

Color Perceptions of Deuteranopic and Protanopic Observers

By Deane B. Judd

It is well established that about 2 percent of otherwise normal human males are confusers of red and green from birth. There is considerable interest in the question: What do red-green confusers see? From a knowledge of the normal color perceptions corresponding to deuteranopic and protanopic red and green, we may not only understand better why color-blindness tests sometimes fail, and so be in a position to develop improved tests, but also the color-deficient observer may understand better the nature of his color-confusions and be aided to avoid their consequences. If an observer has trichromatic vision over a portion of his total retinal area, and dichromatic vision over another portion, he may give valid testimony regarding the color perceptions characteristic of the particular form of dichromatic vision possessed by him. Preeminent among such observers are those born with one normal eye and one dichromatic eye. A review of the rather considerable literature on this subject shows that the color perceptions of both protanopic and deuteranopic observers are confined to two hues, yellow and blue, closely like those perceived under usual conditions in the spectrum at 575 and 470 $m\mu$, respectively, by normal observers. By combining this result with standard response functions recently derived (Bureau Research Paper RP1618) for protanopic and deuteranopic vision, it has been possible to give quantitative estimates of the color perceptions typical of these observers for the whole range of colors in the Munsell Book of Color. These estimates take the form of protanopic and deuteranopic Munsell notations, and by using them it is possible not only to arrange the Munsell papers in ways that presumably appear orderly to red-green confusing dichromats, but also to get immediately from the notations an accurate idea of the colors usually perceived in these arrangements by deuteranopes and protanopes, much as the ordinary Munsell notations serve to describe the visual color perceptions of a normal observer.

I. Introduction

The question, "What colors do color-blind observers confuse?" is a very practical one, capable of objective solution by putting each color-blind observer to trial and noting his mistakes. For the two most common forms of partially color-blind observers, deuteranopia and protanopia, each form comprising about 1 percent of the otherwise normal male population, a general answer, approximately valid for all observers properly so classed, has been found and described [51, 81].¹

The question, "What colors do color-blind observers see?" is a more subtle one, involving a fine point in the theory of knowledge, yet of considerable practical importance, too. Strictly

¹ Figures in brackets indicate the literature references at the end of this paper.

speaking, the subjective life of each observer cannot be known to anyone else, and there is no way of knowing whether the perception of red by one normal observer bears any resemblance to that which another normal observer calls by the same name. In this sense it is also impossible to discover what colors are seen by the partially color-blind. However, from the similarity in responses between normal observers, it is a fairly safe conclusion that their color perceptions are closely similar. In the same inductive sense, it is possible to discover how the color perceptions of the color-blind are related to those of the normal observer. It is one purpose of the present paper to review the evidence by which these are known. A second purpose is to give a comprehensive intertranslation between normal color perceptions of surface colors on the one hand and

protanopic and deuteranopic surface-color perceptions on the other.

The outstanding characteristic of protanopic and deuteranopic observers is that they confuse both red and green with gray, and indeed they confuse red with green. For this reason they are rightly called red-green confusers, less aptly red-green blind. Since to the normal eye red is nearly as distinct from green as black is from white, it may be deduced that red-green confusers fail to experience both the normal red and the normal green perception; but the deduction may not be pushed further. From a stimulus normally yielding red, a red-green confuser might perceive red or green or some other of the normal color perceptions, or some perception not normally experienced.

The impossibility of passing from knowledge of what colors are confused to knowledge of those that are seen by color-blind observers was recognized almost as soon as color-blindness was discovered. Thus we find Wilson [97] remarking in 1855, "It must be remembered, however, that there is no common language between the colour-blind and the colour-seeing." Then in 1880-81 Holmgren gave essentially the argument of the preceding two paragraphs in complete and clear detail and published it in four languages [39, 40, 42, 46]. Donders [15] in 1881 stated (p. 84), "If they (the color-blind) name their colors yellow and blue, this by no means proves that they see yellow and blue as we see them, but merely that in our yellow and blue their colors appear most characteristically." A year later v. Kries inserted the argument into his early analysis of visual sensations [60], "For bilateral color-blindness the facts are essentially different. Here is lacking the possibility of comparing directly normal and abnormal sensations with each other. The old statement that we cannot know what the color-blind really sense, self-explanatory as it is, appears, however, still not always to have been fully and completely understood."

