 45 converts to 50 CSU. This conversion does allow comparison of matching ranges of observers with wide ranges. The CSU preserves the anomalous quotient (i.e., anomalous quotients will be identical when calculated from CSUs as from raw scores). Data from different instruments should be compared only if primary and test wavelengths are identical. The CSU conversion has not been widely used.

Maintenance. The Nagel anomaloscope is a constant deviation spectroscope with three entrance slits to provide spectral lights for the Rayleigh equation. The amount of 589 test light and ratio of 545 nm to 670 nm mixture lights is achieved by moving slits in the optical path. The slit mechanisms are quite delicate and will slip if the instrument is handled roughly. The Nagel anomaloscope should be placed where it will not be disturbed. If the slits are displaced, the match midpoint and/or yellow brightness setting will vary. The anomalous quotient may still be used, but comparison of the data to those of other instruments might not be valid, since the spectral distribution of the primaries may have been affected.

Calibration. A spectroscope may be used to check the wavelength bands passed by the slits. Sample spectroradiometric data were given by Pokorny and colleagues (1977) for a Nagel Model II anomaloscope. For routine clinical use, no calibration is required by the user. The lamp voltage should be stabilized to provide a reproducible correlated color temperature (Schmidt, 1955). The primaries and slit mechanism of Nagel anomaloscopes differ between models, and because of that it may be difficult to compare the results of various population studies that have been published, even if data are expressed in terms of the anomalous quotient (Moreland, 1974).

Validity. The Rayleigh equation provides differential diagnosis for simple and extreme protanomalous and deuteranomalous trichromacy and for protanopia and deuteranopia. It is possible that the distinction between an extreme anomaly and the corresponding anopia may be missed, because the Nagel anomaloscope does not cover the full dichromatic confusion range. Nevertheless the Nagel Model I is considered a standard test of red-green color vision, and validation measures of other color vision tests are based on comparisons of their results with results on the Nagel Model I.

Anomaloscope data on observers with normal color vision were reported by Willis and Farnsworth (1952) and Schmidt (1955) for the Nagel Model II anomaloscope and by Helve (1972) for the Nagel Model I anomaloscope. Helve tested 186 normal observers who were selected from 1,200 conscripts (median age 21 to 22 years). Matching ranges and match midpoints were evaluated under neutral adaptation. The distributions of matching ranges and midmatching points for normal and anomalous trichromats are shown in Figure 3-1 where the percentage

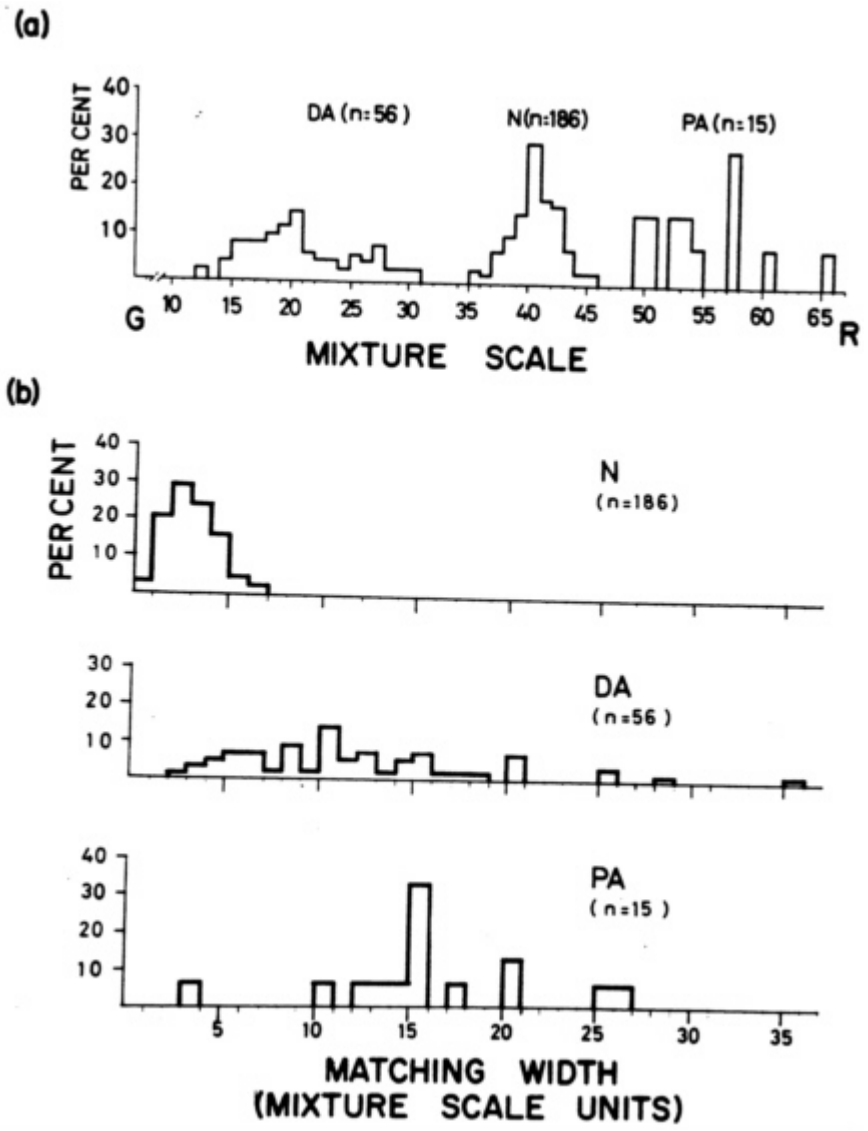

FIGURE 3-1 Norms for the Nagel Model I anomaloscope. (a) Histogram showing the percentage distributions of matching midpoints among the deuteranomalous (DA), normal (N), and protanomalous (PA) subjects; (b) Histograms showing the percentage distribution of the matching ranges among the normal (N), deuteranomalous (DA), and protanomalous (PA) subjects. The results refer to measurements made with the eye adapted to white light. Data are from Helve (1972), as reproduced by Pokorny et al. (1979), by permission.

distributions are shown for raw scale units. For normal trichromats, the distribution of matching ranges is skewed with a modal value at 3 scale units. The distribution of match midpoints is peaked and symmetrical with a mean value near 40 scale units. Matching widths of anomalous trichromats are usually broader than those of normal trichromats. The match midpoint occurs between 50 and 65 raw scale units for protanomalous trichromats and between 12 and 31 raw scale units for deuteranomalous trichromats. These raw scale units vary between different instruments. The mean normal match on a given Nagel Model I anomaloscope varies between 40 and 50 scale units.

When converted to anomalous quotients, the total range of the match midpoints for normal observers was 0.80 to 1.20. (Total range of all matches was 0.65 to 1.30). In previous studies of the match midpoint using the Nagel Model II, Schmidt (1955) reported a range of 0.45 to 2.00 and Willis and Farnsworth (1952) reported a range of 0.72 to 1.41.

The protanope and deuteranope are distinguished on the Nagel Model I anomaloscope by their settings of the 589 nm brightness adjustment. The deuteranope sets the brightness at approximately the same position (near 15) for all red-green mixtures. The protanope sets the yellow brightness to higher values when the mixture field is near the green primary and to lower values when the mixture field is near the red primary (Pokorny et al., 1979).

Pickford-Nicolson

Available from Rayner and Keiller, Ltd., London, England

General Description. The Pickford-Nicolson anomaloscope was designed to measure the Rayleigh equation; an equation similar to the Engelking-Trendelenburg equation; and the Pickford-Lakowski equation. The Pickford-Nicolson anomaloscope is a filter anomaloscope that uses broadband filters to provide primary and test wavelengths. The instrument presents the observer with a circular split field. The test field appears in the left half, its radiance varied by means of a knob with a scale on the top of the instrument. When the knob is adjusted, the test field varies from dark at scale zero to increasingly brighter test fields to its maximum at scale 82. The primary mixture appears in the right half. The relative proportion of the primaries can be adjusted continuously; the mixture ratios are read from a scale on the top of the instrument.

For the Rayleigh match, a yellow test is matched to a mixture of green and red. At scale zero, the mixture field appears red to the color-normal observer and changes continuously from red through orange, yellow, yellow-green, to green at scale 80. In the pilot model (Pickford and Lakowski, 1960), the normal match is at 36 to 39 units of red-green mixture and 20 units of yellow. The luminance of the red primary is greater than that of the green primary. The field luminance at the normal match is 8.6 cd/m^2. For the Engelking-Trendelenburg equation, a blue-green test is matched to a mixture of green and blue. At scale zero, the mixture field appears green and changes continuously

from green through pale blue-greens and green-blues to blue at scale 80. In the pilot model, the normal match occurs at a mixture of 45 to 49 units, and the desaturated blue-green test field is set at 40. The field luminance is about 5 cd/m^2. For the Pickford-Lakowski equation, a yellowish white (Illuminant A) is matched to a mixture of yellow and blue. At scale zero, the mixture field appears yellow and changes continuously to white and then blue at scale 80. In the pilot model, the normal match occurs at a mixture of 36 to 41 units, and the white brightness value is about 25. The field luminance is about 7 cd/m^2. The position of the normal matches varies between instruments because of variation in the color filters (Lakowski, 1971).

The examiner sets up the required equation by inserting the correct filter pair into the mixture field. An aperture (controlled with a knob on top of the instrument) controls the luminance of the mixture field. This aperture is usually in the open position and is never adjusted during the test procedure. A filter pair is also used in the test field to allow desaturation of the test field. A neutral filter is used with the 585 nm test filter in the Rayleigh equation and with the 495 nm test filter in the Engelking-Trendelenburg equation. Using a knob on the top of the instrument, the examiner can set the amount of desaturation. In the pilot model, the desaturation knob was at 60 for the Rayleigh match and at 67 for the Engelking-Trendelenburg match. For the Pickford-Lakowski match, the white provided by Illuminant A is made slightly reddish by using a 642 nm filter to adjust the color balance, and the desaturating knob is at 43. For any of the three equations, once the desaturating knob is set, it is not changed again during the experimental procedure.

The color fields appear on a diffusing screen at the front of the instrument. By use of apertures (5 to 50 mm in diameter), circular split fields of various sizes or even two small circles may be presented. The field size is determined by viewing distance; distances of up to two meters may be used. Usually the observer is at one meter, giving a range of about 20 seconds to almost 3 degrees, depending on the aperture.

Administration. The testing procedure detailed by Pickford (1951, 1957; Pickford and Lakowski, 1960) is followed. Ambient illumination provided by the room light or window light is allowed, provided that no source of illumination is directed at the viewing screen. Maximal illumination on the desk or table holding the instrument should be no more than 100 lux. The examiner sits at the front side of the instrument close enough to adjust the knobs but also seated so that he or she can view the screen and point at the stimulus field if necessary.

The observer sits about one meter from the screen, which should be at eye level. A preliminary screening with a plate test is recommended so that the examiner knows whether the observer has a color defect. Each eye is tested separately. All manipulations of the anomaloscope are performed by the examiner. The test starts with presentation of a normal match, and the test luminance is adjusted if necessary. The observer reports on the field appearance. In the Rayleigh equation, a response of "equal" or "close" suggests a normal trichromat or

dichromat; a response of mixture field "green" suggests a protanomalous trichromat; a response of mixture field "red" suggests a deuteranomalous trichromat. As with the Linksz procedures, the observer's response determines the examiner's next steps. If the normal match was accepted or close, the matching range is next examined. For the normal trichromat, the examiner starts with a mixture that is definitely not a match (e.g., mixture too "orange") and moves toward the match in one-unit steps until "match" is reported. Then, starting from a "match" position, the examiner moves back toward the "no-match" position. Three or four such runs are made at each end of the matching range. For the dichromat, the full red-green range is examined in larger (10-unit) steps. Because the luminance of the red primary is greater than that of the green primary, changes in the mixture ratio are accompanied by luminance changes; the examiner must adjust the yellow test-field luminance at each red-green mixture. For the anomalous trichromat, large steps on the red-green scale are used to establish the gross range of anomalous settings. The ends of the matching range are then established using small steps and the method of limits as described for normal trichromats.

The Engelking-Trendelenburg and Pickford-Lakowski equations are examined in a similar manner.

Scoring. The anomaloscope contains scales from which are read a number proportional to the primary ratio in the mixture field and a number proportional to the luminance of the test color. In testing an observer, the examiner writes down the scale values, which are then available for further transformation or comparison.

There are two statistics for the primary ratio: the range and the midpoint of the matches. In the case of the Rayleigh equation, the matching range includes all of the scale values on the red-green mixture scale that a given observer says match the yellow test field. A third statistic is also noted: the scale value indicating the value of the yellow scale. This scale value is used to evaluate relative luminosity losses of color-defective observers. Anomalous quotients may be calculated, but they cannot be compared with anomalous quotients derived from other Pickford-Nicolson anomaloscopes or from the Nagel anomaloscope.

An alternative method of expressing the equation of a given observer relative to that of a population of normal observers is to use the statistical properties of the distribution of match midpoints made by normal observers (Pickford, 1957). For the Pickford-Nicolson anomaloscope, match midpoints of a population of normal observers show a normal (symmetrical, peaked) distribution. Such a distribution is characterized by its mean and its standard deviation. A way of expressing deviation from the mean value is to define what is termed the normal deviate or z score:

$$-z = \frac{x - \mu}{\sigma}$$

where x is the scale value of a given observer, μ is the mean scale value of the population, and σ is the standard deviation of the normal population. Using tables available in standard statistics

textbooks, it is possible to estimate with what frequency any match (or a more deviant match) would be expected to occur as a variant of the originally sampled normal population.

For the Pickford-Nicolson anomaloscope, matching widths of a population of normal observers have a skewed distribution. Pickford (1957) suggested that these widths be characterized by their modal (most frequently occurring) value, and that data be expressed in terms of the mode. Lakowski (1971) suggested that percentiles (observed frequency/total × 100) could be used.

Finally the midpoint and matching range may be plotted on the 1931 x,y chromaticity diagram (see Appendix for a description of the CIE x,y chromaticity diagram). The data may be further transformed into one of the CIE's Uniform Color Spaces to give data expressed as just-noticeable difference (JND) units in the Uniform Color Space (Lakowski, 1965a). Lakowski (1965a, 1971) performed this transformation, and Figure 3-2 Figure 3-3 through Figure 3-4 show data expressed in JND units. The idea is a good one, since observers may be directly compared regardless of which primaries and test lights were used. However, the calculation requires calibration of the anomalocope into the JND scale. Results should be considered approximate since there is a lack of agreement among colorimetrists as to the best color space to use.

Maintenance. The Pickford-Nicolson is a filter anomaloscope that uses glass filters. The instrument is sturdy and requires no special maintenance.

Calibration. A spectroradiometer may be used to check the filter output. Filters in different instruments may vary significantly. Precise calibrations were reported by Pickford and Lakowski (1960) for the pilot model and by Lakowski (1971) for his model. Further calibration is not required for screening purposes but would be necessary for experimental work.

Validity. The Rayleigh equation provides differential diagnosis of simple and extreme anomalous trichromacy (protanomaly and deuteranomaly) as well as dichromacy (protanopia and deuteranopia), although some deuteranopes may not accept a full matching range on the Pickford-Nicolson anomaloscope due to the choice of desaturated primaries (Pokorny et al., 1979). As with the Nagel anomaloscope, it is possible that the distinction between an extreme anomaly and the corresponding anopia may be missed because the primaries that are used do not cover the full dichromatic confusion range. We have not found sufficient data comparing Rayleigh matches of congenital red-green color-defective observers on the Nagel and Pickford-Nicolson anomaloscopes.

The Engelking-Trendelenburg and Pickford-Lakowski equations have been most useful in identifying acquired color vision defects. The Engelking-Trendelenburg equation is not suitable for diagnosis of tritanomaly, and neither equation will differentiate a tritanope from an incomplete tritan. Lakowski (1971) has presented norms for over 124 observers with normal color vision assessed in the Pickford-Nicolson anomaloscope. In that study, the Rayleigh, Engelking-Trendelenburg,

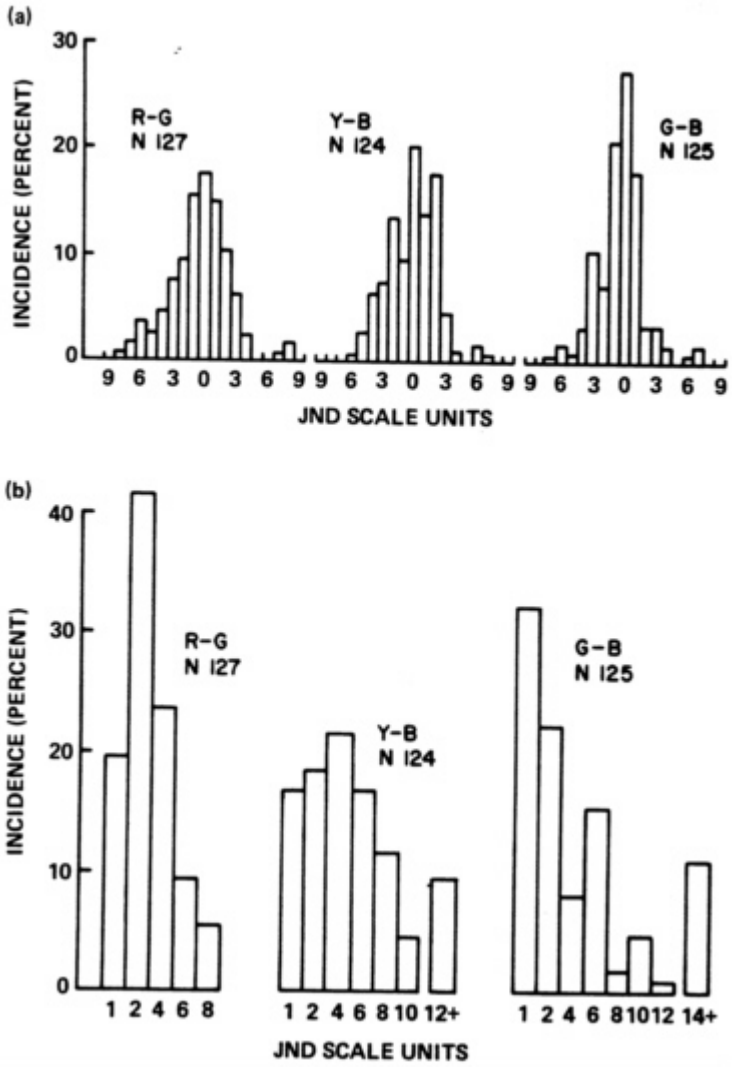

FIGURE 3-2 Norms for the Pickford-Nicolson anomaloscope. (a) Histogram showing percentage distributions of matching midpoints for normal subjects (16 to 60 years of age) on Rayleigh (R-G), Pickford-Lakowski (Y-B), and Engelking-Trendelenburg (G-B) equations. Abscissa indicates JND (just-noticeable-difference) scale units with zero representing the mode. (b) Histogram showing percentage distribution of matching ranges.
Data from Lakowski (1971), as reproduced in Pokorny et al. (1979), by permission.

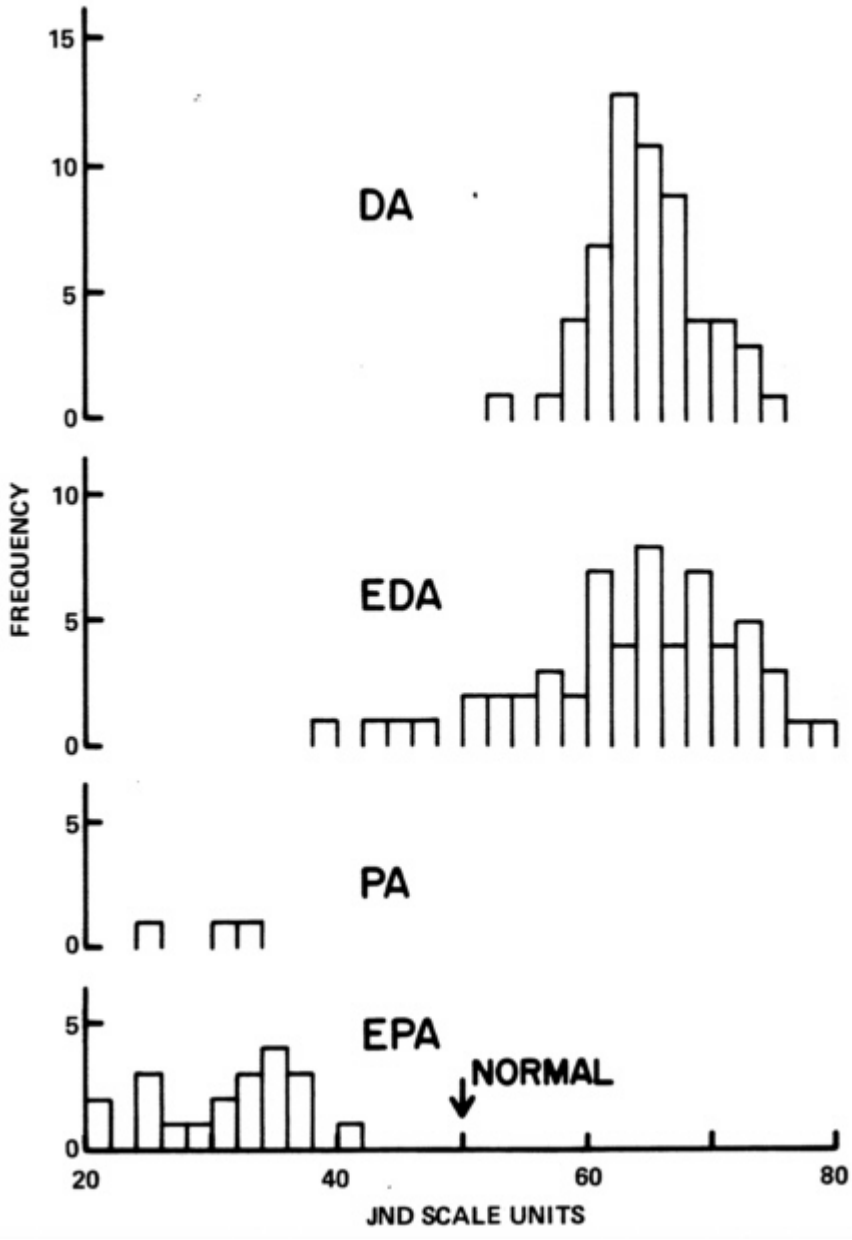

FIGURE 3-3 Distribution of match midpoints on the Rayleigh equation for anomalous trichromats (mean age is 20) using the Pickford-Nicolson anomaloscope.
Based on scale units and data from Lakowski (1971).