These repeated and clear explanations did not, however, prevent Edridge-Green [19] in 1911 from giving a "proof" that red-green confusers see red and violet by means of precisely the same arguments previously used by Pole [82] to "prove" from observations with his own color-blind eyes that they see blue and yellow. These arguments are invalid in either case, as pointed out explicitly by Hartridge [27], but Pole's conjecture, for that

is all it was, was corroborated by later valid evidence. After having convinced himself (on insufficient ground) that his sensations were the same as what normal observers call yellow and blue, Pole put forward in 1856 an original, very practical suggestion (Roy. Soc., p. 176; Phil. Mag., p. 285) now in widespread daily use, namely, "It has been thought that the use of these colors (red and green) for railway and ship signals becomes dangerous where color-blind persons have to observe them. This danger may be obviated by very simple means—if the green be made a *blue* green at the same time that the red is a *yellow* red, they become quite as distinct to the color-blind as to the normal eyed." Present color specifications for marine and railway signaling pair a red slightly on the yellow side with a nonyellowish green, and this choice is also prevalent for stop and go signals for highway traffic. This plan has also been extended only recently by the American Standards Association [52] to the marking of industrial hazards.

The practical importance of inquiring into the color perceptions, in addition to the color confusions, of partially color-blind observers lies in the fact that resolution of this question facilitates consideration of precautions against the dangers of color-blindness and also aids in the design of tests for its detection. Thus Pole made his useful suggestion only after he had made a fortunate conjecture as to the connection between his color vision and those of the normal eyed. By this assumption he supplied himself with a terminology that immediately suggested the kind of red and green safe for railway and ship signals. It is the third purpose of this paper to develop a method of expressing the color-perceptions of the average red-green confuser in terms that are immediately comprehensible both to those trained in the interpretation of colorimetric coordinate systems and to the untrained alike. It is expected that this method will assist both normal observers and red-green-confusing observers to understand the relation between their two systems and so aid in avoiding the undesirable consequences of red-green confusion.

II. Review of the Literature

It has been pointed out by Holmgren [42], by v. Kries [62], and doubtless by many others, that

persons born with one normal eye and one color-blind eye give us our most direct evidence of the color perceptions of the color-blind. Less reliable evidence may be obtained from persons who confuse red and green because of diseases of the eyes or optic nerves, and who are therefore familiar with normal colors through past experience before becoming afflicted. And, finally, some information may be obtained from the peripheral parts of the normal retina that respond with confusions similar to those of deuteranopia. Any observer, a portion of whose retinas yields normal color vision while another portion yields either the kind of red-green confusion characteristic of protanopia or that characteristic of deuteranopia, can give valid testimony.

It is now a fairly well accepted view that red-green confusers see neutral colors (black, gray, white, silver, "colorless" and so on) normally, and chromatic colors of two hues, approximately what normal observers call pure yellow and pure blue [14], with little or no admixture of red and green. Evidence obtained from all three types of admissible observers consistently supports this view. We shall, however, review the literature to see whether this rough indication can be made more precise.

1. Peripheral Parts of the Normal Retina

It has been widely stated in textbooks for many years that there is, in the normal eye, a retinal zone of considerable extent (perhaps 20° to 50° from the fovea centralis) within which yellow, blue, black, and white are perceived much as at the fovea, but red-green distinctions are scarcely, if at all, possible. Since the luminosity function of this region in a light-adapted state is substantially the same as normal [30, 61, 68 (p. 46)], the properties of this retinal zone near the periphery approach those of deuteranopia, the distinctions from deuteranopia being reduced visual acuity, reduced ability to distinguish both black from white, and yellow from blue, and presence of a slight, instead of vanishing, ability to distinguish red from green. As a preliminary observation will immediately show, the precise hues of the yellowish and bluish colors seen by means of this retinal zone are hard to determine. A spectrum stimulus yielding a color of orange hue by foveal vision yields a progression of less and less reddish hues as it is moved more toward the periphery.

There are determinable for each observer, however, within certain limits the wavelengths of the spectrum stimuli yielding colors of invariable hue regardless of retinal region stimulated. It is obvious that the hues of the bluish and yellowish colors perceived by the nearly deuteranopic peripheral region are to be found among these invariable hues. Table 1 is extracted from a summary by Tschermak [95] and shows results of four investigators. As might be expected from the difficult nature of the observations and the many factors influencing the results [17; 69, p. 273], there is considerable difference between the reports of the various investigators. Goldmann's results refer to a protanomalous observer [24] and on this account have less weight than the others. Some observers can make such observations with good reliability (Hess, 2 to 3 m μ uncertainty), others less certainly (Dreher, 10 m μ uncertainty); and there is furthermore a large individual difference (40-m μ spread among Dreher's three observers). Although Hess' results refer to one observer only (himself), they are probably as good as any, and have, at least, been the most widely quoted [30]. These results indicate the deuteranopic yellow to be a hue corresponding, for normal vision under visual conditions, to about 575 m μ ; and deuteranopic blue to be that corresponding to about 470 m μ , with uncertainties of about 10 m μ .

TABLE 1. Stimuli that yield bluish or yellowish colors of invariable hue, regardless of retinal region affected

Author	Year	Wavelength of spectrum stimulus yielding invariable hue, regardless of retinal region	
		Yellowish	Bluish
		m μ	m μ
Hess [33].....	1980	574.5	471
Baird [4].....	1905	570	460
Dreher [17].....	1912	568	461
Goldmann [26].....	1925	567	466

2. Red-Green Confusion Acquired Through Disease

Toxic agents and disease affecting the conducting (transmissive) elements of the optical apparatus (nerve elements and connections, optic nerve, and tract) cause a progressive lessening of the ability to distinguish red from green. This

defect becomes progressively worse until red-green blindness is reached, which is distinguished from inherited deuteranopia chiefly by its poorer light-dark discrimination. There is also some lessening of the ability to distinguish yellow from blue, which may progress until total color-blindness results [59, p. 141; 68, p. 45]. The luminosity function is essentially the same as for normal vision [57], and white, gray, and black are perceived in a relatively normal way. Köllner [59, p. 148] says, "In the dichromatic state the patient sees in the spectrum only yellow and blue, and the yellow corresponds to the hue which is elicited in the normal eye by light of wavelength 575 m μ , the blue to the hue corresponding to that of wavelength 471 m μ ." These facts, like those of peripheral vision by the normal eye, indicate that the deuteranopic observer sees a yellow like that corresponding to about 575 m μ for the normal observer, and a blue corresponding to about 470 m μ .

3. Unilateral Red-Green Blindness

Unilateral inherited defects of vision are probably much more common than would be supposed from accounts of such cases appearing in the literature. An Army physician observed in 1920 [5], "It has been recently discovered that because a man has excellent color vision in one eye he does not necessarily have it in the other." And a recent estimate [66] places the incidence of unilateral defects at about 4 percent of the total color defectives. Since, however, color vision of both eyes is most frequently tested at the same time, it follows that most unilateral defects go unnoticed [58, 66, 88]. Table 2 lists chronologically all cases of unilateral defects in color vision that could be uncovered by a reasonable search of the literature. There are 40 original articles listed involving 37 cases, a case of unilateral protanopia being dealt with twice by Hippel [36, 37] and once by Holmgren [42], a case of unilateral tritanopia being dealt with both by Kirschmann [54] and by Dieter [13], a case of unilateral deuteranomaly both by v. Kries [62] and by Trendelenburg [94] and one article by Bonner [101] mentioning two cases previously unreported.