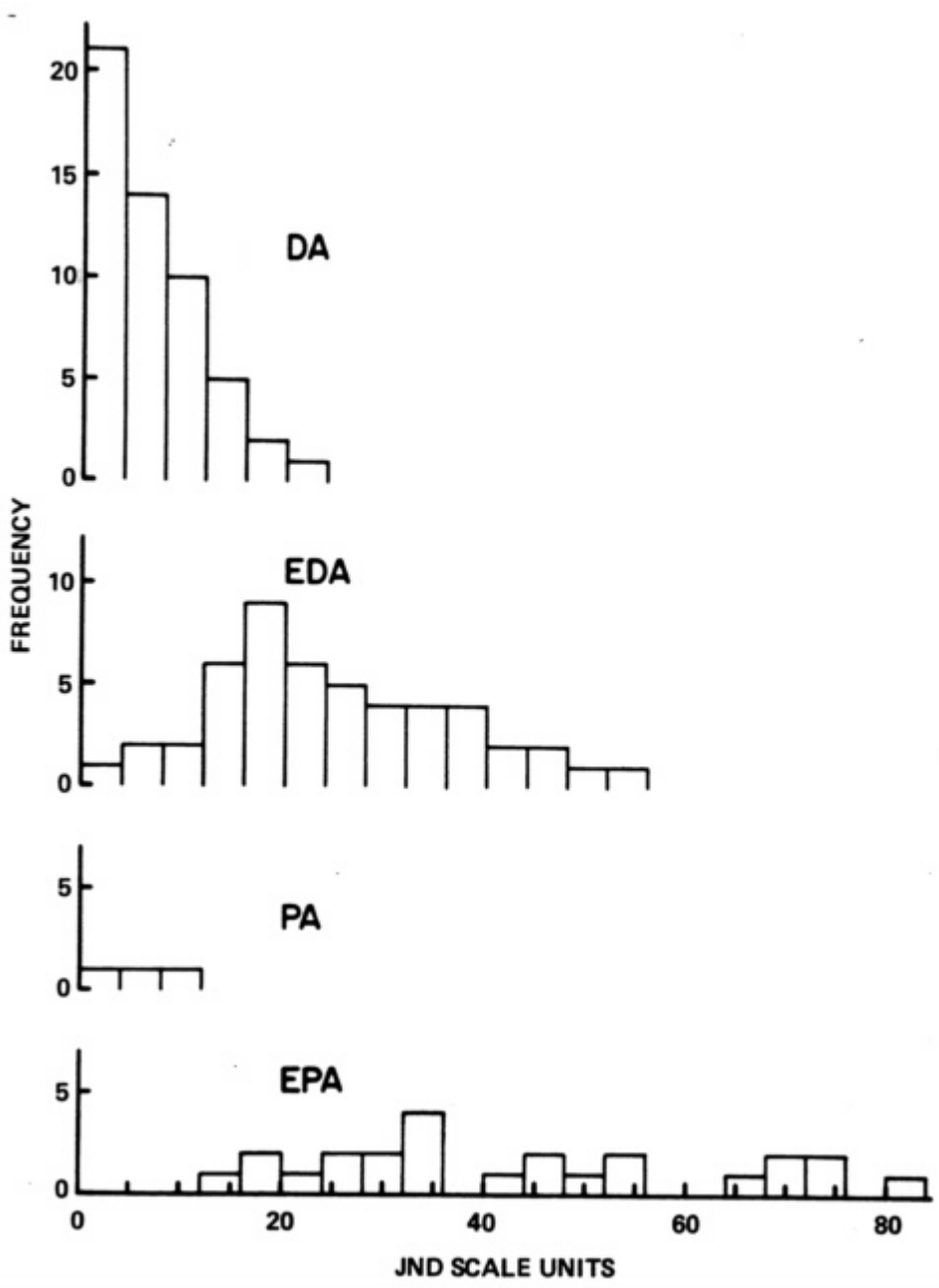

FIGURE 3-4 Distribution of matching ranges on the Rayleigh equation for anomalous trichromats (mean age is 20) using the Pickford-Nicolson anomaloscope.
Based on scale units and data from Lakowski (1971).

and Pickford-Lakowski equations were evaluated. Figure 3-2a shows the match midpoints reproduced from Lakowski (1971) and Figure 3-2b shows the matching ranges, in Lakowski's just-noticeable-difference scale units. The match midpoints show peaked, symmetrical distributions for all three equations. The matching ranges are asymmetric for all three equations. Match midpoints and matching ranges of the Rayleigh equation for anomalous trichromats are shown in Figure 3-3 and Figure 3-4. The data, as for the Nagel anomaloscope, indicate displaced match midpoints and larger matching ranges compared with data of normal trichromats.

Neitz OT

Made by Neitz Instrument Co., Ltd, Tokyo, Japan

Available in the United States from Kowa Optimed Inc., 20001 S. Vermont, Torrance, CA 90502

General Description. The Neitz anomaloscope was designed to measure the Rayleigh equation in the general population. The design was based on the Nagel anomaloscope; however, interference filters were used to give primary and test wavelengths. Some human engineering improvements were incorporated that make the instrument easier to use. As with the Nagel, the Neitz presents a circular split field; the upper half contains the primary mixture field, and the lower half contains the yellow test field. Knobs extending to both sides of the instrument control the appearance of these fields; the upper knobs control the primary mixture, and the lower knobs control the yellow luminance. Large and legible scales, color-coded to indicate what the knobs are doing, are on one side (left when facing instrument). The scales are identical to those of the Nagel Model 1. The yellow luminance varies from 0 (dark) to 87 (bright yellow). The red-green mixture knob varies from 0 (all green) to 73 (all red). The calibration is set at the factory; the normal match occurs at 40 units of red and 15 units of yellow. At the normal match, the field luminance is approximately 5 cd/m^2. The red and green primary lights have approximately equal luminance.

The observer views the bipartite field through a telescope tube. A focusing barrel on the telescope allows for minor adjustments, which are accompanied by a 10 percent variation in the field size. The field size at average focus is approximately 2°. On the front panel below the telescope tube is a Trendelenburg adapting field to present a uniform adapting field (Illuminant A). The test should be run in darkness or semidarkness.

Administration. Measurement requires a skilled and trained person. The procedures given for the Nagel anomaloscope should be followed.

Scoring. The anomaloscope contains a red-green scale from which may be read a number that is proportional to the amount of red in the mixture field, and a Y scale from which is read a number proportional to the luminance of the test color. In testing an observer, the examiner notes the scale values, which then are available for further transformation as noted for the Nagel anomaloscope.

Maintenance. The instrument is sturdy and well constructed. No special maintenance procedures are required.

Calibration. The spectral transmittances of the filters were described for the experimental model (Ohta et al., 1980). Peak transmittance for the experimental model was at 546 nm for the green primary, 672 nm for the red primary, and 591 nm for the yellow test field. For routine clinical use, no calibration is required by the user.

Validity. Classification of 74 red-green defective observers by the Neitz anomaloscope was compared with classification by the Nagel anomaloscope (Ohta et al., 1980). A coefficient, of association k, may be computed for these data and is 0.96, indicating that the Neitz anomaloscope produces essentially the same classification as the Nagel. The only differences in classification were two observers who were classified as extreme deuteranomalous by the Nagel but who were classified as simple deuteranomalous on the Neitz.

As with the Nagel, it is possible that the distinction between an extreme anomaly and the corresponding anopia may be missed, because the anomaloscope does not cover the full dichromatic confusion range.

Other Remarks: The Neitz is an attractive new anomaloscope for the classification of red-green color vision. The instrument offers advantages in clinical use. The advantage of the interference filters is that the instrument is mechanically stable, and calibration should remain as set at the factory. The filters probably should be checked periodically to ensure that no physical deterioration has occurred. Some human engineering features, such as the large color-coded scales, make the instrument easy to read.

Some General Considerations in Anomaloscope Testing

There are a number of features of anomaloscope testing that deserve emphasis. These features include initial setting of norms for the instrument, the use of color names, and the use of the Trendelenburg adaptation screen.

Establishing Norms. When an anomaloscope is purchased or introduced into a laboratory or clinic, the first step is to establish norms for the instrument. Matching ranges are established for all normal observers who are working in the laboratory or clinic, and others may be invited to participate. Such an informal set of norms

will probably serve to establish a clinical norm for the Rayleigh equation. A more formal survey with matched age groups will be necessary for the Pickford-Lakowski equation. Once norms have been established, the examiner is better equipped to deal with occasional "peculiar" matches.

In the Rayleigh equation, the yellow luminance settings accepted by congenital red-green defective observers are characteristic and diagnostic of the defect. It is important for the examiner to obtain the appropriate normative information on dichromats so that the characteristic settings are easily recognized. The examiner should be alert to the occasional observer who sets or accepts "impossible" luminance settings (e.g., an observer who turns the yellow test to very high levels to match the red primary and then claims that a color match exists). This type of behavior can occur with children and is indicative of the observer's poor attention or cooperation.

Using Color Names. All normal and some color-defective observers can and do use color names reliably (see, for example, Jameson and Hurvich, 1978, and Pokorny et al., 1979). However, caution is in order. The examiner should let the observer use his own terminology and should not tell an observer what the colors are. For example, if the green primary and yellow tests are presented in a Rayleigh match, the examiner should not ask "Do you see the green on top and the yellow on the bottom?" but "What color do you see on the bottom?" There are two reasons for this practice. First, normal trichromats may see the Rayleigh test field as orange or yellow-orange. Introducing color terms to a normal (or anomalous) trichromat may involve the unwary examiner in an unnecessary argument about color terminology. Second, the color-defective observer may not perceive these two colors; he may see the color pair as green and red, or yellow and red, or as shades of the same color. He may be perturbed or confused by the examiner's assertion.

Color terms used by dichromats and many anomalous trichromats depend on the luminance relations between the two halves of the field. In the Rayleigh equation, a protanope may see a dim test field as red, but if the luminance is raised he may say "Now the red has switched sides." Such reports indicate improper luminance relations. The skilled examiner can make use of such reports to set a proper luminance balance. If such reports occur, the yellow test luminance should be checked carefully before the red-green scale is changed. Thus, color names can be very helpful to the examiner in abbreviating the test procedure.

Trendelburg Screen. The Trendelenburg adaptation screen was proposed by Drescher and Trendelenburg (1926) to allow the observer to maintain a neutral state of adaptation during testing with the Nagel anomaloscope. The Trendelenburg screen is not used during testing with the Pickford-Nicolson anomaloscope. The difference is essentially that the Nagel uses a telescope-view and the Pickford-Nicolson uses a direct-view. With the Nagel the observer places his or her eye at the aperture and looks down the viewing tube. The color fields appear in a dark

surrounding, and the observer may adapt to the stimulus array with continued viewing. With the Pickford-Nicolson, the observer is in a lighted room and remains adapted to the ambient illumination. Matching ranges of color-defective observers can be strongly affected by local adaptation resulting from continued fixation. If a careful examination of the red-green matching range is to be made using a Nagel or Neitz anomaloscope, viewing time should be limited and the Trendelenburg screen should be used.

Pseudoisochromatic Plates

American Optical Color Vision Test

Pseudo-Isochromatic Plates for Testing Color Perception by American Optical Corporation, Buffalo, NY 14215

15 plates

Available from:

1. American Optical Co., Catalog #13375 AO Color Test, Buffalo, NY 14215
2. House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The American Optical (AO) psuedoisochromatic color test is designed as a rapid-screening test for red-green color defects. The test consists of 15 single- and double-digit numerals in script form. An instruction sheet is included, together with a sample scoring sheet. Plate 1 is a demonstration plate: a double-digit numeral composed of colored circles of various sizes appears against a background of different colored circles. Colors are chosen so that all observers with visual acuity better than 20/200 can read the plate. If an observer fails to read this plate, the test should be discontinued. The remaining 14 plates are based on pseudoisochromatic principles and are of the vanishing type.

Administration. The observer must read the numeral on the plate within two seconds. The plates are held at 75 cm, perpendicular to the line of sight, under daylight illumination. The pages are well designed for easy turning. The plates are not numbered, but the numerical sequence is given on the record sheet. The plate sequence can be changed. The examiner should number the plates in their original sequence. Test time is two minutes per eye.

Scoring. Scoring instructions accompany the test. An incorrect response to as many as four plates is considered normal due to legibility confusion; some observers are confused by the appearance of script numerals. Incorrect responses to five or more plates indicate defective color vision.

Maintenance. No information is provided in the manual. The set of plates should be kept closed and dust-free when not in use.

Calibration. No calibration is required by the user. The accompanying manual recommends the Macbeth Easel Lamp as the illuminant.

Reliability. According to test-retest data reported by Seefelt (1964), the statistic of agreement, κ, is 0.96. Seefelt reported lower reliability when the test was administered under mass screening conditions rather than clinical testing conditions.

Validity. Seefelt (1964) reported validity data: The statistic of agreement, κ, was 0.97 for clinical screening but decreased to 0.90 under conditions of mass screening as performed by the U.S. Air Force. The major discrepancy is in the number of normal observers who are misclassified. The AO plates have been compared to other plate tests (Chapanis, 1948, 1949; Hardy et al., 1954b; McCulloch et al., 1959; and Steen and Lewis, 1972.

Other Remarks. With this test, no protan-deutan differential diagnosis is possible. There are no tritan plates. The test is useful for screening red-green defects only. The test appears to be based on the Stilling and Ishihara plates.

American Optical Hardy-Rand-Rittler (AO H-H-R) Plates

AO H-R-R Pseudoisochromatic Plates, by LeGrand H. Hardy, Gertrude Rand, and M. Catherine Rittler, American Optical Co., Buffalo, NY 14215

24 plates

AO H-R-R-plates are not available at this time. However, the International Research Group on Color Vision Deficiencies is circulating a petition for reprinting.

General Description. The AO H-R-R test is designed to screen red-green and blue-yellow color defects; to differentiate protan, deutan, and tritan defects; and to estimate the degree of color defect. The test consists of 24 plates in which colored circles of various sizes and lightnesses form outlines of symbols on a background of gray circles of various sizes and lightnesses. These symbols are a cross, a circle, and a triangle. An instruction sheet and a sample scoring sheet are included.

The first four plates are demonstration plates: three have symbols and one is blank. These four plates are intended to screen for hysteria and malingering (see page 00 for special problems in testing). Observers with visual acuity better than 20/200 should be able to give correct responses. If an observer gives an incorrect response to a

demonstration plate, the test should be discontinued. The demonstration plates are followed by six screening plates (two for blue-yellow and four for red-green color defects). Plates are of the vanishing type, and the hues in the symbols for the screening plates are close to gray. The screening series is followed by 14 hidden-figure diagnostic plates. Ten of these are for red-green color defects; plates that can be read by protans and those that can be read by deutans are indicated in separate columns on the scoring sheet. Four of the diagnostic plates are for blue-yellow color defects. The hue distinctness of the symbols increases as each series progresses.

Administration. The observer must identify the symbols by giving an immediate response. The plates are held 75 cm from the observer, perpendicular to the line of sight, under daylight illumination. A source approximating Illuminant C and giving 100 to 600 lux illumination should be used. The pages are awkward to turn. The plates themselves are not numbered, but a numerical sequence is given on the record sheet; the plate sequence is fixed. The duration of the test is from two to three minutes. An observer who responds correctly to all six screening plates is considered to have normal color vision, and the test is discontinued. If the observer makes an error on plates 1 or 2 (screening plates for blue-yellow defect), the examiner proceeds to plates 17 to 20, the diagnostic plates for blue-yellow defects. If the observer makes an incorrect response to screening plates 3 to 6 (screening plates for red-green defects), the examiner proceeds to plates 7 to 16, the diagnostic plates for red-green color defects. If the observer passes all diagnostic plates, the screening series is repeated. Failure to perceive any symbol constitutes an error. In addition, assigning an incorrect name or location to a symbol is considered an error.

Scoring. Demonstration plates are not scored. Failure to give a correct response to the demonstration plates may be an indication of hysteria or malingering. An observer who responds correctly to all six screening plates, either on test or retest, is considered to have normal color vision. An observer who makes errors on the screening plates on both test and retest is considered color-defective and is classified as blue-yellow if errors were on plates 1 or 2 and red-green if errors were on plates 3 to 6.

A diagnostic analysis is made on the basis of reading plates 7 to 20. An observer is classified as a protan if the majority of correct readings are in the protan column, and as a deutan if the majority of correct readings are in the deutan column. The observer is unclassified red-green defective if readings are distributed in both columns equally or if errors occurred only on red-green screening plates. A similar diagnostic procedure is made for errors that occur in the blue-yellow plates.

A classification of severity using the terms “mild,” “medium,” and “strong” may also be made. In the red-green series, misreadings that include plates 7 to 11 indicate a mild defect, errors that extend to plates 12 to 14 are considered to indicate medium defect, and errors

that include plates 15 or 16 indicate strong defect. For the blue-yellow series, errors on only screening plates 1 or 2 indicate an unclassified defect, errors on plates 17 or 18 a medium defect, and errors on plates 19 or 20 a strong defect.

Vos and coworkers (1972) recommended a modified procedure and scoring structure called HRR-R for the red-green plates of the first edition of the AO H-R-R.

Maintenance. The instruction sheet includes the following advice regarding maintenance: "Keep book closed when not in use" and "Do not touch . . . plates with . . . fingers." The test claims the use of exceptionally permanent pigments and stable bases.

Calibration. Lakowski (1966, 1969) has reported sample spectrophotometric data. No calibration is required by the user. The instructions recommend the Macbeth Easel Lamp and specify the use of sources approximating Illuminant C.

Reliability. The statistic of agreement, $\hat{\kappa}$, can be calculated from data calculated by Hardy and colleagues (1954a) and Paulson (1971) for reliability of screening, qualitative diagnosis (protan, deutan, blue-yellow defect), and quantitative diagnosis (severity).

Author	Test of	$\hat{\kappa}$
Hardy et al. (1954a)	Screening	.97
Hardy et al. (1954a)	Qualitative diagnosis	.98
Paulson (1971)	Qualitative diagnosis	.38
Hardy et al. (1954a)	Quantitative diagnosis	.79
Paulson (1971)	Quantitative diagnosis	.53

Validity. The statistic of agreement, κ, can be calculated from data tabulated by several authors.

Author	Test of	κ
Sloan and Habel (1956)	Screening	.90
Belcher et al. (1958)	Screening	.88
Walls (1959)	Screening	.91
Crone (1961)	Screening	.90
Paulson (1971)	Screening	.96
Hardy et al. (1954b,c)	Qualitative diagnosis	.91
Frey (1958)	Qualitative diagnosis	.22
Walls (1959)	Qualitative diagnosis	.70
Crone (1961)	Qualitative diagnosis	.78
Frey (1963)	Qualitative diagnosis	.55
Helve (1972)	Qualitative diagnosis	.81
Vos et al. (1972)	Qualitative diagnosis (HRR-R)	.58

Frey (1958)	Quantitative diagnosis	.22
Walls (1959)	Quantitative diagnosis	.45
Sloan (1961)	Quantitative diagnosis	.34
Frey (1963)	Quantitative diagnosis	.31
Helve (1972)	Quantitative diagnosis	.24

Many of these authors and others have compared the AO H-R-R to other plate and lantern tests (McCulloch et al., 1959; Walls, 1959; Collins et al., 1961; Dvorine, 1963; Paulson, 1971; Verriest, 1968a, 1968b; Richards et al., 1971; Pinckers, 1972; Steen and Lewis, 1972; Verriest and Caluwaerts, 1978).

In summary, the AO H-R-R as a screening test detects at least 85 to 90 percent of color-defective observers classified by anomaloscope. Qualitative diagnosis is variable. The major factor reducing $\hat{k}$ is the number of color-defective observers who remain unclassified. If a classification is obtained, it is usually correct: the conditional $\hat{k}$ for the authors above ranges from 0.61 to 1.00. Quantitative diagnosis shows poor association of the grades mild, medium, and strong with the categories simple anomalous, extreme anomalous, and dichromat. The primary problem is that the grade "medium" is distributed among anomalous trichromats and dichromats. The grade "mild" is strongly associated with simple anomalous trichromats; the conditional $\hat{k}$ on "mild" ranges from 0.7 to 1.0. The grade "strong" is less associated with dichromats: the conditional $\hat{k}$ on "strong" ranges from 0.34 to 0.6.

Other Remarks. This test is useful for rapid screening of red-green and blue-yellow defects. It provides differential diagnosis of protan and deutan, classifies three levels of severity, and provides differentiation of defects. It is especially useful in testing children and others who comprehend geometric symbols but not numerals.

Dvorine

Dvorine Pseudo-Isochromatic Plates by Israel Dvorine, 4th Printing, Harcourt, Brace and World, Inc., New York, 1963

23 plates

Available from:

1. Bernell Corp, South Bend, IN 46601
2. Stoetling Co., Chicago, IL 60623

General Description. The Dvorine psuedoisochromatic plate test is designed to screen red-green defective color vision and to differentiate between protan and deutan defects. The test consists of single- and double-digit numerals (15 plates) and paths to be traced with a soft-tipped paintbrush (eight plates). The latter plates are intended for use with illiterates. Instructions for administration and scoring, with a sample scoring sheet, are provided. Printed scoring sheets may be purchased separately.

Of the 15 numeral plates, plate 1 is a demonstration plate. A double-digit numeral composed of colored circles of various sizes appears against a background of different-colored circles. Colors are chosen so that all observers with visual acuity better than 20/200 can read the plate. If an observer fails to read this plate, the test should be discontinued. The remaining 14 plates are based on pseudoisochromatic principles and are of the vanishing type. Twelve of these plates are screening plates (plates 2 to 5 and 8 to 15); two are diagnostic plates (plates 6 and 7).

Administration. The observer must read the numeral on the plate within five seconds. The plates are held 75 cm, perpendicular to the line of sight, under daylight illumination. The pages are awkward to turn. The plates are not numbered, but the numerical sequence is given on the record sheet. The plate sequence can be changed, and the examiner should number the plates in their original sequence. Test time is two minutes per eye.

Scoring. Scoring instructions accompany the test. For the numerals, an incorrect response to two or fewer plates is considered normal due to legibility confusion. An incorrect response to three or more plates indicates defective color vision. For the purpose of civil aviation, five or more incorrect responses result in failure of the test. There are three plates for differentiation of protans and deutans. A classification of severity is based on the number of plates missed: 0 to 2 is normal; 3 or 4 indicates a mild color defect; 5 to 11 indicates a moderate color defect; 12 to 14 indicates a severe color defect.

Maintenance. No information is provided in the manual. The Dvorine, like other plate tests, should be kept closed and dust-free when not in use.

Calibration. Lakowski (1966) presented spectrophotometric analysis for sample plates. No calibration is required by the user. Standard Illuminant C or an approximation must be used.

Reliability. We found no test-retest data in the course of our research.

Validity. A number of authors have presented data from which coefficients of agreement, $\hat{\kappa}$, may be calculated.

Author	Test of	$\hat{\kappa}$
Sloan and Habel (1956)	Screening	.95
Belcher et al. (1958)	Screening (3 errors)	.97
Frey (1962)	Screening	.95
Frey (1963)	Qualitative diagnosis	.88

In general, screening validity is very high ($\hat{k}$ = 0.95 to 1.00), and the test will detect at least 95 percent of color defective observers. Qualitative classification is good according to Frey (1963). The value of $\hat{k}$ is reduced primarily by those color-defective observers who are unclassified, the conditional $\hat{k}$ is 0.97. Peters (1956) and Dvorine (1963) suggested that quantitative classification be defined by the total error score. We have found no evaluation of this suggestion that would allow calculation of a statistic of agreement. Other authors have compared the Dvorine to other color vision tests (Peters, 1954; Pickford and Lakowski, 1960; Steen and Lewis, 1972).

Other Remarks. The Dvorine test is useful for rapid screening of red-green defects. The test provides differential diagnosis for protan and deutan defects and classifies three levels of severity. No tritan plates are provided. A number of plates may be misread due to legibility confusion. Included is a color-naming test of medium- and low-saturation colors. The test is widely used in the United States and is recognized by U.S. civil and military licensing authorities.

Farnsworth F2, Tritan Plate

Tritan Plate, Naval Submarine Medical Research Laboratory

1 plate

The test is not commercially available. However, the Medical Research Laboratory of the U.S. Navy at New London has satisfied requests for copies from individual researchers. Specifications of the plate have been given to interested manufacturers, who are now looking into the feasibility of a commercial reprinting. At the present time, address requests to: Naval Submarine Medical Research Laboratory, Box 900, Groton, CT 06349.

Taylor (1975) has given instructions for office construction of the plate.

General Description. The Farnsworth F_2 plate was designed to screen for tritan defect. The test consists of a single plate containing the outlines of two different-colored squares (blue and green), formed by colored circles, appearing on a background of purple-colored circles. An instruction sheet accompanies the test.

Administration. The observer must identify the location of the squares. Color names should not be the only or primary identification. The plate is held perpendicular to the line of sight under average daylight (Illuminant C). Test time is a few seconds.

Scoring. Normal trichromats report seeing two squares in their correct location; the green square is always clearer and better defined. An individual who sees only the blue square, or reports that

the blue square is clearer than the green square, is considered to have made a tritan error. Such an observer should be tested further for tritan defect. An observer who sees only the green square is not making a tritan error. Observers with congenital red-green defect make this error. The instruction sheet advises preliminary screening for red-green defect to identify such observers.

Maintenance. The single plate arrives in an envelope. The instruction manual suggests that it be placed at the back of an available book of red-green screening plates. If this is impossible, the plate may be protected in an envelope to maintain a dust-free, light-free environment.

Calibration. Lakowski (1966) has published spectrophotometric data. No calibration is required by the user. The test specifies "average daylight or equivalent" for the illuminant.

Reliability. We have not located test-retest data from which the coefficient of agreement, $\hat{\kappa}$, may be calculated.

Validity. We have not located data from which the coefficient of agreement, $\hat{\kappa}$, may be calculated for tritans. There are insufficient data in the literature to allow validation of the plate among diagnosed tritans.

Pinckers (1972) evaluated the F_2 plate as a screening plate for red-green color defects. The coefficient of agreement, $\hat{\kappa}$, is 0.90, indicating that the plate is successful in screening such observers. However, the F_2 plate should be used to screen for red-green defects only in young populations without eye disease, since Pinckers (1972) noted that observers with acquired color vision defects fail the F_2 plate by failing to see either the blue, or the green, or even both squares. Other authors who have compared the F_2 to other tests of color vision include Pickford and Lakowski (1960), Taylor (1970), and Ohtani and colleagues (1975).

Ishihara

Tests for Colour Blindness by S. Ishihara, Kanehara Shupper Co., Ltd, Toyko, Japan, 1962. There are three editions varying in the numbers of plates (38, 24, or 16 plates).

Available from:

1. Bernell Corp., South Bend, IN 46601
2. House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The Ishihara test for color blindness is designed to screen red-green defective color vision and to differentiate between protan and deutan defects. The test consists of single- and double-digit numerals (approximately two-thirds of the plates) and

paths to be traced with a camel's-hair brush (one-third of the plates). The latter are intended for use with illiterates. The numerals are in script, and some Americans may be confused by their appearance. An instruction manual is provided, but no sample scoring sheet accompanies the plates. There have been numerous editions, and there are slight variations in the color printing. In all editions, plate 1 is a demonstration plate: a double-digit numeral formed by small colored circles appears on a background of different-colored circles. Colors are chosen so that all observers with acuity better than 20/200 can read the demonstration plate. If an observer misses the demonstration plate, the test should be discontinued. The remaining plates are based on pseudoisochromatic principles. Screening plates include vanishing plates, transformation plates, and hidden plates. Diagnostic plates to differentiate protans from deutans show a colored numeral on a gray background.

The number of plates of each type varies with the edition. For the 38-plate edition, plates 1 to 21 are for screening red-green defects, and plates 22 to 25 are for differential diagnosis of protans and deutans. The remainder are for use with illiterates. The test may be abbreviated for mass screening by using plate 1 and one plate from each of 2 to 5, 6 to 9, 10 to 13, 14 to 17, and 18 to 21. In the 24-plate edition, plate 1 is a demonstration plate, plates 2 to 15 are for screening, plates 16 and 17 are for differential diagnosis as protan or deutan, and plates 18 to 24 are for illiterates. In the 16-plate edition, plates 2 to 9 are for screening, plate 10 is for differential diagnosis, and plates 11 to 16 are for illiterates.

Administration. The observer is instructed to read the numerals within three seconds. The plates are held at a distance of 75 cm perpendicular to the line of sight under daylight illumination. The pages are well designed for easy turning. The plates are numbered, and the sequence can be changed.

Scoring. No record sheet is provided, but scoring instructions accompany each test. The demonstration plate is included in the score. In the 38-plate edition, four errors or fewer is normal; eight errors or more is deficient. In the abbreviated mass-screening version, zero error is considered normal and any error calls for a retest with a full set of plates. In the 24-plate edition, two errors or fewer is normal; six errors or more is deficient. In the 16-plate edition, two errors or fewer is considered normal; four errors or more is deficient. It is not clear how errors in the two-digit numbers are to be scored. Most users count two errors on one plate as a single error.

Maintenance. The manual indicates that “exposure to unlight causes fading of the color of the plates.” If the set of plates is kept closed when not in use, and if the plates are not touched with the fingers, they will be valid indefinitely.

Calibration. Lakowski (1965b) has published spectrophotometric data for the tenth edition of the Ishihara plates as well as some sample data for the fifth edition (Lakowski, 1969). No calibration is required by the user. The test specifies "natural daylight" for the illuminant but does not give a further definition. Illuminant C or an approximation must be used.

Reliability. We have not located test-retest data from which the coefficient of agreement, $\hat{\kappa}$, may be calculated.

Validity. Several authors have reported data comparing the Ishihara to anomaloscope classification from which the coefficient of agreement, $\hat{\kappa}$, may be calculated.

Author	Test of	$\hat{\kappa}$
Hardy et al. (1945)	Screening	1.00
Sloan and Habel (1956)	Screening	.97
Belecher et al. (1958)	Screening	.95
Frey (1958)	Qualitative Classification	.10
Frey (1963)	Qualitative Classification	.70
Green (1962)	Qualitative Classification	.32
Hardy et al. (1954a)	Qualitative Classification	.52

The values of $\hat{\kappa}$ for screening efficiency are uniformly high; Ishihara is considered one of the best screening tests. The values of $\hat{\kappa}$ for qualitative classification are variable and are reduced primarily by those color-defective observers for whom no classification is made. Provided a classification is made, the conditional $\hat{\kappa}$ ranges from 0.61 to 1.00. Other authors who have compared the Ishihara test to other tests of color vision include Chapanis (1948; 1949), Pickford and Lakowski (1960), Crone (1961), Katavisto (1961), Hansen (1963), Verriest (1968a, 1968b), Taylor (1970), Verriest and Caluwaerts (1978).

Other Remarks. This test is useful for rapid screening of red-green defect. It provides differential diagnosis for protan and deutan defects, and classifies two levels of severity. No tritan plates are provided. A few plates may be misread due to legibility confusion. The Ishihara is probably the most widely used test and is recognized by many employers and licensing authorities. The manual warns of discrepancy in the results if "direct sunlight" or "electric light" is used.

Standard Pseudoisochromatic Plates

Standard Pseudoisochromatic Plates by Ichikawa, Hukami, Tanabe, and Kawakami, Igaku-Shoin, Tokyo, Japan 1978

19 plates

Available from Igaki Shoin Medical Publishers Inc., 50 Rockefeller Plaza, New York, NY 10020

General Description. The Standard Pseudoisochromatic Plate test for color blindness is designed to screen red-green defective color vision and to differentiate between protan and deutan defects. The test consists of single- and double-digit numerals. The numerals are digital numerals such as those used in calculators and digital clocks. Instructions are provided, and a sample scoring sheet accompanies the plates. There are also reference figures in gray to allow pretesting or instruction in reading digital numerals.

In all plates, the numerals are formed by colored dots appearing on a background of different-colored dots. Test plates are based on the vanishing principle. The first four plates are demonstration plates (including one nonsense figure); if plate 1 is failed, malingering or hysteria is suspected; the subject should be shown the reference figures. Plates 5 to 14 are screening plates; plates 15 to 19 are classification plates. Plates 5-19 contain two digits. For the screening series, one numeral is read by the normal observer, the other by the red-green defective observer, or both numerals are read only by the normal observer. For these plates many normal observers will see both numerals, but the "normal" numeral will be more distinct. For the classification series, one numeral should be read by protans, the other by deutans.

Administration. The observer is instructed to read the numerals within three seconds. If an observer passes the screening series, the test is discontinued. An observer who makes many errors (on normal and defective numerals) should be shown the reference figures and retested.

The plates are held at a distance of 75 cm at right angles to the line of vision under daylight illumination of at least 500 lux. The pages are awkward to turn; the plates are numbered (on the back); the sequence cannot be changed. Tinted lenses must not be worn.

Scoring. A sample record sheet and scoring instructions accompany each test. The demonstration plates are not included in the sample sheet. For the screening series, a score of 8 on the "normal" column (two errors or less) is considered normal; three or more misreadings of the "normal" column is considered failure.

On the classification series, the observer is classified as protan or deutan according to which column numerals are read. An observer who fails the screening series but reads protan and deutan classification plates is classified as "slight" red-green defect. If the observer fails both protan and deutan classification plates he is classified as "severe" red-green defect. Total color blindness, tritan, or acquired color defects are suspected if an observer fails demonstration plate 2 or 3.

Maintenance. The plates should be kept closed when not in use and should not be touched with the fingers.

Calibration. No data are available.

Reliability. No data are available.

Validity. Three of the creators of this test (Hukami et al. 1980) presented validation data for a series of 131 red-green defective observers. All color-defective observers made 3 or more errors in the normal screening series. Many defectives read both normal and defective numerals, and in some "borderline" cases as many as six or seven numerals were read. The screening test as defined by the authors (2 errors or less) therefore showed perfect screening efficiency.

Classification validity was impressive with a $\hat{k}$ of 0.91. No misclassification occurred. The $\hat{k}$ was reduced by the nine defective observers for whom no classification was obtained.

Other Remarks. This is a promising new test for which preliminary data suggest high screening validity and good classification. There is a need, however, for independent validation.

Tokyo Medical College

13 plates

Available from Murakami Color Research Laboratory, 10-7 Nishinaka-Dori, Tsukizima, Chuo-ku, Tokyo, Japan.

General Description. The Tokyo Medical College test for color blindness is designed to screen red-green and blue-yellow defective color vision and to differentiate between protan and deutan defects. The test consists of double-digit numerals in standard Arabic form. An instruction manual and scoring sheet are provided. The test is based on pseudoisochromatic principles. Numerals composed of a set of colored dots appear in a background of different-colored dots. A white paper grid with small circular cutouts overlies the colors and defines the size of the colored dots; numeral and background appear through this white grid. There are five screening plates for red-green defect and two for blue-yellow defect. These are followed by three plates that are designed to differentiate protan and deutan defects and three that estimate the severity of the protan and deutan defects.

Administration. The observer is instructed to read the numerals within three seconds. The plates are held at a distance of 75 cm perpendicular to the line of sight under daylight illumination. The pages are well designed for easy turning. The plates are numbered, and the sequence can be changed.

Scoring. Scoring instructions are provided.

Maintenance. The book should be kept closed. The overlying grid provides some protection against touching of the colored surfaces.

Calibration. Lakowski (1966, 1969) reported sample spectrophotometric data. No calibration is required by the user. Illuminant C or an approximation must be used.

Reliability. No test-retest data were located in the course of our research.

Validity. A number of authors have compared the Tokyo Medical College test with anomaloscope results.

Author	Test of	$\hat{k}$
Sloan (1961)	Screening	.99
Sloan (1961)	Qualitative diagnosis	.30
Green (1962)	Qualitative diagnosis	.57
Frey (1963)	Qualitative diagnosis	.48
Vos et al. (1972)	Qualitative diagnosis	.57
Sloan (1961)	Quantitative diagnosis	.27
Frey (1963)	Quantitative diagnosis	.19

In summary, the Tokyo Medical College test is a recognized screening test for congenital color vision defect. Qualitative classification is poor, primarily because 20 to 50 percent of the color-defective observers remain unclassified. For those observers who were classified, the conditional $\hat{k}$ ranged from 0.77 to 1.00. Umazume and Matsuo (1962) reported greater success with the qualitative diagnostic plates, but their data do not allow calculation of $\hat{k}$. Quantitative classification is poor, primarily because simple anomalous trichromats are distributed in all three severity categories; however, only simple anomalous trichromats are classified as mild (conditional $\hat{k} = 1.0$). Additional comparisons with other tests have been made by Dvorine (1963).

Other Remarks. This test is designed for rapid screening of red-green and blue-yellow defects (Umazume and Matsuo, 1962; Umazume et al., 1954; Umazume et al., 1955, 1956). It provides differential diagnosis of protan, deutan, and blue-yellow defects and classifies three levels of severity. Lakowski (1966) has shown that the blue-yellow plates are not optimally designed to screen for tritan defect.

Other Plate Tests

Bausch and Lomb Ortho-Rater Color Vision Test Slides 71-21-21 and 71-21-50

Available from House of Vision, 137 N. Wabash, Chicago, IL 60602.

These two slides require the Bausch and Lomb Ortho-Rater for administration. The Bausch and Lomb Ortho-Rater is available from House of Vision.

General Description. These two color vision test slides are part of a series of slides that are incorporated into an instrument for rapid and simple testing of visual acuity, phoria, and depth perception. The slides are inserted on one of two cylindrical drums (one for distance vision and one for near vision). As these drums are rotated, different slides appear for judgment by the observer. The test slides are illuminated by an incandescent lamp within each drum. Slide 71-21-21 consists of nine colored circles: three identical reds, three identical greens, and three identical yellows. Slide 71-21-50 consists of reproduction of four pseudoisochromatic plates. Test conditions for these two slides involve binocular distance vision.

Administration. Slide 71-21-21: The observer is asked to identify the color of each of the circles. The slide takes 15 seconds to administer.

Slide 71-21-50: The observer is asked to read the numbers on the plates. The slide takes eight seconds to administer.

Scoring. Slide 71-21-21: Identification of one red circle and one green circle is considered a passing score.

Slide 71-21-50: The score is the number of digits (not the number of plates) read correctly. A score of 5 or 6 indicates normal color vision; a score of 3 or 4 indicates doubtful color vision (color-defective, or color-normal with poor distance acuity); and a score of 0, 1, or 2 indicates defective color vision.

Maintenance. No special maintenance is required.

Calibration. No data are available.

Reliability. No test-retest data are available.

Validity. Validity of both of these slides was evaluated (Paulson, 1973). Slide 71-21-21 was administered to 34 normal observers, 161 protans, and 215 deutans. All normal observers passed this test; however, 88 percent of the protans and deutans also passed, giving a $\hat{k}$ of 0.02. Slide 71-21-50 was administered to 25 normal observers, 145 protans, and 166 deutans. Of the protans and deutans, 99.4 percent failed; however, 56 percent of the normals also failed, giving a $\hat{k}$ of 0.57. All subjects had normal visual acuity for distance.

Other Remarks. Slide 71-21-21 has several other weaknesses. First, all of the color-defective observers who failed the test by the official scoring method did so by failing to identify correctly any of the red circles. Of these incorrect responses to red, 90 percent were "orange" responses. Thus the test may be criticized on the grounds that the observer may have failed the test because of slight error in color naming rather than defective color perception; even a few normal observers will call one of the reds, "orange." Second, although Army Regulation 601-270 states that the observers are not to be advised in advance as to the colors used in the test, the fact that the three colors in the test are red, green, and yellow inevitably becomes general knowledge. This knowledge enables those few color-defective observers who might otherwise fail the test, to pass it because they could call "red" those three colors that look orange to them or that look different from the three greens and three yellows. Third, the slide is easily memorized because the colors cannot be exposed and judged individually; the colors are numbered and are permanently arranged.

Slide 71-21-50 has another weakness. It also is easily memorized because the four pseudoisochromatic plates are permanently arranged and cannot be randomly displayed.

Slide 71-21-21 is used for qualification of commissioned officers and for entrance to the U.S. Military Academy; in addition, it is in use at the Armed Forces Entrance and Examining Stations. Slide 71-21-50 has been authorized for use by the Federal Aviation Administration for qualification of pilots.

City University Color Vision Test

11 plates using Munsell colors

Available from:

1. Keeler Instruments, 21-27 Marylebone Lane, London WlMGDS, England
2. House of Vision, 137 N. Wabash, Chicago IL 60602

General Description. The City University Color Vision Test is designed to screen moderate to severe red-green and blue-yellow defects of color vision and to differentiate protan, deutan, and tritan color vision defects. The test consists of 11 plates. Each plate contains five colored circles--a central test color surrounded by four comparison colors. Instructions and a sample scoring sheet are provided. The first plate, plate A, is a demonstration plate. The remaining 10 plates are test plates. On each test plate, three of the four comparison colors are chosen so that the center color and a comparison color are typical confusion colors for protanopes, deuteranopes, and tritanopes.

Administration. The observer must indicate which of the four comparison colors (top, bottom, left, or right) is most similar to the central test color. The observer may choose two comparison colors. A soft-tipped brush may be used as a pointer, and a response should be given within three seconds. The plates should be placed 35 cm from the observer's eye perpendicular to the line of sight. Daylight illumination providing 600 lux should be used. The plates are not numbered and are difficult to turn.

Scoring. The demonstration plate is not scored. For the 10 test plates, the observer's choice is circled under one of four columns: normal, protan, deutan, and tritan. The number of circled responses is totaled for each column and is expressed as a fraction of 10.

Maintenance. The plates must be protected from fingertips, dust, and light. The book should be kept closed and dust-free when not in use.

Calibration. The colors are Munsell colors for which CIE specification is available. Hill and coworkers (1978) have plotted the coordinates in the CIE Uniform Color Space. No calibration is required by the user.

Reliability. No test-retest data were located in the course of our study.

Validity. Hill and coworkers (1978) reported data for 20 observers. Qualitative classification was at chance level. Verriest and Caluwaerts (1978) noted that dichromats fail the test with correct classification (96 percent accuracy). Among anomalous trichromats, however, 31 percent of protanomalous and 51 percent of deuteranomalous trichromts fail the test; classification of those who fail is correct for only 40 percent of the protanomalous and 72 percent of the deuteranomalous trichromats. Insufficient data were given to calculate $\hat{\kappa}$. Ohta, Kogure, Izutsu, Mijamoto, and Nagai (1978) reported data for classification of severity. With the expectation that anomalous trichromats will pass and dichromats fail, the coefficient of association, $\hat{\kappa}$, is 0.64.

Other Remarks. This test was designed by Fletcher using Munsell colors chosen from the Farnsworth Panel D-15 test (Fletcher, 1972, 1978). The test is not suitable for screening in the general population. It may be used for observers with severe defects for whom a test format other than the Panel D-15 is required.

Sloan Achromatopsia Test

7 plates

Available from Munsell Color Co., Baltimore, MD 21218

General Description. The Sloan Achromatopsia Test is designed to test for complete achromatopsia, a rare type of color vision defect (Pokorny et al., 1979). The test consists of seven plates. Each plate contains a series of gray rectangles whose reflection increases gradually in 17 steps across the card from almost white to almost black. The rectangles are numbered from 1 to 9 in steps of 0.5. In the center of each rectangle appears a colored circle of fixed hue and reflectance. The seven cards differ from each other in the color of the circle; the colors used are red, yellow-red, yellow, green, purple-blue, red-purple, and gray. Complete achromats can find an exact match of the colored circle and one of the rectangles on each card. Observers who are not complete achromats can make only a brightness match of the colored circle to a rectangle, except for the gray card, for which an exact match exists for all observers.

Administration. The observer must indicate which gray rectangle matches the colored circle. The test starts with the gray card, for which there is an exact match of the circle and one of the rectangles. The other cards are then presented. The cards are presented at 50 cm perpendicular to the line of sight under daylight illumination. There are no record sheets. Test time is two to three minutes per eye.

Scoring. The examiner notes the number of the rectangle that is chosen. The instructions include the numerals of rectangles chosen by complete achromats and those chosen by normal observers in ordinary and low (rod vision) illumination. The results are compared with these sequences.

Maintenance. The cards come loose in an envelope and must be protected from dust and light. Observers must not touch the pigments.

Calibration. The test uses Munsell papers, for which a CIE specification is available. No calibration is required by the user. Illuminant C or an approximation must be used.

Reliability. No test-retest data are available in the literature.

Validity. The manual prepared by Sloan gives average matches of achromats with theoretically expected matches. No other data are available.

Titmus Color Perception Test and Titmus Pediatric Color Perception Test

Two slides designed for use with the Titmus Vision Screener.

Available from House of Vision, 137 N. Wabash, Chicago, IL 60602.

General Description. The Titmus Color Perception Test consists of a slide containing reproductions of Ishihara pseudoisochromatic plates. The slide is used in the Titmus Vision Screener and is viewed

binocularly through a stereoscope that presents an image of the slide at 20 feet. The Titmus Pediatric Color Perception Test also is a slide designed for use in the Titmus Vision Screener. The pediatric slide contains eight blocks of colored dots in each of which an E is embedded. The arms of the E point in one of four directions.

Administration. In the adult slide, the observer identifies the numerals of the six reproductions. In the pediatric slide, the child indicates the direction in which the arms of the E are pointing.

Scoring. For the adult slide, any error is considered failure. For the pediatric slide, errors in any three (or more) blocks is considered failure.

Maintenance. No special maintenance is required.

Calibration. No data are available.

Reliability. No data are available.

Validity. The Titmus Color Perception Test does not miss color-defective observers, but it wrongly classifies normal trichromats as defective (Lewis and Steen, 1971; Holland, 1972; Steen et al., 1974). The Titmus Pediatric Color Perception Test has not been validated in a pediatric population. In an adult group (Alexander, 1975), it was noted that failure of either blocks 2 or 3, could occur in normal trichromats. Observers classified as color defective by the Ishihara failed both blocks 2 and 3 while those classified as color defective by both Ishihara and the Farnsworth Panel D-15 failed three blocks (2, 3, plus one other) on the Titmus Pediatric Color Perception Test. Alexander concluded that the pediatric slide could be used as a screening device with adults if the scoring was revised as follows: normal--pass all or fail one block (either 2 or 3); deficient--fails blocks 2 and 3.

Other Remarks. The adult slide is recommended for use with Illuminant C; the Titmus Color Vision Screener, however, provides Standard Illuminant A. Holland (1972) has suggested that reduced visual acuity is intrusive to color vision evaluation. Lampe (1969) has stated that the adult slide is not suitable for use with children. The validity data suggest that the Titmus Color Perception Test is not a suitable screening device.

Arrangement Tests

Farnsworth Dichotomous Test for Color Blindness (Panel D-15)

The Farnsworth Dichotomous Test for Color Blindness, Panel D-15. Manual by Dean Farnsworth, The Psychological Corporation, New York, 1947.

16 Munsell color test caps

Available from:

1. The Guidance Centre, Toronto, Canada.
2. The Psychological Corp., New York, NY 10017.
3. House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The Farnsworth Dichotomous Test for Color Blindness (Panel D-15) is designed to select those observers with severe discrimination loss. In addition to indicating red-green discrimination loss, the test also indicates blue-yellow dicrimination loss and detects monochromacy. The test consists of 15 colored caps placed in a box, with one reference cap at a fixed location. The samples are chosen to represent approximately equal hue steps in the natural color circle and are similar in chroma to those of the FM 100-hue test. They are set in plastic caps and subtend 1.5° at 50 cm. The movable caps are numbered on the back according to the correct color circle. An instruction manual and scoring sheets are provided. Additional scoring sheets are available.

Administration. The examiner prearranges the caps in random order on the upper lid of the open box. The subject is instructed to "arrange the caps in order according to color" in the lower tray, starting with the cap closest in color to the fixed reference cap. The box is presented at a comfortable distance under daylight illumination of at least 270 lux. The majority of individuals with normal color vision can complete the test within one minute. The observer is allowed as long as is necessary to complete the task. People with poor coordination may have difficulty in handling the caps.

Scoring. The order of the caps is plotted directly on the score sheet on a diagram that shows correct cap positions extending in a circle from the reference cap. Errors occur when caps are misplaced from the correct order. The scorer draws lines connecting the caps in their actual order. In correct order, the lines retrace the hue circle. An example of a minor error might be reversing the order of caps 5 and 6. This error leads to a reversal in the plot at caps 6 and 5 since cap 4 is connected to cap 6, cap 6 is connected to cap 5, and cap 5 is connected to cap 7. A major error occurs when distant caps (e.g., 3 and 12) are placed next to each other. The line connecting these caps now crosses the hue circle. Subjects with normal color vision will make at most only one or two minor errors. Occasionally a single line crossing the circle may occur when the observer reverses part of the series. Dichromats and extreme anomalous trichromats make multiple (6 to 12) crossovers, forming a nearly parallel series of lines. The axis of the crossover lines is characteristic of the type of defect; the axes corresponding to protan, deutan, and tritan defects are indicated on the scoring sheet. Occasionally an observer will make a few minor errors and a few major errors. In this case, a retest is required. According to the original design, the test is failed if an

observer makes two or more major crossovers at the beginning of the test that are parallel to an axis line on the scoring sheet. The criterion for pass-fail was designed for use in the Naval Submarine Medical Research Laboratory (NSMRL) test battery (see "Test Batteries," in Chapter 4).