It should be noted that the skill and resources of the several investigators varied over a wide range, so that both the type of defect for the

TABLE 2. *Unilateral defects of color vision*

Author	Date	Probable cause of defect	Type of defect
v. Baumgartner [6]	1858	Blow on eye.....	Temporary achromatopsia.
Brische [11]	1862	Attack of vertigo.....	Temporary cyanopsia.
Nemeschöck [77]	1868	Skull-bone degeneration.	Tritanopia and chloropsia.
Woinow [98]	1871	Noticed after head-wound, but perhaps inherited.	Atypical, red phobia.
Becker [7]	1879	Inherited.....	Acromatopsia.
Hippel [36]	1880	.....do.....	Protanopia.
Holmgren [42]	1881	.....do.....	Do.
Hippel [37]	1881	.....do.....	Do.
Holmgren [44]	1881	.....do.....	Tritanopia.
Steffan [90]	1881	Apoplexy.....	Approach to achromatopsia.
Snell [89]	1891	Skull fracture.....	Protanopia, deuteranomaly.
Hermann [32]	1892	Unknown.....	Tritanopia.
Kolbe [56]	1892	Inherited.....	Red-green weakness.
Schneidert [86]	1892	.....do.....	Red-brown confusion.
Donders [16]	1894	.....do.....	Abnormal Rayleigh equation.
E d r i d g e - Green [19]	1899	Probably retinitis.....	Tritanopia, yellow-blue weakness.
Hering [31]	1900	Optic-nerve atrophy.....	Approach to deuteranopia.
Hess [34]	1900	Nerve injury.....	Do.
Snell [89]	1902	Noticed after blow on head, but perhaps inherited.	Deuteranopia.
Kirschmann [54]	1903	Inherited.....	Tritanopia.
Hilbert [33]	1904	.....do.....	Slight abnormalities.
Beaver [8]	1904	Nerve injury.....	Achromatopsia.
Piper [80]	1905	.....do.....	Achromatopsia, tritanopia.
Samojloff [85]	1906	Inherited.....	Abnormal Rayleigh equation.
Köllner [57]	1909	Optic-nerve atrophy.....	Achromatopsia, tritanopia.
Hayes [28]	1911	Inherited.....	Protanomaly.
Egner [29]	1913	.....do.....	Do.
Lehtman [65]	1917	.....do.....	Abnormal contrast effects.
v. Kries [62]	1919	.....do.....	Deuteranomaly.
Goldschmidt [26]	1919	Gunshot headwound.....	Protanomaly.
Bonner [10]	1923	Optic atrophy (tuberculous).	Green weakness.
Jennings [48]	1925	Noticed after blow on head, but perhaps inherited.	Red-green blindness.
Bonner [11]	1926	Unknown.....	Achromatopsia.
	1926	.....do.....	Red-green blindness.
Dieter [13]	1927	Inherited.....	Tritanopia.
Miles, Beaumont [66]	1931	Unknown.....	Red-green blindness.
Miles, Craig [67]	1931	.....do.....	Do.
Neipperg [75]	1932	Inherited.....	Do.
Trendelenburg [94]	1941	.....do.....	Deuteranomaly.
Sloan [87]	1947	.....do.....	Deuteranopia.

defective eye and the degree of approach to the norm in cases having one supposedly normal eye are subject to various degrees of doubt. Similarly, in many cases the report of the probable cause of the defect is based on very incomplete data. If there were no evidence of disease or

injury, the defect is listed as probably inherited. In one case, however, it is known definitely that the defect was inherited; the subject found by v. Kries to have unilateral deuteranomaly was found later [94] to have transmitted a bilateral deuteranomaly defect to his daughter. Table 2 is intended to give brief summaries of all cases of unilateral defects of color vision, and the information is as precise as can be given in a few words; but these summaries are, of course, often unsatisfactory substitutes for the original articles that should be consulted if more detailed information is desired.