Maintenance. The colors must be protected from dust and fingertips. Observers and examiners must handle the caps by their plastic rims or wear gloves. Observers must not touch the pigments. The caps should be replaced in the box in a mixed order, and the box should be kept closed.

Calibration. The caps are constructed from Munsell colors; Munsell notation and CIE specification are tabulated by Paulson (1973). Bowman (1973) and Adams and colleagues (1975) have analyzed intercap distances in color difference. Birch et al. (1979) claim that the distance between caps 7 and 8 is unduly large and that placing cap 15 next to cap 7 should not be considered an error (as illustrated in the instruction manual). No calibration is required by the user. Illuminant C or a close approximation must be used.

Reliability. Test and retest data given in the test manual show coefficient of agreement, $\hat{\kappa}$, of 0.96. Higgins and Knoblauch (1977) obtained perfect reliability ($\hat{\kappa}$ = 1.0) in their evaluation of screening. Reliability of qualitative classification was 0.85 (Higgins and Knoblauch, 1977).

Validity. Classification data from which $\hat{\kappa}$ may be calculated have been given by several authors.

Author	Test of	$\hat{\kappa}$
Green (1962)	Qualitative Classification	.73
Majima (1969)	Qualitative Classification	.94
Helve (1972)	Qualitative Classification	.83
Majima (1969)	Quantitative Classification	.83
Helve (1972)	Quantitative Classification	.51
Higgins and Knoblauch (1977)	Quantitative Classification	1.00
Verriest and Caluwaerts (1978)	Quantitative Classification	.53

Qualitative classification is reasonably good. The major factor reducing $\hat{\kappa}$ is the number of observers for whom no classification is obtained (conditional $\hat{\kappa}$ ranges from 0.96 to 1.00). Similar data are shown by Hardy and colleagues (1954a,b,c), Linksz (1966), Verriest (1968b), and Verriest and Caluwaerts (1978). Quantitative classification shows that, in general, simple anomalous trichromats pass while extreme anomalous trichromats and dichromats fail. For this classification, the $\hat{\kappa}$ is primarily reduced by those simple anomalous trichromats

who fail. The conditional k for a passing score ranges from 0.83 to 1.00, indicating that a passing score is associated with simple anomalous trichromacy.

Other authors who have compared the Farnsworth Panel D-15 with other color vision tests include Crone (1961), Sloan (1961), Verriest (1968a,b), Richards and colleagues (1971), Pinckers (1972), and Steen and Lewis (1972).

Other Remarks. Sloan (1954) published scoptopic lightness of the caps from which an expected arrangement by achromats can be deduced. The axis lies between the deutan and tritan axes. Pinckers (1971) suggested that Munsell caps could be chosen from the Farnsworth-Munsell 100-hue test to construct a "homemade" Panel D-15. The results may be combined on the FM 100-hue test scoring sheet. Higgins and Knoblauch (1977) compared these two versions of the D-15 test and found that they give closely similar information.

Farnsworth H-16 Test

17 Munsell color test caps

The Farnsworth H-16 Test is not commercially available, but the Naval Submarine Medical Research Laboratory of the Naval Submarine Base (Groton, CT 06349) has satisfied a few requests from individual researchers.

General Description. The Farnsworth H-16 Test is designed to select congenital dichromats and to differentiate protanopes from deuteranopes. The test consists of 17 colored caps--a reference cap and 16 test caps. The samples are chosen to represent approximately equal hue steps in the natural color circle. The colors are of higher chroma (i.e., are more saturated) than those of the FM 100-hue test or the Farnsworth Panel D-15 test. These colors are set in plastic caps and subtend 1.75° at 50 cm. The movable caps are numbered on the back according to the correct color circle.

Administration. Administration of the test is identical to that of the Farnsworth Panel D-15. The majority of individuals can complete the test in one minute; observers should not be allowed more than two minutes. People with poor coordination may have difficulty in handling the caps and might require a little more time.

Scoring. The order of the cap arrangement is plotted directly on a score sheet that shows correct cap positions extending in an elongated circle. The procedure is the same as that for the Farnsworth Panel D-15. Dichromats who fail the test make multiple (6 to 12) crossovers and connect specific caps at the beginning of the series with specific caps at the end of the series; the axis of these parallel crossover lines determines whether the observer is a protanope or deuteranope. Color-defective observers who pass the test (anomalous trichromats)

usually make only a few minor errors or a combination of minor and major errors in the midsection of the test.

Maintenance. Requirements are the same as those for the Farnsworth Panel D-15.

Calibration. The caps are constructed from Munsell colored papers; CIE specifications are available and have been published by Paulson (1973). No calibration is required by the user. Illuminant C must be used.

Reliability. Test-retest reliability data from the Naval Submarine Medical Research Laboratory indicate a coefficient of greater than 0.90.

Validity. Validity data in the NSMRL files indicate a high correlation between failure on the Farnsworth H-16 Test and dichromacy as determined by an anomaloscope.

Farnsworth-Munsell 100-Hue Test

Farnsworth-Munsell 100-Hue Test for the Examination of Color Discrimination. Manual by Dean Farnsworth, Munsell Color Company, Inc., Baltimore, Maryland, 1949 (revised 1957).

85 Munsell colors

Available from:

1. Munsell Color Corp., Baltimore, MD 21218
2. The Psychological Corp., New York, NY 10017
3. House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The Farnsworth-Munsell (FM) 100-hue test was designed to test hue discrimination among people with normal color vision and to measure the areas of color confusion in color-defective observers.

The test consists of 85 movable color samples arranged in four boxes of 21 or 22 colors each. The samples were chosen to represent perceptually equal steps of hue and to form a natural hue circle. The colors are set in plastic caps and subtend 1.5° at 50 cm. They are numbered on the back according to the correct color order of the hue circle. Two pilot colors are fixed at either end of each box. An instruction manual and scoring sheets are provided. Additional scoring sheets are available.

Administration. One box is presented at a time. The examiner prearranges the caps in random order on the upper lid. The observer is instructed to “arrange the caps in order according to color” in the lower tray where the two fixed caps appear. The box is presented at a comfortable distance under Illuminant C providing at least 270 lux.

The observer is allowed as long as is necessary to complete the task. The majority of individuals with normal color vision can complete a box in two minutes. People with poor coordination may have difficulty in handling the caps.

Scoring. Errors are made whenever caps are misplaced from the correct order. Error scores are calculated according to the distance between any two caps. If cap 10, for example, is placed between 9 and 11, there are zero errors for cap 10; if cap 10 occurs between 9 and 13, however, it would have an error score of 2. The manual gives detailed instructions for plotting the observer's arrangement of the caps and for scoring this plot to arrive at the total error score. In an alternative scoring technique (Kinnear, 1970), cap scores are plotted sequentially. Each box contributes to one-quarter of the circle. Error scores for all four boxes are summed to give a total error score for the test.

Maintenance. The colors must be protected from dust and fingertips. Observers and examiners must handle the caps on their plastic rims. Observers must not touch the pigments. The caps should be replaced in the box in a mixed order, and the boxes should remain closed when not in use. It is possible to order a single cap if one is lost or destroyed.

Calibration. The caps are formed from Munsell colors for which CIE specification is available. No calibration is required by the user. Illuminant C must be used.

Reliability. An observer with normal color vision might improve his or her error score on first retest. With subsequent repetition, however, there is minimal change in total error score. It is intended in future productions of this test to have a short practice panel to minimize practice effects. Chisholm (1969) presented test-retest statistics for observers with acquired color vision defects. Aspinall (1974b) has presented statistics for inter-eye comparisons and has also presented a theoretical upper limit of error scores for nonrandom arrangement of caps (1974a).

Validity. Observers with normal color vision may make some errors in all four boxes (Figure 3-5). The distribution of error scores is asymmetric and for young observers has a range of 0 to 150 (Figure 3-6). Average scores tend to increase with age, especially after the age of 40 (Ohta, 1961; Lakowski, 1962; Verriest, 1963; Krill and Schneiderman, 1964). Verriest's data are shown in Table 3-2. Error scores also depend on the level of illumination (see "Illuminants," in this chapter). If the test is to be used clinically, age norms should be established for the level of illumination that is used.

In color defects, the primary axis of discrimination loss depends on the defect (Figure 3-7 Figure 3-8 through Figure 3-9). Farnsworth (1943, 1957), Verriest (1963), and Perdriel (1962) reported caps for the center of the confusion zones, which thus characterize the major axis of

congenital color defects (Table 3-3). Additionally, Verriest (1963) noted that errors on the scotopic axis accumulate at caps 50 to 57. The bipolar axis may not be evident when error scores are low.

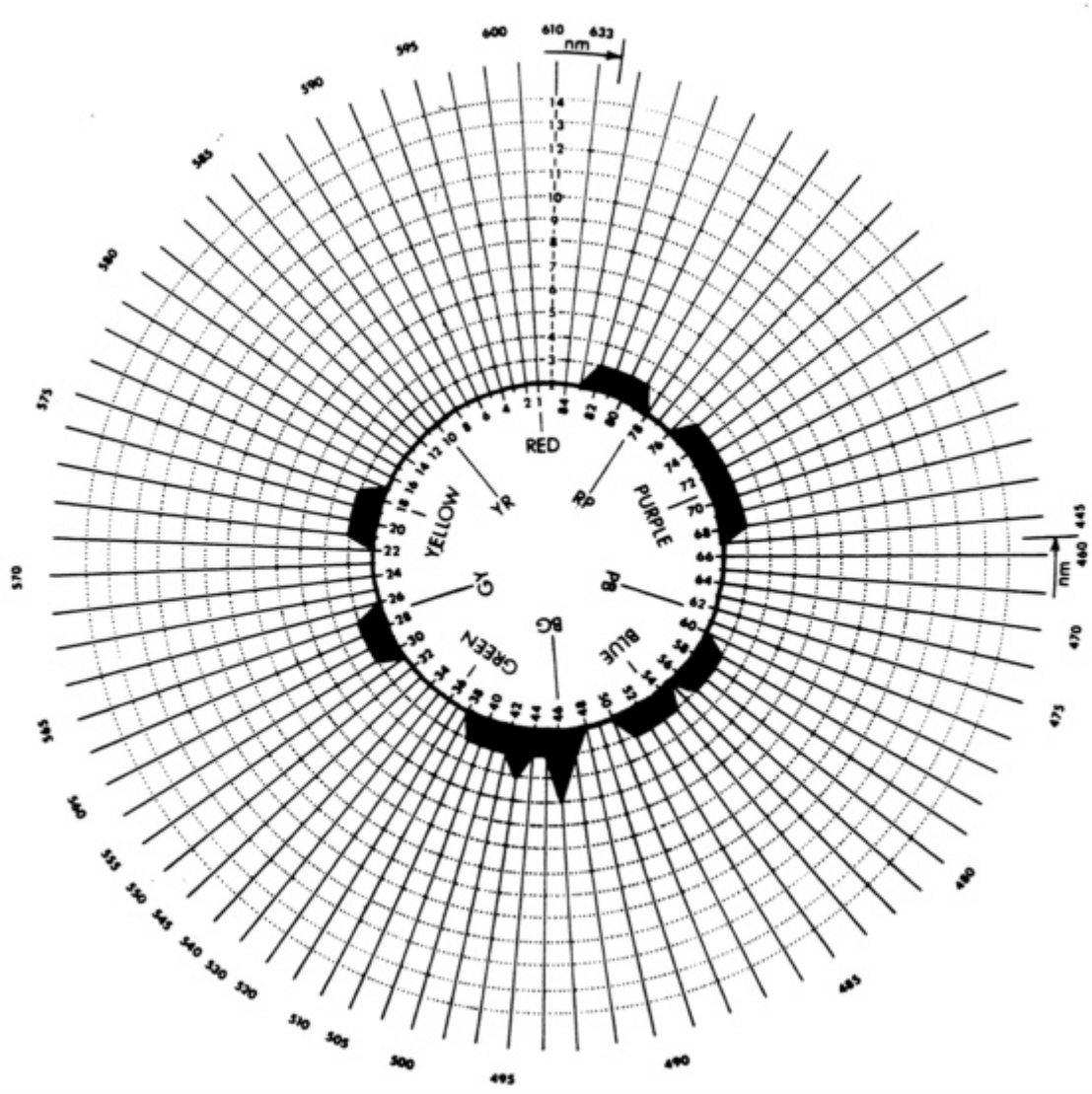

FIGURE 3-5 Example of errors on the FM 100-hue test made by a normal trichromat. The total errors were 40. Based on unpublished data from V.C. Smith and J. Pokorny.

The average error scores of color-defective observers indicate the severity of the defect (Taylor, 1966; Lakowski, 1971). Lakowski's data are shown in Figure 3-10. Error scores for color-defective observers increase with age (Lakowski, 1974).

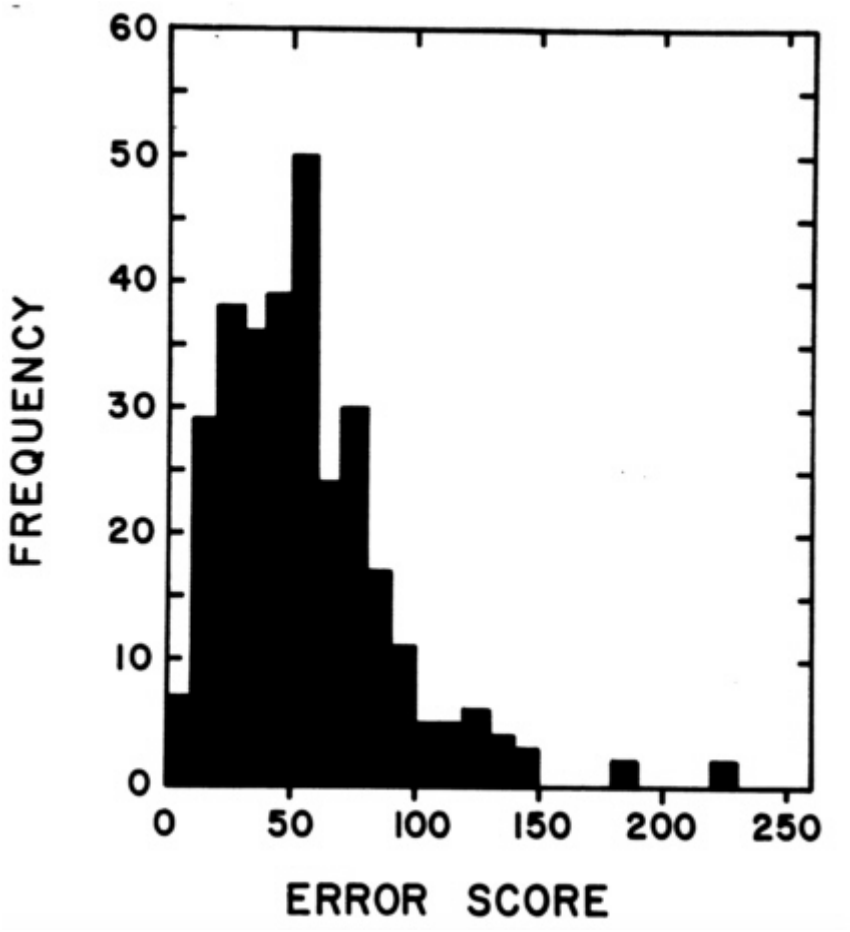

FIGURE 3-6 Distribution of FM 100-hue test error scores made by a group of 311 normal observers (printers' apprentices, aged 13 to 18).
Based on data from Lakowski (1976).

Other Remarks. The FM 100-hue test is one of chromatic discrimination. Lakowski (1971) has shown that the total error score is correlated with the matching range on the anomaloscope and with the wavelength discrimination function--a test of the wavelength difference needed for an observer to detect a color difference. The FM 100-hue test is not designed for the screening of color defect. Farnsworth suggests that error scores for normal observers should be classified only in three categories (superior, average, and inferior), and that error scores should not be regarded as representing a continuous scale of performance. However, error scores may be compared to population statistics; Kinnear (1970) and Aspinall (1974b) suggest that the square

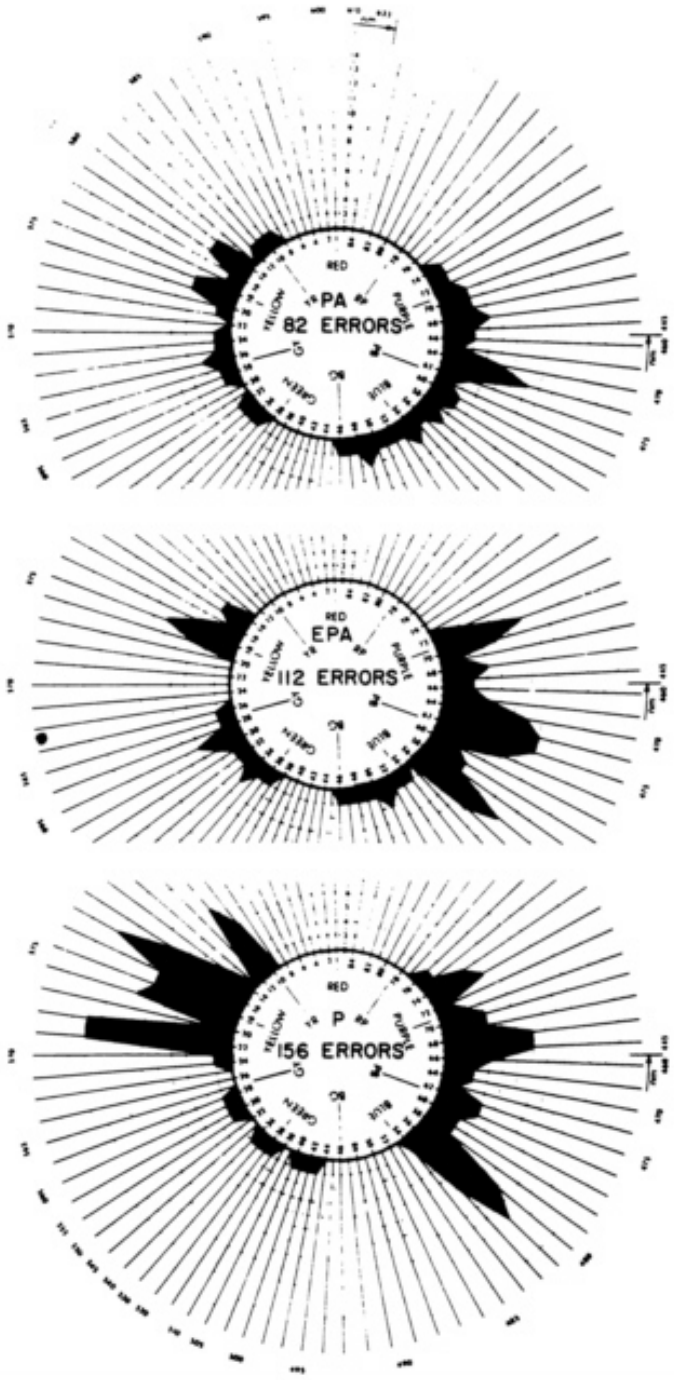

FIGURE 3-7 Example of FM 100-hue test profile for representative protanomalous trichromat, extreme protanomalous trichromat, and protanope (students of mean age 20).
Based on data from Lakowski (1971).

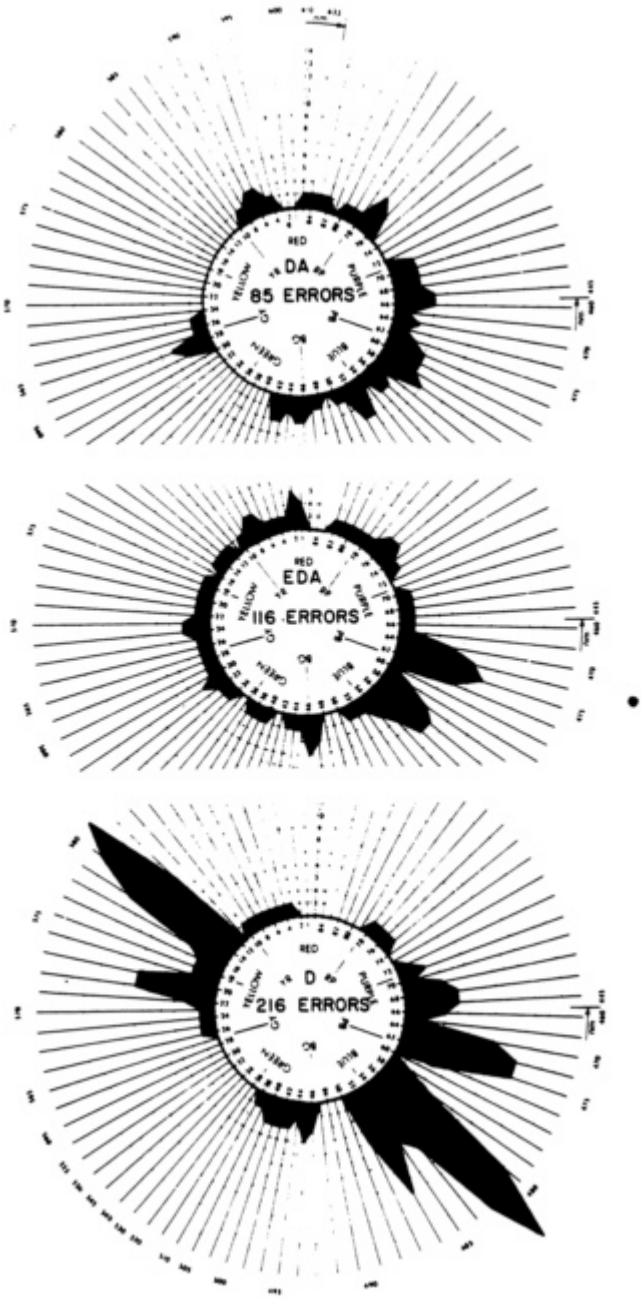

FIGURE 3-8 Examples of FM 100-hue test profile for representative deuteranomalous trichromat, extreme deuteranomalous trichromat, and deuteranope (students of mean age 20).
Based on data from Lakowski (1971).

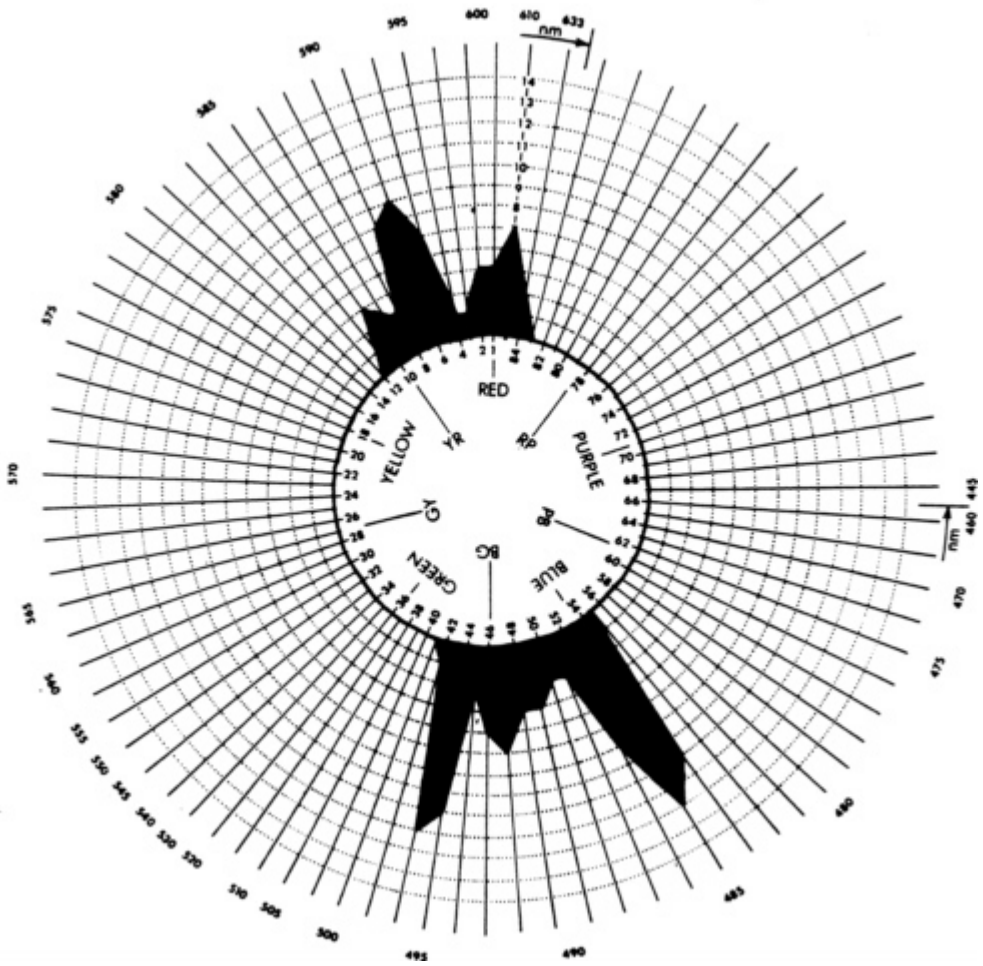

FIGURE 3-9 Example of FM 100-hue test profile for a tritanope.
Source: Farnsworth (1957) by permission of Farnsworth-Munsell 100 HUE TEST, available from Munsell Color, 2241 N. Calvert St., Baltimore, Md 21218, USA.

root of the error score is an appropriate transformation for quantitative analyses. Aspinall (1974b) gives the following formula: a change in score is significant at the 0.05 level if the difference of the square roots exceeds 2.27 and at the .01 level if the difference exceeds 2.99. It is appropriate to use error scores quantitatively in comparing two eyes of an individual with an acquired color defect (Aspinall, 1974b); in following temporal changes of an acquired color defect (Chisholm et al., 1975); and in comparing the errors in different quadrants (Helve, 1972; Smith et al., 1976).

TABLE 3-3 Axes of Discrimination Loss

Author	Protan	Deutan	Tritan
Farnsworth (1943)	19 and 65	15 and 59	84 and 46-47
Farnsworth (1957)	62-70	56-61	46-52
Perdriel (1962)	22 and 66	14 and 58	84-85 and 52-64
Verriest (1963)	63-67	57-61	46-48

Recently, automated techniques for scoring the FM 100-hue test and plotting the errors have been developed (Taylor and Donaldson, 1976; Donaldson et al., 1978; and Taylor, 1978).

Lanthony Desaturated Panel D-15 Test

Lanthony's Desaturated Panel D-15, Hue Test according to Farnsworth-Munsell, Luneau Ophtalmologie, Paris, 19

16 Munsell colors

Available from House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The Lanthony Desaturated Panel D-15 Test is designed to select observers with mild chromatic discrimination loss. The test is used in conjunction with the standard panel (Farnsworth Panel D-15 Test) and was designed specifically for acquired color vision defects. The test consists of 15 colored caps placed in a box with one reference cap at a fixed location. The samples are chosen to represent approximately equal hue steps in the natural color circle. The colors are much paler and lighter than those of the Farnsworth Panel D-15 Test and appear almost white. They are set in plastic caps and subtend 1.5° at 50 cm. The movable caps are numbered on the back according to the correct color circle. An instruction manual and scoring sheets are provided. Additional scoring sheets are available.

Administration. The Desaturated Panel D-15 is performed after testing on the Farnsworth Panel D-15. The results of the two tests are plotted side by side on the specially designed score sheet. Administration of the test is identical to that of the Farnsworth Panel D-15, discussed above. The majority of individuals with normal color vision can complete the test in one minute. The observer is allowed as long as is necessary to complete the task.

Scoring. The order of the caps is plotted directly on the scoring sheet on a diagram that shows correct cap positions extending in a

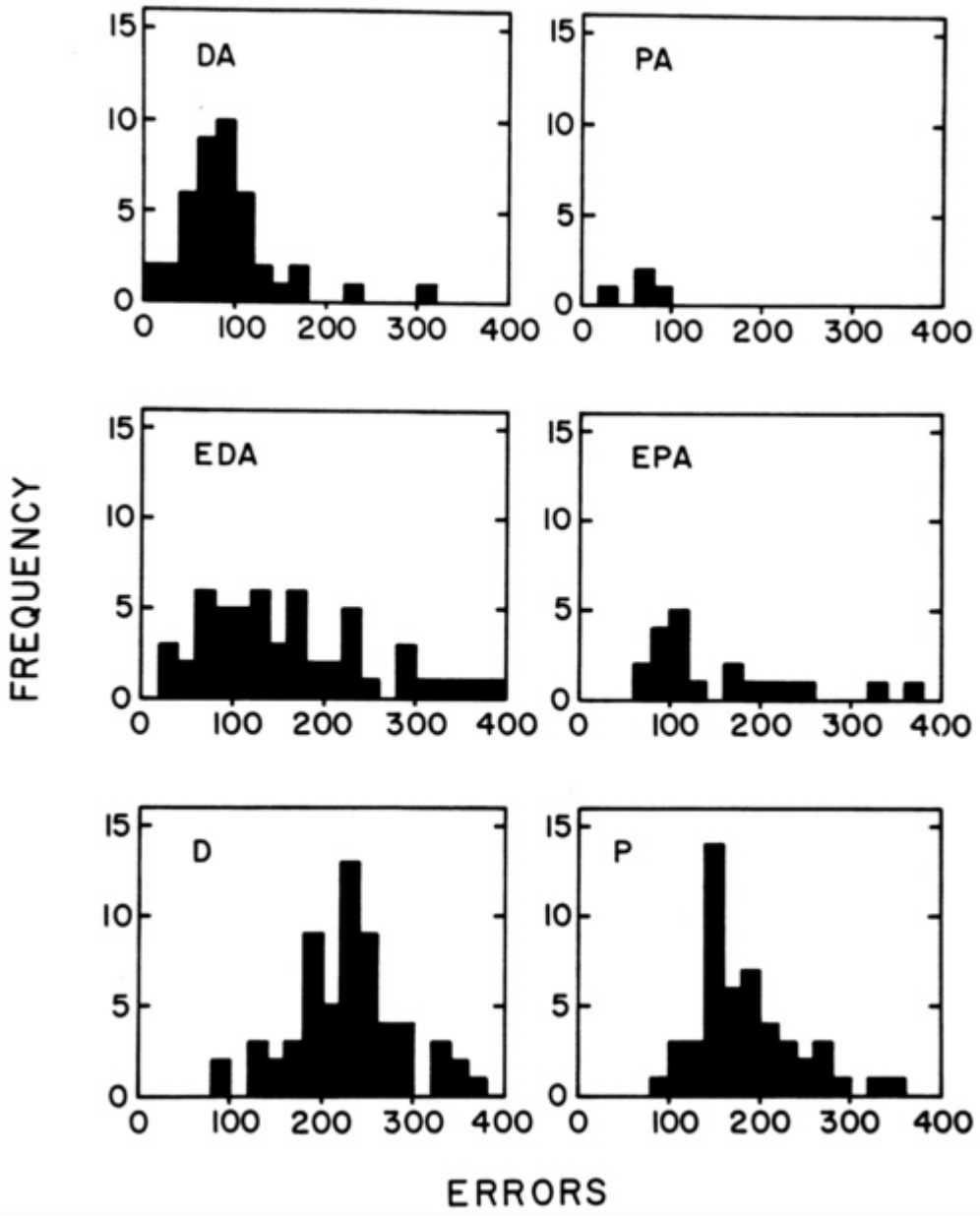

FIGURE 3-10 Distribution of FM 100-hue test scores for anomalous trichromats and dichromats (students of mean age 20).
Based on data from Lakowski (1971).

circle from the reference cap. The procedure is the same as that for the Farnsworth Panel D-15. Subjects with normal color vision usually make only one or two minor errors. Occasionally a single line crossing the circle may occur when the observer reverses part of the series. Simple anomalous trichromats make some minor and major errors. Dichromats and extreme anomalous trichromats make multiple (6 to 10) crossovers forming a nearly parallel series of lines. The axes of these crossover lines are the same as those found on the Farnsworth Panel D-15.

Maintenance. Requirements are the same as those for the Farnsworth Panel D-15.

Calibration. The caps use Munsell colors specified by Lanthony (1974b). CIE specification of the caps is available. No calibration is required by the user. Illuminant C or a close approximation must be used.

Reliability. We have not located test-retest data in our research.

Validity. Verriest and Caluwaerts (1978) noted that 82 percent of observers with congenital red-green color defects failed the Lanthony Desaturated Panel, including 98 percent of the dichromats and 70 percent of the anomalous trichromats. Qualitative classification was excellent for dichromats, but only 78 percent of the anomalous trichromats were correctly classified. Insufficient data were given to calculate  . Pinckers and colleagues (1976) and Lägerlof (1978) have discussed the use of the Lanthony Desaturated Panel in acquired color vision defects.

Other Remarks. This is a new test designed specifically to detect mild discrimination loss in congenital and acquired color defect (Perdriel et al., 1975). It is not a screening test and should not be used for this purpose. The test may be used to classify the severity of discrimination loss in congenital red-green color defects and the progression of defect (recovery or deterioration) in acquired color vision defects.

The Lanthony New Color Test

New Color Test de Lanthony Selon Munsell, Luneau Ophtalmologie, Paris, 19

70 Munsell colors

Available from House of vision, 137 N. Wabash, Chicago, IL 60602

General Description. The New Color Test was designed specifically for use in acquired color vision defects. The test allows determination of neutral zones (colors that are confused with gray) and tests chromatic discriminative ability at each of four saturation levels.

The New Color Test includes four boxes, each with 15 colored caps. The 15 hues are the same in the four boxes and are designated by their initials (in French). The hues represent approximately equal steps in the color circle. All the caps have equal lightness. The boxes differ in saturation: the first box (high saturation) has Munsell chroma 8 (Box 8/6); the second (medium saturation) has Munsell chroma 6 (Box 6/6); the third (medium saturation) has Munsell chroma 4 (Box 4/6); and the fourth (low saturation) has Munsell chroma 2 (Box 2/6). In addition to these 60 colored caps, the test includes 10 gray caps of varying lightness, with values increasing from 4 to 8 in steps of 0.5; there are two caps at value 6. They are designated by Munsell nomenclature, N4 to N8. The caps subtend 1.5° at 50 cm. An instruction manual and scoring sheets are provided. Additional scoring sheets are available. The test is presented at a comfortable distance using Standard Illuminant C providing 250 lux.

Administration. The test is performed in two phases: a separation phase followed by a classification phase. In the separation phase, the 15 colored caps of the box at chroma 8 (Box 8/6) and the 10 gray caps are mixed together and are presented to the observer, who must separate the caps into two groups: a group of caps that appear gray and a group of caps that appear colored. In the classification phase, the observer first arranges the caps in the group that appears gray in a row ranging from dark to bright. This part of the test allows determination of position in the gray scale of the colored caps that appear gray to the observer. Second, the observer arranges the caps that appear colored according to their natural color order. This procedure differs from that used in the Farnsworth Panel D-15 in that the observer chooses the starting cap; there is no fixed starting cap. Furthermore, since the classification phase follows the separation phase, there may not always be 15 colored caps remaining, although there may be some gray caps in that group. This procedure is repeated for Boxes 6/6, 4/6, and 2/6.

Scoring. There are two scoring sheets, one for each phase of the test. Separation phase: The errors are plotted on a circular diagram on which hue is represented on the circumference and chroma is represented as a radial distance from the center. The diagram includes four concentric rings (4 chroma), and each ring contains 15 compartments (15 hues). The results of the test are expressed by penciling in the hue compartments that correspond to the colored caps wrongly placed among the grays. Classification phase: The positions in the gray scale of those colored caps grouped among the grays are indicated on a diagram with hue on the abscissa and the value on the ordinate. For each colored cap that is wrongly placed among the grays, a circle is drawn at its position on the gray scale. Finally the order of the colored caps is recorded on a diagram analogous to that of the Panel D-15 but with four concentric rings. At each chroma level, a line is drawn connecting caps placed adjacent to one another.

Maintenance. Requirements are the same as those for the Farnsworth Panel D-15.

Calibration. The caps use Munsell colors specified by Lanthony (1975b). CIE specification is also available. No calibration is required by the user. Illuminant C or a close approximation must be used.

Reliability. No test-retest data were located during the course of our research.

Validity. A number of authors are evaluating this test for acquired color vision defects (Lanthony, 1975a, 1978; Pinckers, 1978a, 1978b, 1979).

Other Remarks. This test is designed specifically for acquired color vision defects (Lanthony, 1974a). The separation phase allows determination of neutral zones according to the colored caps confused with the grays at four saturation levels. The classification phase allows determination of relative luminosity according to the position of colored caps in the gray scale, and of chromatic discrimination according to the arrangement of the colored caps.

Sahlgren's Saturation Test

12 caps in a case

Available from Visumetrics, Hallstenhagen 26, S-421 56 V Frolunda, Sweden

General Description. Sahlgren's Saturation Test was designed to evaluate the loss in saturation discrimination that is characteristic of acquired color vision defects. The 12 caps include five greenish blue and five bluish purple samples of varying saturation plus two gray caps. The colors are set in plastic caps and subtend 3.45° at 30 cm. They are labeled on the back with their color and a saturation score of zero for the gray caps and of 5, 10, 20, 30, and 40 for the two sets of colored caps. The samples were taken from the Natural Color System, which is the official Swedish color standard.

Administration. The caps are arranged in random order on the upper lid of the box. The test is presented using an approximation to Illuminant C that provides 400 lux. The observer is instructed to transfer all caps that appear bluish purple or greenish blue to the lower lid, leaving only the caps that appear gray in the upper lid. The test takes less than two minutes.

Scoring. The test is scored by summing the saturation scores printed on the back of the caps. A score of 10 is considered the upper limit of normal.

Maintenance. The caps should be stored in the closed box. Observers must not touch the pigments.

Calibration. The caps are taken from the Swedish Natural Color System; their specification is given by Frisen and Kalm (1981). No calibration is required. Illuminant C must be used.

Reliability. No test-retest data are available.

Validity. This test is described by Frisen and Kalm (1981). One of the 20 normal control subjects, who were aged 17 to 66 years, obtained a score of 15. The upper normal limit was set at 10. Scores for observers with congenital color defects ranged from 0 to greater than 50; 45 percent of the observers with congenital color defects had an abnormal score. Scores for observers with acquired color defects ranged from 0 to greater than 50; 90 percent of the observers with acquired color vision defects had an abnormal score. A χ^2 comparing pass-fail data for normal observers with acquired color vision defects (either retinal disorders or optic neuropathies) gave a value of 0.85, indicating good screening efficiency for acquired color vision defects.

Other Remarks. This is a new test that requires further validation in the clinic. It offers a rapid and easy alternative to plate tests in the assessment of acquired color vision defects.

Lantern Tests

British Board of Trade Lantern (1912)

12 filters of various reds, greens, and clears; Martin's Board of Trade Modification (1938) (also known as Martin Colour Vision Testing Lantern)--4 filters of green, clear, and 2 different reds; and Martin's Board of Trade Modification Transport Type (1943)--5 filters of green, clear, yellow, and 2 different reds. Manufactured by Kelvin, Bottomley, and Baird, Ltd., of Glasgow and London.

Not commercially available now.

General Description. In the 1912 model, the 12 lights (reds, greens, and clear lights) varied within the limits approved for navigation lights. The colors are shown singly or in horizontal pairs. There are two aperture sizes (0.2 and 0.02 in.), which are viewed at 20 feet to represent ships' lights at 200 and 2,000 yards. In the 1938 model (redesigned for electric light) there were four colors: one green, one clear, and two different reds. Again, these are shown singly or in pairs, with the same two aperture sizes available. The brightness of the lights is equated. A neutral filter may be placed over the left light or over the right light to reduce its luminance to one-third of its original value. In the 1943 model, a yellow light was added to the lantern for use in testing transport personnel.

Administration. The test is performed in a dark room at a distance of 20 feet. A voltage-controlled line is needed for the 1938 and 1943 models. The lights are presented in random order, and the observer names their colors. Administration is complicated for the examiner because of the many controls for selecting colored lights, aperture size, single versus paired presentation, and, in the 1938 and 1943 models, the placement of a neutral filter.

Scoring. No standardized scoring method has ever been developed. This is the primary disadvantage of this test for color vision.

Maintenance. No maintenance is required.

Calibration. No calibration is required. However, the replacement bulb must be certified by the Physics Laboratory of London.

Reliability and Validity. No reliability or validity studies are available.

Other Remarks. The lantern stimulates the navigation lights of a ship and is used at a number of examination centers in the British Commonwealth for the fishing fleet and merchant navy.

Color Threshold Tester

Color Threshold Tester, Stock No. 6515-388-3700, Macbeth Corporation, P.O. Box 950, Newburgh, New York.

8 colored lights (2 reds, 2 greens, orange, yellow, blue, and white) plus 8 neutral filters of various intensities.

Available from Macbeth Corp., P.O. Box 950, Newburgh, NY 12550

General Description. This lantern was developed for the U.S. Air Force to determine quantitatively whether the color-defective applicant was competent to make the color perception requirements of a particular job. The colors of the lights were based on two considerations: (1) some were colors close to the standards for aviation signal colors, and (2) some were colors that would be difficult for the color-defective person to identify. The lantern presents one light at a time, located halfway between two blue guide lights. The eight colored lights are presented at eight different luminances.

Administration. A demonstration of the eight colored lights is given at the brightest of the eight luminances. The examiner then turns the luminance knob to the dimmest of the eight luminances and presents the eight colored lights consecutively, #1 to #8. The luminance knob is then turned to increase the luminance to level 2, and the colored lights are presented consecutively #8 to #1; the luminance knob is turned to level 3 and the colored lights are presented

consecutively #1 to #8, and so on. The test is performed in a dark room at a distance of 10 feet. It takes about five minutes to administer the test. The observer names the colors presented.

Scoring. The exact color name is not always required for a correct response: red must always be called red, but orange may be called orange, yellow, or amber; green may be called green or blue; blue may be called blue or green; yellow may be called yellow, white, amber, or orange; and white may be called white or yellow. The part-score for each of the eight colored lights is obtained by counting the correct response, starting from luminance level 8 and continuing to lower luminance levels until an error occurs. Correct responses at still lower levels are not counted. The score for the entire test is the sum of the eight part-scores. A perfect score, of course, is 64 and is obtained by 95 percent of normal subjects. A score of 50 or better (obtained by all normal subjects and 30 percent of defective observers) is required for Class II or III medical certificates.* A score of 34 or better (obtained by 68% of defective observers) is required for entrance to the Air Force Academy.

Maintenance. The cover in front of the stimuli should be closed when the instrument is not in use, so that the filters will not become dusty.

Calibration. No calibration is required.

Reliability. Sloan (1944) reports correlation coefficients for the scores obtained by color-defective observers of 0.94 for same-day sessions and 0.80 for different-day sessions.

Validity. The Color Threshold Test (CTT) was designed for quantitative classification. Test scores of color-defective observers show a broad distribution. Sloan (1944) has compared CTT scores of defective observers with quantitative classifications obtained on other tests. Paulson (1973) has compared CTT scores of 130 deutans and 94 protans with results on the Farnsworth Lantern and other tests.

Other Remarks. The method of administration (consecutive order #1 to #8 at intensity level 1, and then consecutive order #8 to #1 at intensity level 2, etc.) often results in two contaminants on the final test score. First, the preceding colored light affects the observer's response. For example, a particular colored light might be named correctly for intensity levels 1, 3, 5, and 7 but incorrectly for intensity levels 2, 4, 6, and 8 because it appears after different

*FAA requirements for medical certificates are described in “Guide for Aviation Medical Examiners,” Federal Aviation Administration (June, 1970).

colors in the two sequences. Second, the fixed pattern of administration (versus random administration) permits the observer to become aware of the pattern after a few of the eight runs have been given and also enables an observer to memorize the test.

Edridge-Green Lantern (1891)

7 colored glass filters and 7 modifying glass filters (ground glass, ribbed glass, neutral glass, etc.)

Available from House of Vision, 137 N. Wabash Ave., Chicago, IL 60602. Replacement filters available from Clement Clark Ltd., London, England, and Hamilton Ltd., London, England.

General Description. The Edridge-Green Lantern is designed to produce a range of colors and tints. In addition to the seven colored and seven modifying glass filters, there are seven aperture sizes. The colored filters represent signal colors; the modifying filters represent smoke, fog, rain, and so forth; the various aperture sizes represent color judgments made at different distances.

Administration. The test is performed in a dark room at a distance of 20 feet. The lights are presented in random order, and the observer names the colors of the lights. Some of them are very difficult even for those with normal color vision. Administration is complicated for the examiner because the five rotating discs (containing the colored filters, the modifying filters, and the apertures) can be rotated singly or jointly, making hundreds of combinations possible.

Scoring. Although there are rules for the scoring, most often the test resolves into a contest of color-naming wits between the examiner and observer.

Maintenance. No maintenance is required.

Calibration. No calibration is required.

Reliability and Validity. No reliability or validity studies are available.

Other Remarks. This test is claimed to simulate railway signals and is used in testing engine drivers in Great Britian. It was used by the U.S. Navy for qualification of midshipmen and line officers prior to adoption of the Farnsworth Lantern Test in 1953.

Farnsworth Lantern (FaLant)

6 red, 6 green, and 6 white glass filters plus 9 dimming filters.

Available from Macbeth Corporation, P.O. Box 950, Newburgh, NY 12550

General Description. This lantern, developed for the U.S. Navy, is designed to pass normal trichromats and those persons whose color vision defect is mild and to fail those with more severe defects. The test is intended to select one-third of the color-defective population for assignment to naval duties that involve color-judging tasks. Nine combinations of red, green, and white lights are presented vertically and in pairs. A dimming filter is combined with one of the lights in each pair to reduce its luminance by up to 50 percent. Unlike other lanterns that use lights that simulate navigational, aviation, or railroad signal lights, the Farnsworth Lantern uses specific red, green, and white lights that are confused by people with more severe color vision defects. The reason for this choice was as follows. The spectral characteristics of signal lights that are used for different purposes (e.g., navigation or railroad signals) are different. Thus "red" or "green" lights comprise a relatively wide variety of spectral colors. Color-defective observers, however, confuse specific colors. Therefore, they would find some red-green pairs easy to distinguish but would be unable to distinguish other red-green pairs of lights. The idea behind the Farnsworth Lantern, therefore, is that an individual who can distinguish these pairs of lights which are known to be confused by color-defective observers, will certainly be able to distinguish all other pairs.

Administration. The test is simple to administer. All of the instructions for administration, scoring, and operation of the lantern test are printed as a metal plate affixed to the back of the instrument. Examiners are cautioned that failure to follow all these rules will result in invalid test results. The test is given in a normally lighted room at a distance of 8 feet. The lights are presented randomly. The observer reads a brief set of instructions and then names the colors presented. The test requires less than one minute to administer.

Scoring. If no errors are made on the first set of nine pairs of lights, the observer is passed. If errors are made on the first run, two more consecutive runs are presented, again in random order, without a break or comments between runs. The errors on these last two runs are averaged; an average error score of 1 or less is a pass score whereas an average error score of 1.5 or more is a fail score.

Maintenance. No maintenance is required. The bulb does not burn unless the examiner depresses the knob that rotates the lights. It is a 1000-hour bulb with an automatic cutoff, and a replacement bulb is located in the base of the instrument. The filters are very stable. They have been found to have the same chromaticities for over 20 years.

Calibration. The chromaticity specifications have been published by Paulson (1973). No calibration is required.

Reliability. Test-retest data were presented by Paulson (1966). The statistic of association, , was 0.98.

Validity. The Farnsworth Lantern was designed to pass normal trichromats and anomalous trichromats with good discrimination (i.e., mild discrimination losses). Some comparisons of Farnsworth Lantern data with data from other tests in the NSMRL battery (pseudoisochromatic plates, Farnsworth Panel D-15, and Farnsworth Panel H-16) are given by Paulson (1966).

Other Remarks. The Farnsworth Lantern Test is the final qualifying test for the U.S. Navy, the U.S. Coast Guard Academy, and the U.S. Merchant Marine Academy. It also may be used by the U.S. Army for qualification of pilots and by the U.S. FAA Aviation Medical Examiners. In addition, it is used by some U.S. railroad systems and other organizations.

Other Tests

Holmgren Wool Test

Wool skeins

Available from:

1. Bernell Corp., South Bend, IN 46601
2. House of Vision, 137 N. Wabash, Chicago, IL 60602

General Description. The Holmgren Wool Test was one of the original tests designed to screen red-green color defects. The test consists of 75 small strands and three large strands of colored wools. The large strands serve as test colors, the small strands as comparison or matching colors. There is no identification of the skeins. An instruction sheet accompanies the test, but there is no scoring sheet or scoring instructions.

Administration. The skeins are placed in a heap. One test skein is selected. The subject is asked to select skeins from the heap that most nearly match the test skein in color. There is no exact match; similarly colored skeins, or skeins of lighter or darker shades of the same color, may be selected. The procedure is repeated for each test skein.

Scoring. There are no scoring instructions. The examiner looks for hesitation and for the selection of dissimilarly colored skeins (e.g., for the red test skein, the selection of other colors, such as green, blue, brown, or yellow skeins).

Maintenance. The yarns are subject to fading when exposed to light or dust. Handling should be avoided. The set should be kept in the cardboard container when not in use.

Calibration. Sample spectrophotometric data have been reported by Rasmussen and Lakowski (1978). The skeins vary considerably from set

to set. No calibration is required by the user. The illuminant is not specified.

Reliability. No data are available.

Validity. No data are available.

Other Remarks. This test is primarily of historical interest. It is not recommended as a suitable screening test.

Lovibond Color Vision Analyzer

27 glass filters

Available from Tintometer Ltd., Salisbury, England

General Description. The Lovibond Color Vision Analyzer presents 27 colors in a circular display with a central neutral gray. The colors subtend 1°, complete the full color circle, and are arranged in random order in the display. The luminance of the central gray slide is variable. The colored lights may be desaturated by the use of superimposed white light. Instructions are included.

Administration. For a given luminance and saturation level, the observer indicates which colors on the circle match the central neutral slide.

Scoring. The examiner notes which colors are chosen as a match to the neutral slide at each saturation level. Normal observers select colors in the yellow-green and blue-purple regions at low saturations. The saturation level for which colors are accepted as neutral increases with age (Ohta, Kogure, and Yamaguchi, 1978). Congenital red-green color-defective observers select colors in the blue-green and red regions: dichromats select two or more colors at all saturation levels; anomalous trichromats select two or more colors at medium saturation levels. The actual colors chosen are diagnostic of the color defect: nos. 1 and 14 are protan confusion colors; nos. 2 and 15 are deutan confusion colors.

Maintenance. The tintometer glass is very durable and lasts for an extended period of time. The lamp itself, however, has a limited life (usually only 30 hours).

Calibration. The chromaticities of the filters are given in the instructions. No calibration is required of the user.

Reliability. Reliability is good for normal and dichromatic observers but poor for anomalous trichromats due to poor control of the desaturation device (Pokorny et al., 1979). Data for calculation of k are not available.

Validity. The test distinguished normal from red-green color-defective observers (Dain, 1974; Ohta, Kogure, and Yamaguchi, 1978). The following classification data were given by Ohta, Kogure, and Yamaguchi (1978).

Test of	$\bar{x}$
Qualitative classification	.65
Quantitative classification	.88

The $\bar{x}$ for qualitative classification is not good, the major problem being misclassification of protan observers. All deuteranopes were correctly classified. Deuteranomalous trichromats were classified correctly as such in 90 percent of cases and were incorrectly classified as deuteranopes in 10 percent of the cases. Protans were as likely to be classified deutan as protan. Therefore the test cannot be used for qualitative classification. Dain (1974) previously reported excellent qualitative classification but gave no statistics. Quantitative classifiction by Ohta, Kogure, and Yamaguchi (1978) are consistent with Dain's results.

CHAPTER 4

USING COLOR VISION TESTS

EVALUATION OF CONGENITAL AND ACQUIRED COLOR VISION DEFECTS

The hereditary nature of color vision disorders was recognized at the end of the eighteenth century. In the nineteenth century there were major disasters with loss of life in the shipping and railroad industries. These tragedies were attributed to the failure of engineers to recognize a colored signal. As a result, people with congenital red-green defects were and still are excluded from positions as pilots or engineers in commercial air, sea, and rail transport and similar duties in the armed forces. Tests that were developed to evaluate color vision were both practical and empirical. While the anomaloscope remains the only clinical method for precise diagnosis of the presumed genetic entities, many tests have been devised for quick, inexpensive, and efficient screening of the color-defective population. Screening tests are used to identify individuals who may eventually require more extensive color testing. Their usefulness is in the identification of such individuals rather than the diagnosis of the color defect. Screening tests are easy to administer and score and are of modest cost.

Rapid Screening of Congenital Red-Green Color Defects

Rapid screening of red-green color defects may be necessary in the military, schools, or transportation and other industries. The most effective test for rapid screening is one of the validated plate tests designed for this purpose including the Ishihara, Dvorine, AO H-R-R, and other series of pseudoisochromatic plates that detect about 96 percent of the cases confirmed by anomaloscope (Table 4-1). It is common to rely on a single test or even on a few selected plates. It should be noted that some normal subjects read the hidden digits of the Ishihara test; and, of course, some normal subjects will misread occasional plates. The deuteranomalous trichromat with good discrimination may pass the majority of a set of plates.

We are not aware of any screening test employing colored slides of transparencies that has been adequately validated. It is inappropriate to attempt to make a “home” screening test by color photography of an

existing plate test. Color reproduction is affected by the type of film, the illuminant used for photography, the color processing, and the illuminant used to project the transparency. Color processing to precise standards is very difficult. Although in the future color screening tests may be produced using colored transparencies, any such test will require adequate spectrophotometric control as well as validation in the population.

TABLE 4-1 Screening for Congenital Red-Green Defects Using Plate Tests

Status	Test
Validated	AO Plates AO H-R-R Plates Dvorine Ishihara Tokyo Medical College
Not intended for screening	City University
Unsuitable due to poor validation	Titmus Color Perception Test Bausch and Lomb Ortho-Rater Keystone Telebinocular

Diagnosis of Red-Green Defects

Anomaloscopes may be used for diagnosis of red-green color vision defects. The anomaloscope is the only clinical instrument for diagnosis and classification of the presumed genetic entities of dichromacy and to both simple and extreme anomalous trichromacy as defined by Franceschetti (1928). Anomaloscope examination is time-consuming, and only a trained person can use the anomaloscope. The test must include a full examination of the matching range, it is inappropriate to allow one or two matches. An additional problem is that commercially available anomaloscopes are very expensive.

Plate and arrangement tests are not entirely successful at diagnosis of congenital red-green defects. The failure of plate tests results from the fixed color relations of figure and background. There is sufficient variation in the color vision of defective observers that a protan observer may fail a deutan diagnostic plate or vice versa. Confusion axes on arrangement tests similarly may show ambiguity. The characteristic error axis on the FM 100-hue test may not occur if the color-defective observer makes relatively few errors.

Recognition of Congenital Blue-Yellow Defects and Achromatopsia

Recognition of congenital blue-yellow defects requires the use of one or more of the tests designed for this purpose. Plates for blue-yellow defects include the AO H-R-R, the Tokyo Medical College plates, and the Farnsworth F_2 plate. Normal observers with heavy ocular pigmentation may miss the green symbol on the F_2 plate and appear to show a tritan defect. Failure to perceive the blue symbol usually seen by normal observers and tritans is indicative of congenital red-green defect. The F_2 plate should be used in conjunction with another test. Recently, van Norren and Went (1981) suggested that detection of a blue increment pulse on a yellow background provides a sensitive and efficient test. The Farnsworth Panel D-15 and the FM-100 hue test are important in recognition of blue-yellow defects.

Evaluation of Acquired Color Vision Defects

The detection and classification of acquired color vision defects may be accomplished by use of an anomaloscope combined with a test that measures chromatic discrimination. In addition, 8 to 10 percent of males with acquired color defects have a concomitant congenital color defect; the examiner should be alert to this possibility. Plate tests are of variable usefulness in testing acquired color defects. An observer with an acquired color-defect may not give the expected reading; that is, read the numbers designed for normal or congenitally defective observers; misreadings may occur. If an observer with reduced visual acuity fails a plate test, the examiner cannot conclude that there is a specific kind of color defect. Further analysis is necessary. Arrangement tests are of particular importance in acquired color vision defects. The Lanthony Panel D-15 and Lanthony New Color Test were designed specifically for evaluation of acquired color vision defects.

CLASSIFICATION AND QUANTIFICATION OF CHROMATIC DISCRIMINATIVE ABILITY

In some applications it is important not only to screen for color defects but also to classify the defect according to chromatic discriminative ability.

Test Batteries

Many examiners decide on a test battery to fulfill their specific requirements. Choice of a test battery reflects the testing requirements, the availability of tests, the personal experience of the examiners, and the time available for testing.

An example of a test battery for congenital red-green defects is that designed at the U.S. Naval Submarine Medical Research Laboratory (Paulson, 1973) (Table 4-2). The battery includes the use of a set of plates, lantern, arrangement tests, and an anomaloscope. The battery allows recognition of congenital red-green color-defective observers and separation of color-defective observers into four categories: individuals showing (1) mild, (2) moderate, and (3) severe loss of chromatic discrimination, and those showing (4) dichromatic color vision. The mild and moderate categories tend to be predominantly simple and extreme anomalous trichromats; the severe and dichromat categories include individuals who are extreme anomalous trichromats and dichromats. The correlation is not perfect since chromatic discriminative ability varies widely among anomalous trichromats. The NSMRL test battery will not necessarily predict the performance of the defective observer on other color tasks (Kinney et al., 1979).

Verriest (1968b) proposed a test battery (Figure 4-1) for evaluation of congenital defects that includes the Ishihara, F_2 plate, AO H-R-R, Farnsworth Panel D-15, Lanthony Desaturated Panel

TABLE 4-2 NSMRL Test Battery for Determining Degree of Color Vision Defect

Class		Pseudoisochromatic	FaLant	D-15 Test	H-16 Test
I.	Normal trichromatic	Pass	Pass	Pass	Pass
II.	Anomalous trichromat (mild defect)	Fail	Pass	Pass	Pass
III.	Anomalous trichromat (moderate defect)	Fail	Fail	Pass	Pass
IV.	Anomalous trichromat (severe defect)	Fail	Fail	Fail	Pass
V.	Dichromat	Fail	Fail	Fail	Fail

Source: Paulson (1973).

D-15, and Nagel Model 1 anomaloscope. It was suggested that the Lanthony Desaturated Panel be used when the Farnsworth Panel D-15 gives normal results or shows only minor errors. This battery allows good differentiation of protanomaly, protanopia, deuteranomaly, deuteranopia, tritan defect, and achromatopsia.

I. Test battery for congenital color vision defect (Verriest, 1968b)

- A. Ishihara (16- or 24-plate editions)
- B. F_2
- C. AO H-R-R
- D. Farnsworth Panel D-15
- E. Lanthony Desaturated Panel D-15 (if Farnsworth Panel D-15 is normal)
- F. Nagel Model I anomaloscope

II. Test battery for acquired color vision defects (Pinckers, 1978a)

- A. Initial screening
  1. AO H-R-R
  2. Lanthony New Color Test - Box 6/4.
     a. If Box 6/4 failed, do Box 6/8.
     b. If Box 6/4 passed, do the Desaturated Panel.
- B. Red-green defects revealed by initial screening
  1. Ishihara
  2. FM 100-hue
  3. Nagel Model I anomaloscope
- C. Blue-yellow defects revealed by initial screening
  1. F_2
  2. FM 100-hue
  3. Pickford-Nicolson

FIGURE 4-1 Test Batteries for Congenital and Acquired Color Defects

Pinckers (1978a) proposed a battery for diagnosing acquired color vision defects in the ophthalmology clinic. This battery, also shown in Figure 4-1, includes the AO H-R-R, Lanthony New Color test, F_2 plate, Ishihara, FM 100-hue test, and both the Nagel Model I and Pickford-Nicolson anomaloscopes. The minimal requirement for an eye clinic should include a screening test, the Panel D-15 or Lanthony New Color test, the FM 100-hue test, and an anomaloscope. If the screening test does not include blue-yellow plates, the F_2 plate may be added.

Quantification of Chromatic Discriminative Ability

Typically it is not appropriate to use the number of errors on a screening plate test as a numerical indication of chromatic discriminative ability. Color-defective observers fail a screening plate because

to them the colors in the figure match those of the background. For most tests, the colors in the figure and background were chosen empirically on a few "test" observers. There is considerable variation among color-defective observers, and the optimal colors for figure and background will vary among these observers. A color-defective observer with poor chromatic discrimination may make few errors on a screening plate test because the color vision of his eye differs from that of the observers on whom the test was optimized. Conversely a color-defective observer with good chromatic discriminative ability still may fail many of the plates if the colors happen to be optimized for his eye. The Dvorine is one plate test for which it is specifically recommended that the number of errors in reading the plates gives an estimate of severity. However, we were not able to find data evaluating the classification of severity on the Dvorine plates from which the statistic of association, K, might be calculated.

The Farnsworth-Munsell 100-hue test has been used as a quantitative test of chromatic discrimination even though its designer, Dean Farnsworth, originally suggested only that observers could be specified as showing superior, average, or inferior chromatic discriminative ability. It is generally accepted that the test involves not only chromatic discriminative ability but also cognitive parameters, such as concentration, patience, and cooperation. It is appropriate, however, to compare an observer's error score with a set of population norms, and there are some cases in which it is appropriate to use the number of errors on the FM 100-hue test in a quantitative way (see "Arrangement Tests," in Chapter 3).

SCREENING FOR PROFESSIONAL PURPOSES

The choice of a test is dependent on both color vision requirements and test availability. It must be decided whether to choose only those observers with good discrimination. Such decisions are important because the exclusion of dichromats, for example, does not ensure that all selected observers will have good color discrimination. After careful consideration, it may become obvious that not all defective observers need to be excluded or, alternatively, that it is unnecessary to select only the best for the task. There are professions and skills in which good discrimination is advantageous but in which a defect is not an insurmountable handicap. Of course there are situations that require good discrimination, and in these occupations it is absolutely necessary that only those with good ability be selected. Even when color vision requirements are known, one must consider the availability of tests, money, and time, and whether the examiner possesses or is willing to acquire the skills that would enable him or her to administer validly the more complicated tests. Finally, it may be necessary to design a field test rather than use a clinical color vision test; for example, when an employee is required to reject a production line item whose color differs from a standard given tolerance step.

Preliminary screening may be used to eliminate observers with congenital defects. Because each clinical test measures a specific

ability, the task required of the color worker must be considered. If the task involves the perception of small saturation differences, an appropriate test is the Color Aptitude test. If small color differences must be distinguished, the FM 100-hue test may be used. If the task involves metameric matching, such as in color mixing in the textile and printing industries, the anomaloscope should be used.

The screening of candidates for some occupations is performed best by means of specialized field tests that reproduce the actual conditions encountered on the job. For example, the ability to recognize colored signals is evaluated best by a field test using signal equipment. It is extremely important, however, that any such field test be standardized. The same distance, illumination levels, number of stimuli, and so on, should be used for all candidates. The ability to sort materials by color (e.g., cotton, diamonds, pearls, and gasolines) is evaluated best by a field trial using real materials; the materials should be identical to those encountered in the job situation, and the type and level of illumination must be exactly replicated.

TEST ADMINISTRATION: TRAINING PERSONNEL TO ADMINISTER TESTS

The majority of clinical color vision tests are designed for use by personnel with minimal training in color vision testing. Instructions are provided with many plate and arrangement tests; in most cases, careful reading of these instructions will provide sufficient information for correct test administration. Scoring of the FM 100-hue test is somewhat complicated, especially when error scores are high. The manual accompanying the test, however, provides ample instruction. Plotting the errors is somewhat easier using the technique described by Kinnear (1970). Lantern tests are designed for easy administration. The major exception among clinical tests is the anomaloscope: administration of an anomaloscope examination requires knowledge of colorimetry and/or extensive training in use of the instrument. Anomaloscope examination should not be attempted by unskilled personnel. The procedures detailed in the section on anomaloscopes in Chapter 3 must be followed.

Even when the instruction manual for a given test is understood, there are a number of precautions that personnel must follow:

Use a standard procedure. Standardized procedures and conditions must always be used during administration of clinical tests, such as the FM 100-hue test, pseudoisochromatic plates, or the anomaloscope. The level and type of illumination must be constant. A fixed set of verbal instructions must be read to the observer, since variation in instruction might bias responses. The use of color names should be avoided. Use of a standard procedure allows comparisons to be made between data collected by examiners in other clinics or even by the same examiner on different occasions. Recommended procedures for each test are detailed in Chapter 3.

Follow scoring instructions carefully. The test must be scored according to the instructions that accompany the test. The score sheet should contain the following type of information:

- Personal data: e.g., name, address, telephone
- Birth date, sex
- Testing information: date of test, illuminant (for plate and arrangement tests), monocular (which eye) or binocular
- Data relevant to testing situations: occupation, visual acuity, etc.

For plate tests, a sample scoring sheet may be provided; if not, one must be designed. In addition to the information above, a scoring sheet should include a place to record the response to each plate. It is helpful if the sheet indicates the expected responses of normal and color-defective observers. A good score sheet indicates to the examiner how to interpret the result.

For the anomaloscope, the examiner should note the test brightness setting made for each mixture ratio. The examiner should also note whether the setting was accepted as a color match and if not, why not (for example, too much red or too much green in the mixture field).

Match the test to the ability of the observer. The majority of color vision tests are designed for use with observers who are not familiar with the specific test or testing procedure. Patients or prospective employees may be nervous about the testing situation. Thus test results may be biased by cognitive or emotional factors. Cognitive factors of some tests may be beyond the capabilities of some patients, notably individuals with other visual, motor, or intellectual handicaps, the elderly, and the very young. Furthermore, the majority of color vision tests were designed for use with young adults with normal visual acuity. Personnel administering clinical tests should be made aware of these factors and be prepared to deal with the occasional “difficult” observer.

Do not allow observers to wear tinted glasses or tinted contact lenses. Color testing should not be performed on observers wearing tinted glasses or tinted contact lenses. Tinted glasses are easily identified. The examiner should ensure that tinted lenses are not being worn. Tinted contact lenses may not be noticed; all observers should be asked if they wear such correction. Some contact lens wearers also have regular clear glasses. In this case, an appointment should be made for a future date, and the observer should be told to wear the glasses rather than the contact lenses.

The majority of screening tests can in fact be performed with glasses or contact lenses removed. Spherical refractive errors of two or three diopters should not cause difficulties for screening plates if the patient is myopic or is hyperopic with adequate accommodative ability. Refractive error of myopes is often reduced on first removing the hard contact lens. If necessary, an observer may use a hand-held ophthalmic lens for screening plates or ophthalmic trial frames for arrangement tests. The Nagel Model I and Neitz anomaloscopes have adjustments for focus.

Decide whether to use monocular or binocular testing. Few manuals specify whether testing should be monocular or binocular. In research it is customary to test one eye at a time. In the eye clinic, it is especially important to check each eye separately, since eye diseases may affect the eyes to a different degree. On the other hand, routine screening as performed in schools or in the military is usually performed binocularly.

What to do when tests given different results: Occasionally an observer will fail one set of screening plates and pass another set. Alternatively, an observer may show a defect on screening plates but not on the anomaloscope or vice versa. If any set of screening plates is failed the observer is considered to have a color defect. An anomaloscope examination is required to provide further classification of the defect. Observers who show this behavior include anomalous trichromats with good chromatic discrimination. These individuals are called minimale anomalen (Pokorny et al., 1979). Additionally some normal trichromats may show minor color abnormalities (Pokorny et al., 1979). The majority of normal trichromats with minor color defect show generally poor color discrimination and will not only fail color screening tests but show abnormal error accumulations on discrimination tests. Rarely, normal trichromats will fail a screening test but show no other sign of color defect.

SOME SPECIAL PROBLEMS OF TESTING

Color vision tests were designed by adults for use with adults with normal visual acuity. Some adults (e.g., illiterates, observers not fluent in the examiner's language, or the elderly) may present the examiner with special problems. Testing of children also requires special attention. The testing of a suspected malingerer or concealer also may present problems. The general rule is to use common sense and to perform a test only if it is clear (1) that the observer understands the procedure, and (2) that the test can be performed using appropriate techniques.

Testing Illiterates

Illiteracy is relatively rare in countries with compulsory grade-level education. Illiteracy, however, may be encountered in less-developed countries, especially by researchers interested in genetic studies. The problem of illiteracy may then be compounded by language difficulties. If some mutual understanding is reached, tracing of screening plates is still appropriate.

The Ishihara test includes tracing patterns for illiterates; the symbols on the AO H-R-R may be traced with a brush, as may the numerals on the other plate tests. Anomaloscope examination may prove difficult unless the observer understands the task.

Language Problems

Examination of adults not fluent in the examiner's language may be difficult if no translator is available. With good will and by mimicry and sign language, a foreign-speaking individual may be tested on screening plates. The observer should either trace the symbols with a brush or write down the symbol or numeral on an adjacent piece of blank paper (not the score sheet). Alternatively a matching technique may be used in which drawn or cutout outlines of the figures are prepared for the observer to point at or superimpose on the plate. Arrangement tests and anomaloscope examination require a better level of communication.

Testing the Elderly

With respect and consideration, the elderly individual should offer no problems in testing. The arrangement tests may be difficult for individuals with poor manual dexterity, such as those with arthritis. Such individuals may drop the chips and become embarrassed or impatient with the task. Again the solution is common sense. Perform only those tests that are necessary for diagnosis and that are within the patient's ability.

Bifocal prescriptions may offer a problem in anomaloscope testing. The observer may have trouble finding the field in the telescope view of the Nagel anomaloscope or may wonder which part of the bifocal to use. The observer should always look through the part of the bifocal lens that is intended for distance use, usually the upper half of the lens. In some cases, removing the glasses and using the telescope adjustment may be all that is needed. In other cases, the observer may prefer a hand-held ophthalmic trial lens of the appropriate power for distance vision rather than the regular glasses. It is important to ensure that the dividing line of the split field appears clear. The Pickford-Nicolson anomaloscope should offer fewer difficulties to bifocal wearers.

Testing Children

Children under 12 years of age offer special problems in color testing, since many of the tests require intellectual abilities that develop at different ages: screening tests require knowledge of the alphabet or numerals; arrangement tests require the concept of serial ordering. The situation is even more difficult in the case of retarded children.

With increased use of color coding in school materials, it is of growing importance to identify congenital color defects in young children. Many observers with a congenital color defect retain memories of being treated as “stupid” or “troublemakers” because they had difficulties making color discriminations that were immediately evident to color-normal observers (Sloan, 1963). Color tests may also be, helpful in identifying hereditary retinal disease in children.

There are three tests designed especially for children: the Guy's Hospital color vision test,* the Matsubara test, ** and the Titmus pediatric color perception test. The Guy's Hospital color vision test contains design flaws that make it ambiguous and confusing to adults, and thus presumably equally confusing to children (Alexander, 1975). The Matsubara test contains symbols of items that are familiar and important in Japanese culture (e.g., cherry blossoms) but that are not necessarily familiar to American children. To date, none of these tests has received full validation in an American population.

Although a review of the literature revealed rather variable results in testing young children (Alexander, 1975; Verriest, 1981), it is possible to test children successfully with the adult tests, such as the AO H-R-R and the Ishihara screening tests. Care is needed to match the task to the age, attention span, and intellectual development of the child. It is important to give careful instruction to ensure that the child understands what he or she is asked to do. Such instruction should not contain reference to color names or color differences that the color-defective child may not understand. By their very nature, color tests are frustrating and difficult for color-defective observers, and this point must be remembered when dealing with color-defective children.

Pre-school and Kindergarten Children (13 to 5 years old). Today with increased use of pre-schools and educational television, many children of 3 to 5 years know alphabet letters, the numerals from 1 to 10, and simple geometric shapes, as well as the concept of "same" and "different."

Young children may be tested with the AO H-R-R test (Alexander, 1975). If necessary, the examiner may draw the three symbols--triangle, circle, and cross--on a sheet of paper and ask the child "Do you see any of these shapes on the color plate?" If the child says "Yes" he or she is asked to point first to the quadrant of the plate in which the child sees the symbol and then to the symbol on the sheet of paper that matches the symol seen on the plate. It is important to practice the procedure with the demonstration plates and to make certain that the child distinguishes the three geometric shapes.

The AO H-R-R is preferable to the Ishihara or Dvorine with young children even if they know some numerals, since many children of this age will confuse certain numerals and will not be sure how to identify a double-digit numeral. For example, when shown a plate containing the numeral "26," the child may say "6" or "2" or even "9" not knowing that the numeral is called "twenty-six." The alternative of using the tracing patterns designed for illiterates is not optimal, since few

*The Guy's Colour Vision Test for Young Children by Peter A. Gardiner, M.D.

**Colour Vision Test Plates for the Infants, originated by Hiro Matsubara and revised by Koku Kojima. Tokyo, Handaya Co., Ltd.

young children have the necessary manual dexterity to perform an accurate tracing.

First- and Second-Grade Children (6 to 8 years old). Many children of 6 to 8 years can perform the screening tests. However, few children in this age range understand the concept of serial ordering or have the attention span necessary to complete a serial ordering test such as the Panel D-15 (Adams et al., 1975; Cohen, 1976). A 6-year-old may start the Farnsworth Panel D-15 correctly and make minor errors after a few caps, or may put two favorite colors together.

In addition to the plate tests, a limited amount of information may be obtained from 6- to 8-year-olds on an anomaloscope. The Pickford-Nicolson anomaloscope has the advantage that both child and examiner can point to one or the other side of the vertically split field, thereby eliminating the need to describe what is seen. The Nagel anomaloscope has a disadvantage in that some children have difficulty aligning themselves to see the field in the telescope view. The examiner should set both the color mixture and brightness and ask the child, "Do you see a circle of color, or can you tell that there are two colors in the circle?" The examiner must present matches that have an obvious brightness difference (green primary and yellow turned dim), matches that are representative of a normal trichromat, and matches of the common red-green defects.

Third- to Sixth-Grade Children (8 to 11 years old). Children of 8 to 11 years can usually perform the screening tests and the Farnsworth Panel D-15. They will perform on the anomaloscope if the examiner sets the color mixture and watches carefully how the child sets the yellow brightness; the examiner should set it also, if necessary. Children of 8 to 11 years can perform the FM 100-hue test; however, many become bored after one or two boxes, with a consequent performance decrement.

Mentally Retarded. Plate tests are not suitable for screening in the mentally retarded population. Color screening of mentally retarded boys (with plate tests) revealed a high failure rate (20 to 30%) with poor inter-test correlations (Salvia 1969; Salvia and Ysseldyke, 1971a, 1971b; 1972). The high rates represent failure of screening plates by mentally retarded boys with normal color vision defined by anomaloscope. The problems are evident in AO H-R-R, Dvorine, and Ishihara. Arrangement tests, such as the FM 100-hue test and Farnsworth Panel D-15 (Salvia, 1969), also offer difficulties and may reveal high incidences of apparent color defect. Salvia and Ysseldyke (1971a,b) report an incidence of 8.7 percent for congenital red-green color defects when the Pickford-Nicolson anomaloscope was used. If the examiner is confident that the mentally retarded individual understands the anomaloscope test, this test may be used for evaluation of color vision in the mentally retarded population.

Malingering and Concealing

Two contingencies that arise occasionally include the person with normal color vision who claims to have a color vision defect (either by malingering or due to hysteria) and the person with a congenital vision defect who wants to pass a color vision test (concealment). The malingerer is the more difficult to detect.

Malingering and Hysteria. Malingering can occur in connection with the assessment of workmen's compensation after an industrial accident. Hysteria reflects a psychosomatic basis. It can be difficult to detect malingering and hysteria. One way of revealing malingering or hysteria is by use of tests such as visual fields and electroretinography. Generally a battery of tests is used, in which case the observer tends to produce atypical or contradictory results.

The malingerer may claim that he is unable to read any of the pseudoisochromatic plates, including the demonstration plates. If visual acuity is good, failure of the demonstration plates is indicative of malingering or hysteria. On tests such as the Panel D-15 or the FM 100-hue test, the malingerer will arrange the samples haphazardly. High error scores of 400 or more without predominant axis in an adult with normal visual acuity are indicative of malingering. The malingerer gives inconsistent answers on anomaloscope examination. Acceptance of "impossible" matches by an adult is indicative of malingering.

The most difficult cases occur when malingering or hysteria is superimposed on a preexisting congenital or acquired color vision defect (Kalberer, 1971; Pickford, 1972). A comparison of the color vision test results with other visual functions such as visual acuity, dark adaptation, and visual field, may be necessary.

Concealing. A person who deliberately tries to conceal a congenital color vision defect usually wants to be accepted for a job in which normal color vision is a prerequisite, such as in shipping or air transport. That person may have a good chance if the correct answers to a set of screening plates are provided and learned in advance (Perdriel et al., 1975; Verriest and Hermans, 1975). Some defective observers may use tinted glasses or tinted contact lens (e.g., the X-chrom lens) to read pseudoisochromatic plates. It is difficult or impossible to conceal successfully on a properly administered anomaloscope test.

COLOR VISION "CURES" AND "REMEDIES"

Many cures and remedies for red-green color vision defects have been reported in the newspapers, in lay magazines, and even in professional journals. Attempts to cure color vision defects reached a peak during World War II because of the number of young men with red-green color defects who were eager to be accepted into the Navy, Air Force, and office training programs. Some of the alleged cures and remedies, none

of which proved to be successful under control investigation, included warming one eye; staring at flashing red and green lights; wearing colored goggles; being coached in color naming and color matching; and taking injections of iodine, staggering doses of various vitamins, and injections of extracts from cobra venom, marigolds and lobsters. A two-volume book for testing and training color-defective observers, which was published in 1944, claimed that people with color vision defects were merely visually confused and needed to identify their confusion and then correct it by training. Other reports described color-defective observers who were able to pass the color vision test for the military after extensive training on the test.

In 1946 the Army-Navy National Research Council Vision Committee requested from the American Committee on Optics and Visual Physiology (ACOVP) a statement of the efficacy of corrective training. The statement was adopted by the American Academy of Ophthalmology and Otolaryngology, the American Ophthalmological Association, the Section on Ophthalmology of the American Medical Association, and the Association of Schools and Colleges of Optometry. Its conclusions are still valid: “no method had been found for the correction of color blindness, whether called ‘color weakness,' ‘color confusion,' or ‘color defectiveness.' Men can be coached to pass tests, but their physiologic deficiency cannot be repaired. Any claims to the contrary, any treatment which convinces operators that they can see colors they could not see before will decrease safety in transportation, decrease security in national defense, and decrease efficiency in industry” (quoted in Farnsworth and Berens, 1948).

Since that time, several other techniques for improving color vision have been proposed. One of them involves wearing a color filter, in the form of a contact lens, over one eye. With the use of this lens, which is called the X-chrom lens, the two eyes receive different spectral distributions of light. Because of the relative changes in lightness that the filter produces, the lens may help the color-defective observer to make chromatic discriminations and to pass some color vision tests. However, neither the X-chrom lens nor any of the other color vision cures and remedies that have been proposed can restore normal color vision function.

The working group is aware of no scientific study demonstrating that performance of complex real work tasks by people with defective color vision would be enhanced by use of the X-chrom lens. Siegel (1981) has discussed hazards potentially associated with use of the X-chrom lens for tasks such as automobile driving. ACOVP has recommended that examiners be extremely cautious in deciding whether to allow persons to use such devices when being tested for color vision required for occupations (quoted in Siegel, 1981).

CHAPTER 5

RECOMMENDATIONS

There currently are no uniformly accepted criteria for procedures to establish the precise color vision requirements for various types of jobs. However, the expense of such an undertaking is great, and Working Group 41 is reluctant to recommend such an expensive project. Working Group 41 has noted that many jobs may be broadly characterized according to whether the task involves

- normal or good color vision (i.e., exclusion of people with major color defects);
- representative color vision; or
- excellent chromatic discrimination.

Clinical tests exist to evaluate these characteristics in standardized illuminations. For applications in which color matching is made under varying environmental conditions, field tests may be more appropriate. Working Group 41 therefore recommends that color vision requirements for various jobs be established individually within industry and the military as needed (and as funds for the projects arise).

Working Group 41 has indicated a broad range of color vision tasks and the clinical tests that may be used to evaluate each.

- For tasks from which people with major color vision defects must be excluded, any of the validated screening plate tests should be used.
- For tasks that require representative color vision (color matching in printing and textile industries), a color-matching task must be used, and anomaloscope examination is recommended.
- For tasks involving fine chromatic discrimination, the FM 100-hue test is recommended.

From our survey of existing plate tests, it is clear that the quantification of chromatic discriminative ability within a single test is not very successful. Multiple cutoff scoring standards are inappropriate for a single plate test. A test battery, however, may prove suitable to establish a graduation of chromatic discriminative ability among people with color vision defects. However, the test

results will not necessarily predict chromatic discriminative ability of color-defective observers for specific tasks.

A major gap in our knowledge is prediction of color recognition or identification under the widely varying contexts and illuminants encountered in the field. This is of particular importance in jobs that involve diverse duties rather than one easily identified color task. The ability to identify or recognize colors is strongly dependent on field and environmental factors. No standard clinical test can predict color identification/recognition ability, especially in the color-defective population. Furthermore, limited field tests for color recognition/identification may not be valid, since these tests themselves will not necessarily encompass the full environmental range to be found in practice. It therefore would seem beneficial to aim further research at the prediction of color recognition/identification in various field conditions.

APPENDIX

UNDERSTANDING TEST DESIGN

In order to understand how a color test is designed and why it works, it is helpful to understand how normal color vision is represented by color mixture. Normal color mixture data allow specification of color surfaces according to an important visual property: the condition under which two color samples will appear identical to a normal observer.

COLOR MATCHING

As described in Chapter 2, in a color-matching experiment an arbitrary color is matched in visual appearance to a mixture of primary colors. When identical in visual appearance, the two color fields that have dissimilar spectral distribution are called metamers.

A fundamental property of normal human color vision is that it is possible to find a metamer for any spectral hue by variation of only three primary colors. The terms trichromat (a three-color mixer) and trichromacy (the property of being a three-color mixer) come from this property of normal vision.

For spectral lights, the primaries and the spectral light are arranged in pairs so that the spectral light and one primary match the remaining two primaries. Thus, except at the primaries themselves, the appearance of the mixture fields will not be like the spectral hue or any of the primaries. The importance of the experiment relates not to the appearance of the hue but to the equivalence of hue.

One way of presenting the results of color mixture experiments is in a chromaticity diagram. A diagram called the x,y chromaticity diagram was devised by the Commission Internationale of Eclairage (CIE) based on the average color matches of many color-normal observers. Figure A-1 shows the x,y chromaticity chart for the "standard" 1931 CIE observer. An isosceles triangle completely encloses the experimentally determined chromaticity diagram. The spectral wavelengths are represented around the perimeter of the chromaticity diagram, which is called the spectrum locus, and equal energy "white" occurs in the center. Since the chromaticity diagram represents only color matches and not hues, the hue names added to the chart in Figure A-1 are provided for the convenience of those who are not familiar with the appearance of different wavelength regions of the spectrum. Saturation

is not specified by the chromaticity chart, but in general it can be said that saturation along any line from the center to the spectrum locus increases with the distance from the center. The line connecting the coordinates for 380 nm and 700 nm is identified as the line of nonspectral purples. All real colors may be represented within the boundaries formed by the spectrum focus and the purples. Mixtures of any two chromaticities can be represented by a straight line joining the pair of mixture lights on the diagram. Each mixture is a point on the line specified by the relative amounts of the two components of the mixture.

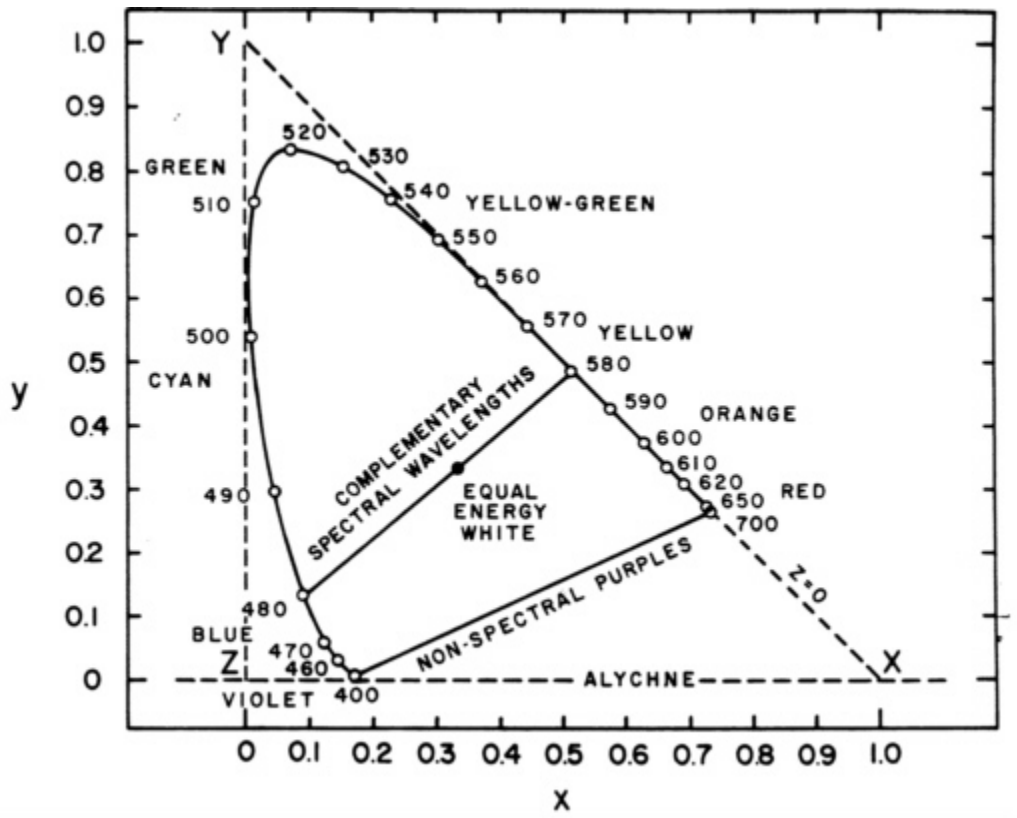

FIGURE A-1 The CIE (x,y) chromaticity diagram.
Source: Pokorny et al. (1979, by permission.

REPRESENTATION OF DEFECTIVE COLOR VISION IN THE CHROMATICITY DIAGRAM

The dichromat is an observer who requires only two primaries for spectral color matching. For example, the dichromat can match any spectral color to a mixture of a blue primary (e.g., 450 nm) and a red primary (650 nm).

The color-matching data of protanopes and deuteranopes can be plotted on the normal chromaticity diagram. The procedure, however, is theoretically correct only if dichromacy is a reduced form of normal trichromacy; that is, if the dichromat is simply lacking one of the normal discriminative mechanisms. For dichromats, some mixture lines on the x,y chromaticity diagram represent a series of colors that cannot be discriminated from one another (so-called isochromatic or confusion lines). Sets of such isochromatic lines are shown in Figure A-2: the upper panel gives isochromatic lines of protanopes; the lower panel gives those of deuteranopes. By associating the coordinates in the x,y chromaticity diagram with their usual series of color appearances to normal trichromats, we can describe approximately which colors are confused by the two types of dichromats. For both protanopes and deuteranopes, one isochromatic line lies on the spectrum locus from 540 nm to 700 nm; protanopes and deuteranopes are said to confuse spectral yellow-greens, yellows, oranges, and reds. From other data we know that, as a general rule, protanopes confuse reds with dark browns; pale blues with purples and magentas; blue-greens, whites, and reds; light greens with light browns (fawn). Deuteranopes confuse red, orange, and light browns; blues, violets, and blue-purples; blue-greens, whites, and purples; light greens, magentas, and purple-reds.

One confusion line passes through equal energy white. It indicates precisely which chromaticities and in particular which monochromatic light (neutral point) can be completely matched with the equal energy white. Chromaticities represented above this line are said to appear “yellow” with increasing saturation; those below the line are “blue,” also with increasing saturation. Accordingly, the visible spectrum is said to appear as shades of yellows and blues to observers with protanopia or deuteranopia.

A word of caution is in order. The CIE standard observer represents a person with average visual photopigments, lens, and macular pigment absorptions. The isochromatic lines are thus similarly indicative of those expected for an average group of dichromats whose ocular media have characteristics similar to those of normal trichromats. For a single dichromatic observer, the “isochromatic” contours may look quite different from those of Figure A-2, just as a single normal observer will make color matches that differ from the group average. Nevertheless the isochromatic lines are useful in the design and evaluation of screening tests for color defects and in indicating what kinds of colors will be confused by protanopes, deuteranopes, and tritanopes. Protanomalous and deuteranomalous trichromats are said to make color confusions that are qualitatively similar to, although of less severity than, the corresponding dichromat (Farnsworth, 1943). This similarity forms the basis for many tests for color defect. Farnsworth also introduced the

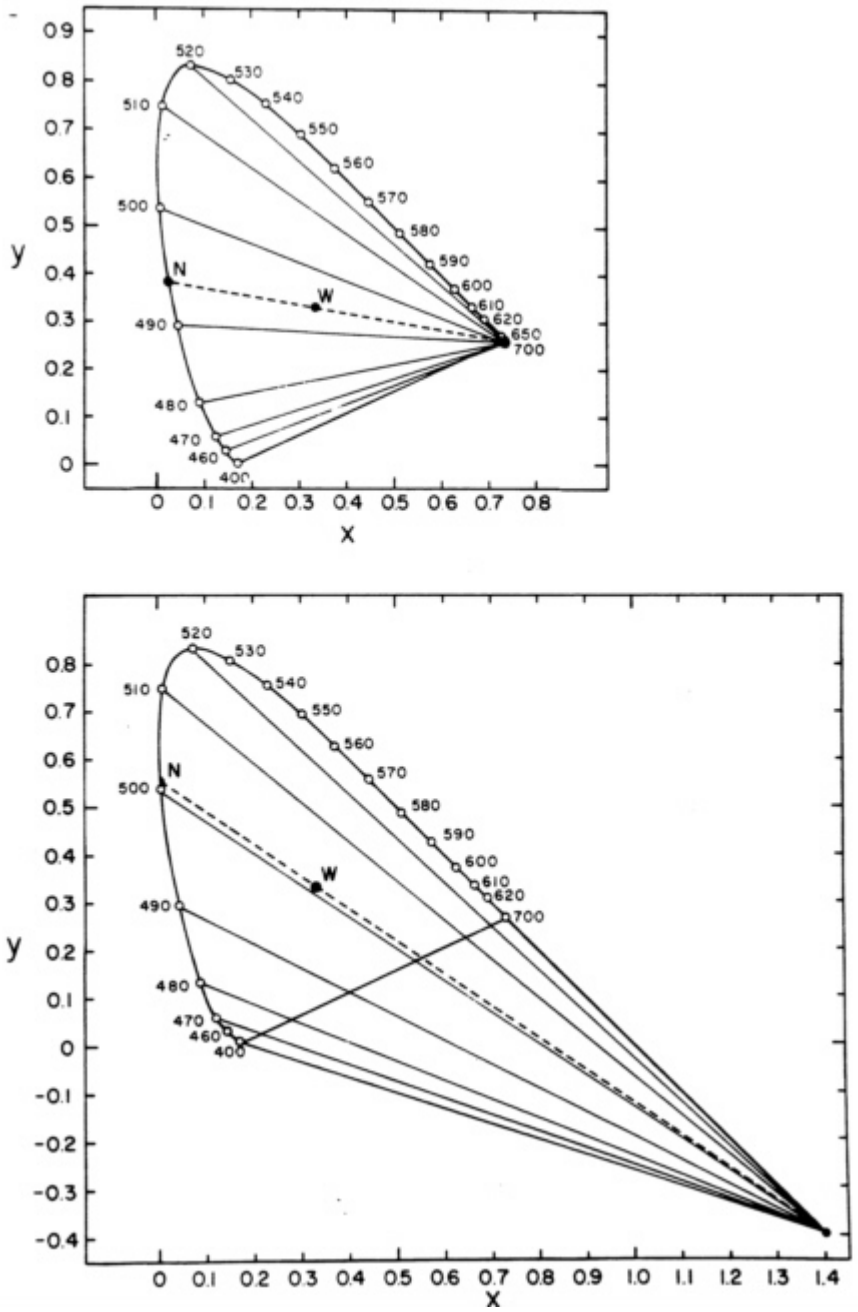

FIGURE A-2 Confusion lines for protanopes (upper panel) and deuteranopes (lower panel).
Source: Pokorny et al. (1979), by permission.

term protan to characterize protanopes and protanomals and the term deutan to characterize deuteranopes and deuteranomals. The data of tritanopes may also be plotted on the CIE (1931) x,y chromaticity diagram; their isochromatic lines converge on the "blue" corner of the diagram.

THEORY OF TEST CONSTRUCTION

Pseudoisochromatic Plate Tests

Most pseudoisochromatic plate tests are constructed empirically. The colors are selected on a trial-and-error basis, and only those plates shown to have high diagnostic efficiency are retained. The trial-and-error procedure is necessary because the surface mode of presentation complicates plate design. Factors such as form, size, glossiness, texture, and glitter will affect the readability of the plates. Stilling (1873) designed the first plates, using great ingenuity and finesse. Applying information obtained from two color-defective assistants (one red-green blind, the other blue-yellow blind) and following Hering's color theory (see Hering, 1964) of opposing pairs, he succeeded in constructing a series of plates in which figures composed of one set of variegated color dots appeared on a background of corresponding confusion colors. For instance, he used red-orange dots on a dull yellow background and yellow-green dots on an orange-brown background to detect red-green deficiencies, and pale blue dots on a pale yellow-green background to detect yellow-blue deficiencies.

Since Stilling's time, various types of plate tests have been constructed. Although some tests are better than others, all make use of four basic plate designs. The first, a vanishing test plate, is the simplest and most frequently used. The colors of the figure and background are confused by certain types of dichromats (i.e., the colors will fall on a given confusion line). A defective observer fails to read the figures that are clearly discerned by normal observers. The figure is said to have "vanished" for the defective observer. In modern tests (such as the Tokyo Medical College test), the color distance between the colors of figure and background is varied; these tests are designed both to screen and to quantify the defect. An observer cannot recognize any of the plates, no matter how great the color distance between the figure and background, is assumed to have a severe color defect. If the plates with the greatest distance between figure and background can be read but those with intermediate and small color difference cannot be read, the defect may be designated as medium; and if only the plates with the smallest color difference are confused, the defect is mild. This principle is illustrated in Figure A-3 with reference to the screening and quantitative red-green plates of the Tokyo Medical College. However, the ability of a given color-defective observer to read a set of plates depends not only on the observer's chromatic discriminative ability but also on how appropriate the selected confusion colors are for that observer.

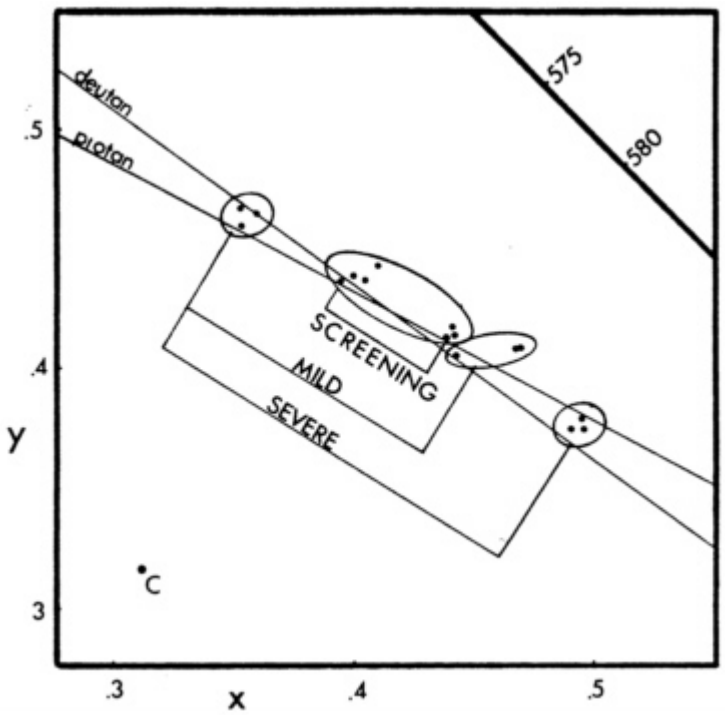

FIGURE A-3 Construction of "vanishing type" plate as applied to the Tokyo Medical College Test. Based on data from Lakowski (1969).

The second type of plate design is the qualitatively diagnostic type. It is an extension of the vanishing type, except that two clusters of colored dots are used to print two digits or symbols against a common background. For a red-green plate, one of the digits or symbols should be visible to the deuteranope and the other visible to the protanope. The inclusion of these plates theoretically allows the examiner to distinguish the different types of dichromats, but in practice this idea is not well realized. Figure A-4 illustrates this design with respect to plate number 13 of the diagnostic series in the AO HRR test.

The third type of plate design is the transformation plate. This is perhaps the most interesting and cleverly designed of the pseudoisochromatic plates. Both normal and defective observers can see a figure in the plate, but each identifies a different one. For example, on plate 5 of the Ishihara test (5th edition), the normal observer sees a "5" composed of yellow-green and light green dots on a background of light and dark orange and pink dots, whereas the red-green dichromat reports seeing a rather neutral "2" on a "warm" background of colored

dots. The design is accomplished by the strategic placement of colored dots that cluster in four locations on the chromaticity diagram, as shown in Figure A-5. For a normal observer, whose reference point for color is the position of Illuminant C, two of the clusters constitute the green figure and two constitute the orange background. The confusion lines for red-green dichromats, however, indicate that their reference point for color appears to be in the red-purple areas of the chromaticity diagram. The positions of the four clusters relative to the confusion lines show that half of the normal figure and half of the normal back- ground become the alternative "figure," and the other half of the figure and background become the "background" for the dichromat.

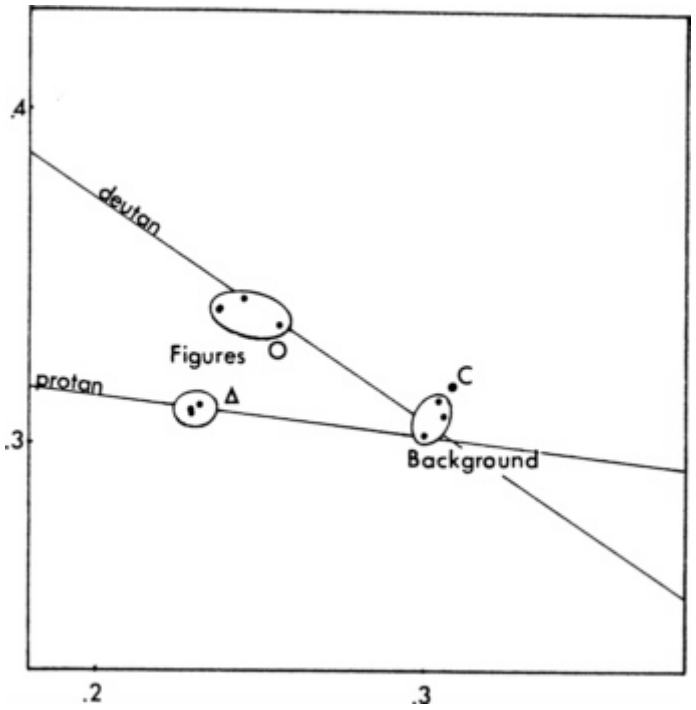

FIGURE A-4 Design of quantitatively diagnostic plate from AO H-R-R test (plate 13).
Source: Lakowski internal communication, Visual Lab., U.B.C., (1976).

The fourth type of plate design is the hidden-digit plate. Hidden-digit plates are designed so that dichromats, but not normal observers, can see the intended figure. In the previous three types of plates, colors for figure and background are separated by large color differences. This is not so in the hidden-digit plate, in which the use of three different colors and small variations in saturation prevent normal observers from seeing a figure but allow observers with

red-green color defects to do so. The latter perceive two color groupings that are distinct enough from each other to follow two separate isochromatic lines: the more saturated orange, khaki, and yellow-green dots form the background, and the less saturated pinks, grays, and greens form the figure. Figure A-6 shows the loci for colors used in plates 10 and 11 of the Ishihara plates (5th edition). The ability to read the hidden-digit plates (itself an error) depends on the degree of red-green defect; those whose defects are more severe read these plates more frequently. The ability of normal observers to read them seems to be a function of age. About half of the normal subjects between 20 and 30 years of age read hidden-digit plates easily, but these plates are hardly ever read by subjects over 50 or by young children.

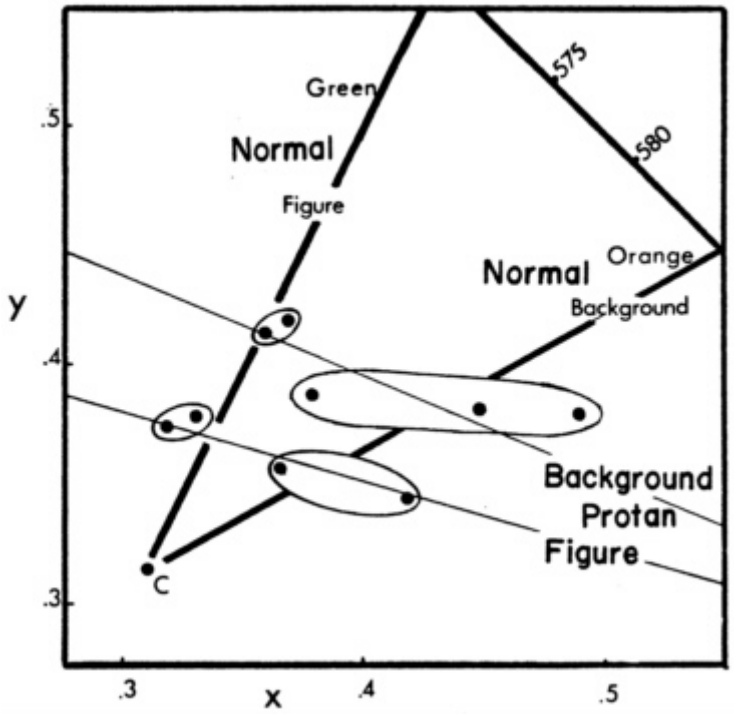

FIGURE A-5 Analysis of "transformation type" of plate from Ishihara, 5th edition (plate 5). Based on data from Lakowski (1969).

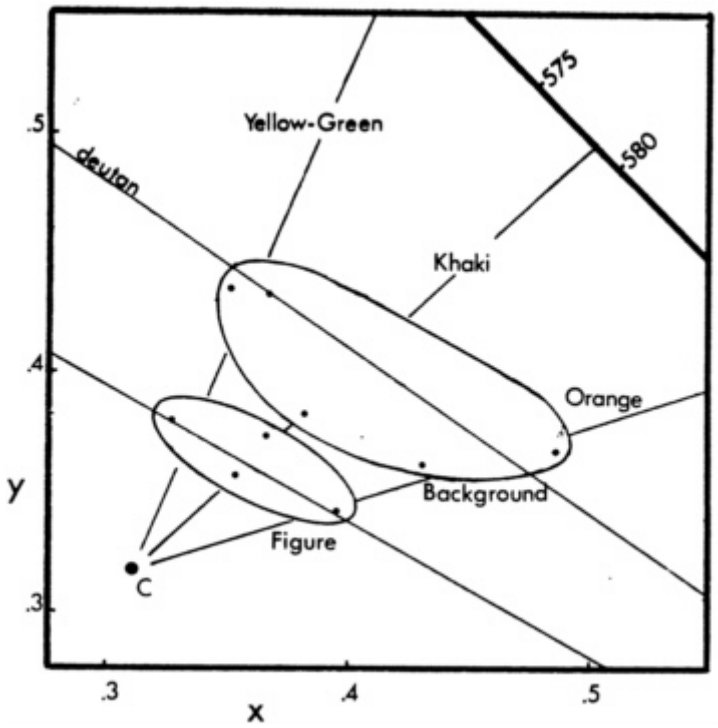

FIGURE A-6 Colorimetric data for "hidden-digit" plates from Ishihara, 5th edition (plates 10-11). Based on data from Lakowski (1969).

Arrangement Tests

Most modern arrangement tests use Munsell colors, the chromaticities of which can be displayed in the CIE chromaticity diagram. From this display we can predict the expected behavior of observer's with congenital color defects.

The chromaticities of the Farnsworth Panel D-15 are shown in Figure A-7 together with confusion lines of the deuteranope and protanope. Since the confusion lines connect pairs of caps that are identical or closely similar for a given dichromat, the expectation is that the protanope or deuteranope will make a characteristic arrangement of caps, connecting caps that oppose each other in the color circle but that lie on the appropriate confusion line. For protanopes a possible arrangement is:

P 15, 1, 14, 2, 13, 3, 12, 4, 11, 5, 10, 6, 9, 7, 8.

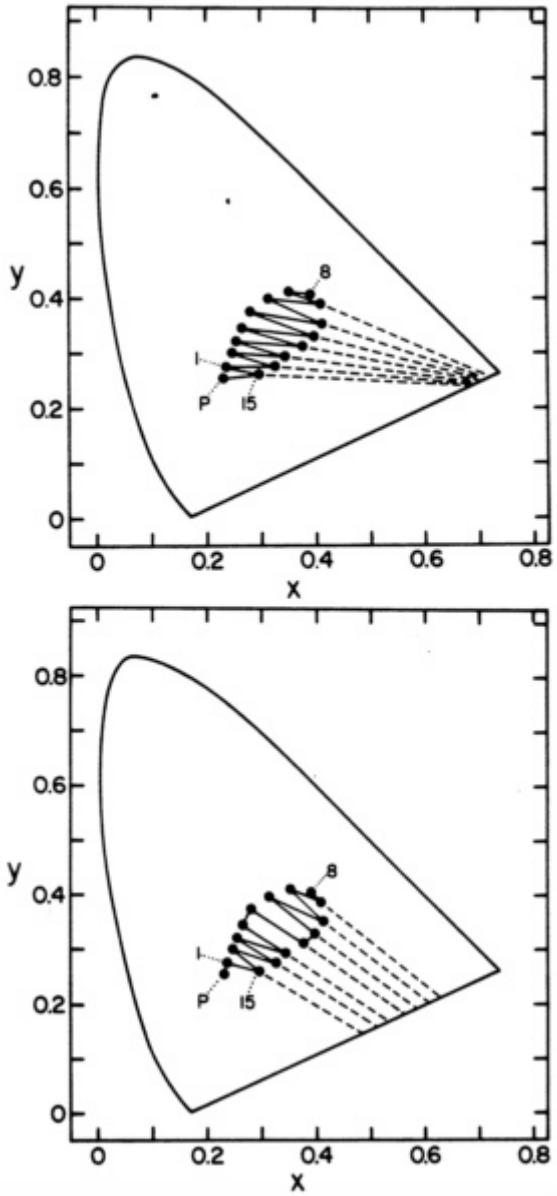

FIGURE A-7 Chromaticity coordinates of caps in the Farnsworth Panel D-15 Test. Confusion lines are indicated by dashed lines for protanopes (upper panel) and deuteranopes (lower panel). An expected cap arrangement is indicated by solid lines.
Figure prepared by Pokorny and Smith for this report.

For deuteranopes a possible arrangement is:

P, 1, 15, 2, 14, 3, 13, 4, 5, 13, 11, 6, 10, 7, 9, 8.

These major axes are indicated on the score sheet together with the axis for a tritanope. A fourth axis, that for the achromat, has also been defined (Sloan, 1954). A typical arrangement for an achromat is:

P, 1, 2, 3, 4, 5, 15, 16, 14, 13, 7, 12, 11, 8, 10, 9.

A similar analysis may be applied to the two arrangement tests designed by Lanthony.

Figure A-8 shows the position of the FM 100-hue test caps in the CIE diagram, together with confusion lines of protanopes and deuteranopes in the FM 100-hue test. For administration of the test, the boxes are presented one at a time, so that color confusions across the color circle are not allowed. The errors occur for locations where a confusion line is tangent to the color circle of the FM 100-hue test. The bipolar error axis that occurs on the FM 100-hue test is therefore orthogonal to the confusion axis. For example, the major confusion axis for the deuteranope is green and red-purple. On the FM 100-hue test, the errors occur at the orthogonal axis, namely, for yellow, yellow-red, blue, and purple-blue caps. Similarly, for the protanope, the major confusion axis is red and blue-green. Errors on the FM 100-hue test occur for yellow, green-yellow, purple-blue, and purple caps. This rotation of the error axis is clearly noted when Panel D-15 confusions and FM 100-hue test errors are plotted on the same diagram (Pinckers, 1971).

Anomaloscope

The experiment that became known as the Rayleigh equation was first described by Rayleigh (1881) and consisted of mixing monochromatic yellow-red with yellow-green to match a monochromatic yellow. He described three methods to obtain this equation--two involving spectral colors and one involving colored discs combined by a rotating prism. Nagel was the first one to use a direct vision spectroscope with spectral colors.

An apparatus such as Rayleigh's or Nagel's (or indeed any other kind of device with similar functions) is usually called an anomaloscope, that is, an instrument for specifying anomalous color vision. Today the anomaloscope is used as an instrument capable of measuring variations in color vision for normal, anomalous, and dichromatic observers, not only in the classic Rayleigh equation but also in other combinations of two lights to match a third. To fulfill such objectives the anomaloscope has to be validly designed, reliably administered, and the data obtained from it must be correctly quantified. The design of an anomaloscope depends on the choice of primaries used for the color mixtures, the areas that such a mixture will subtend at the retina, the level of luminance of mixture obtained,

and the ability to vary with ease the purity and luminance of the test field to which the mixture is being compared.

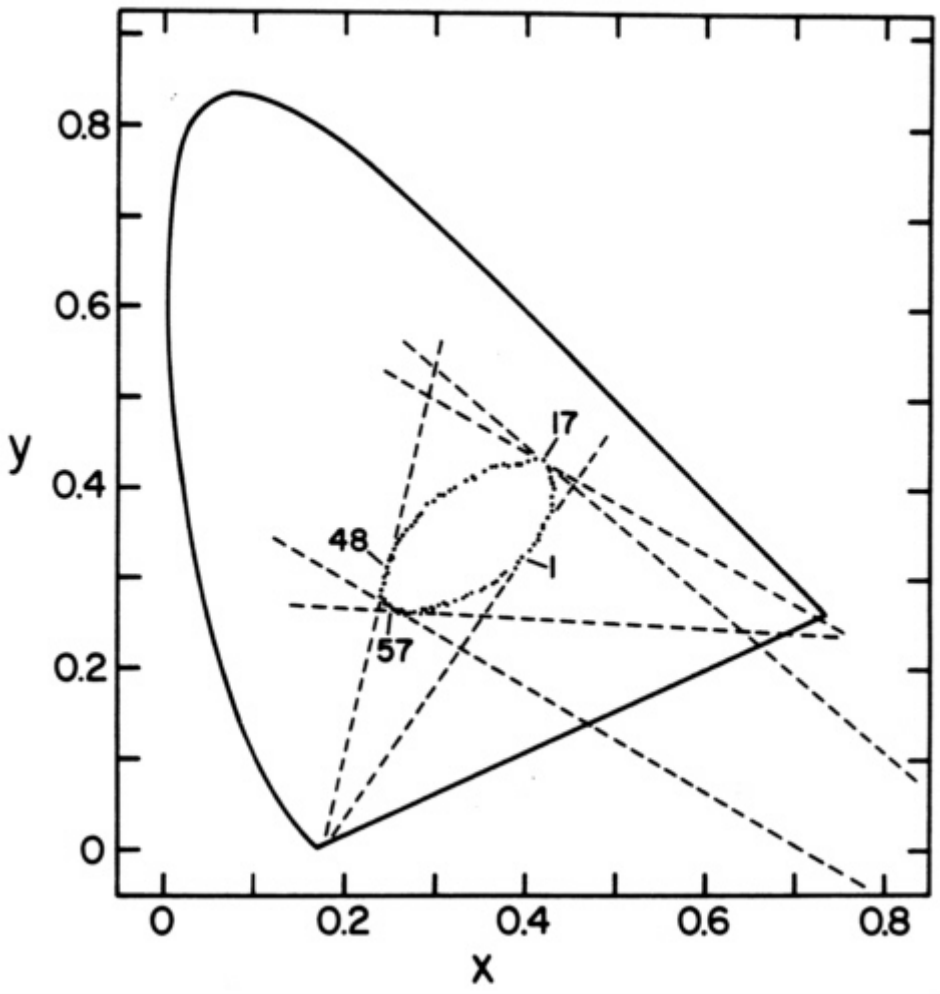

FIGURE A-8 Chromaticities for the 85 caps of the FM 100-hue test. Dashed lines indicate axes of confusion lines for color-defective observers.
Based on data from Lakowski (1969).

The choice of primaries for the Rayleigh equation has been well established, the main principle being that they ought to be chosen with the greatest separation in dominant wavelength between them. Thus in the Nagel Model II, the mixture field originally consisted of a red stimulus wavelength 671 nm (lithium line), and a green stimulus of

wavelength 536 nm (thallium line). However, for the Model I, a longer wavelength was chosen (546 nm, the mercury line). Chromaticities of primaries and the test color on the Nagel Model I are shown in Figure A-9. The primaries lie on the linear portion of the spectrum locus, and, thus, on the confusion lines of red-green dichromats.

The choice of primaries for the Engelking-Trendelenburg equation is not so well established. In the Nagel Model II anomaloscope, they are at 517 nm (for green) and at 470 nm (for indigo), while in the Pickford-Nicolson anomaloscope they are at 552.5 nm and 473.3 nm, respectively. Because neither of these pairs lies on isochromatic lines of tritanopes, desaturation of the blue-green test color is necessary in testing people with tritan defect. Normal observers also require differing amounts of desaturation. Because desaturation was not available on the Nagel Model II, the Engelking-Trendelenburg equation is rarely used.

The luminance of mixtures of primaries, especially at the most frequently chosen ratio, must be well above the threshold level for cone vision but preferably at the top of the mesopic range of vision, although the critical luminance will depend primarily on the size of the viewing aperture. The larger the subtense over 1.5° the higher will be the luminance necessary. In the Nagel and Pickford-Nicolson anomaloscopes, it is about 5 cd/m^2.

The choice of test wavelength varies among instruments but should correspond as nearly as possible to a region in which color discrimination is good. Thus for the Rayleigh equation the wavelength should be near 590 nm, while for the Engelking-Trendelenburg equation it should be near 490 nm. With the Nagel and the Pickford-Nicolson anomaloscopes, the dominant wavelengths for the yellow tests are at 589.3 nm (originally at the sodium line) and 584.3 nm, respectively; for blue-green tests they are at 490 nm and 493.5 nm, respectively.

Furthermore the luminance of the test yellow must be variable. For the Rayleigh equation, luminance variation is necessary to distinguish between protanopes and deuteranopes. The red primary appears dim to the protanope, and hence only a small amount of the yellow luminance is required for a match; a deuteranope, however, for whom the red field is as bright as it is for observers with normal vision, will require a correspondingly higher luminance in the standard yellow to match this primary. For the Engelking-Trendelenburg equation, it is important to vary the luminance of the standard blue-green to accommodate age changes in sensitivity and normal variation in ocular media.

The size of the stimulus field and its consequent subtense at the retina is also important. Anomaloscopes vary in the field size that is used, and the visual angle may vary considerably. In the Nagel Model I, the visual angle is fixed near 2°; in the Nagel Model II it can be varied between about 1.5° and 3°. Additionally, the manufacturer has supplied some Model I instruments that allow variation of field size. In the Pickford-Nicolson anomaloscope, at a viewing distance of one meter, the field varies from 0.5° to 3°, but a 1.5° field is most frequently used. Red-green dichromats do not accept the classic dichromatic matches when the field size extends to 8° (Smith and Pokorny, 1977; Nagy and Boynton, 1979). Thus the classification

of people with red-green defects may differ from instrument to instrument when the size of target varies appreciably.

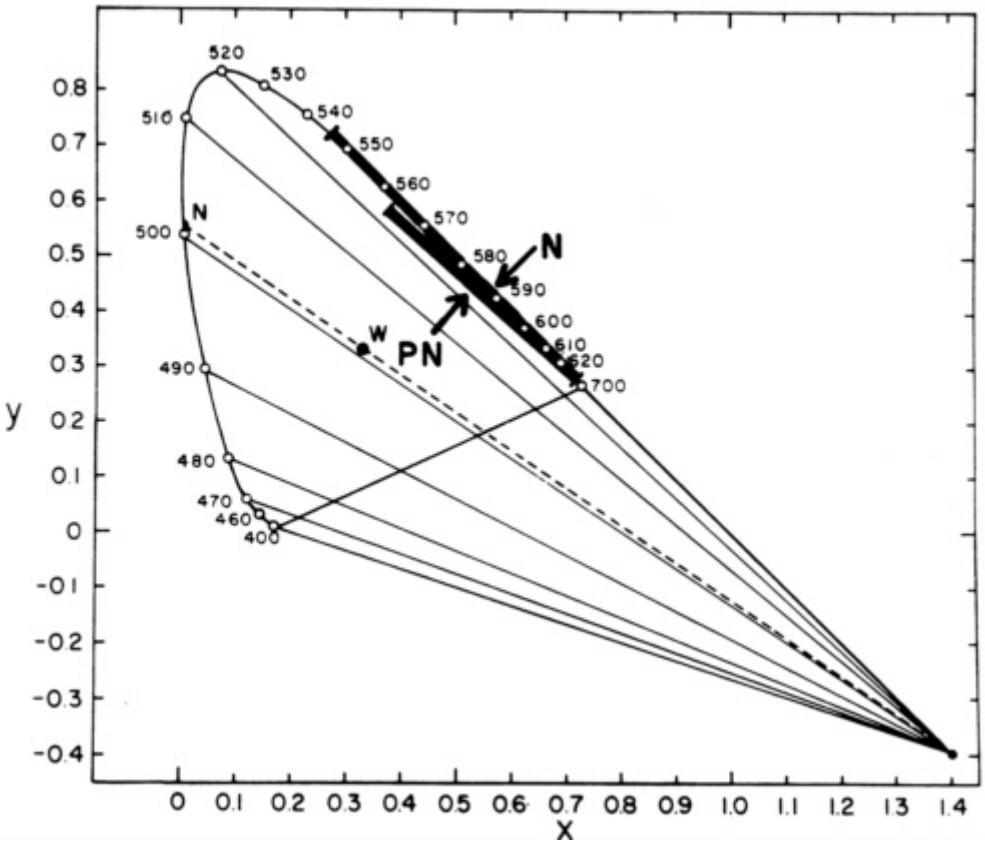

FIGURE A-9 Chromaticities for primaries and test colors on the Nagel Model I and the Pickford-Nicolson anomaloscopes.
Pokorny et al. (1979), by permission.

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