Since many of these cases are to be neglected as having no bearing on the color perceptions of protanopic and deuteranopic observers, it is convenient to introduce here the definitions of the terms by which the type of defect has been indicated in table 2.

Trichromatism—a type of vision in which the colors seen require in general three independently adjustable primaries (such as red, green, and blue) for their duplication by mixture. Normal vision is one form of trichromatism.

Dichromatism—a type of vision in which the colors seen require in general two independently adjustable primaries (such as red and green, or purple and yellow) for their duplication by mixture.

Monochromatism—a type of vision in which the colors seen require only a single adjustable primary to match them. Any light may serve as the primary.

Protanomaly—a type of trichromatism in which the relative luminosity function is too low at the longwave end to fall within normal limits, and in which an abnormally large proportion of red in a red-green mixture is required to match a given yellow.

Deuteranomaly—a type of trichromatism in which the relative luminosity function falls within normal limits and in which an abnormally large proportion of green is required in a red-green mixture to match a given yellow.

Protanopia—a type of dichromatism in which red and blue-green are confused, but no abnormal proportion of red plus green is required to match a given yellow, and the relative luminosity function is too low at the longwave end to fall within normal limits.

Deuteranopia—a type of dichromatism in which

purplish red and green are confused, but no abnormal proportion of red and green is required to match a given yellow, and the relative luminosity function falls within normal limits.

Tritanopia—a type of dichromatism in which reddish blue and greenish yellow are confused.

Achromatopsia—a type of monochromatism in which all colors are perceived as neutral (such as black, gray, and white).

Chloropsia—green vision.

Cyanopsia—blue vision.

Rayleigh [83] equation—the proportions of red and green required in a mixture to match a given yellow. Usually spectrum red (670 m μ) is mixed with spectrum green (535 m μ) in such proportions as to match spectrum yellow (589 m μ).

It would seem that only cases of protanopia and deuteranopia listed in table 2 need be considered, but it has often been noted [28, 62 (p. 148), 74] that under unfavorable conditions (such as small angular extent of observing field, reduced observing time [29], low field luminance, or dark surrounding field) protanomalous and deuteranomalous observers make the same mistakes as protanopes and deuteranopes, and respond as if they had dichromatic rather than trichromatic visual systems (rod-green confusion, presence of a neutral point in the spectrum near 495 m μ , and so on). On this account, many color-perception tests fail to differentiate red-green confusers into groups of dichromats and trichromats. It is possible therefore to obtain information concerning the color perceptions characteristic of dichromatic visual systems from unilateral protanomaly and unilateral deuteranomaly, provided attention is paid to observations obtained by such observers under conditions that reduce these systems to, or nearly to, dichromatism. Table 3 lists all unilateral cases from which information regarding protanopic and deuteranopic color perceptions can be gleaned. It also includes a bilateral case reported by Nagel [72], which has a bearing on deuteranopic color perception. In this case the fovea was dichromatic, the periphery trichromatic, quite beyond the vestigial trace often reported by dichromats. Cases of unilateral achromatopsia and tritanopia listed in table 2 have been omitted, together with those of red-green confusion not giving information regarding color perceptions (Snell,

Kolbe, Shufeldt, Hegner, Lohmann, Jennings, Neippert, Bonner, and Miles and Beaumont). Cases of slight abnormality not approaching dichromatism are also omitted (Donders, Hilbert, Samojloff).

The case of atypical unilateral sense disturbance reported by Woinow [98] has been omitted, because the report is contradictory. The subject was reported to be deuteranopic (green blind) in one eye, and measurements by rotating sector disks indicated confusion of both red and green with gray. There was, however, hysterical fear of red particularly from the eye which, as we have seen, under some conditions could not distinguish red from gray. Furthermore, all objects seen by this eye were tinged with red, but spectrum yellow appeared blue. There is no evidence, except this latter rather confusing report, that the color system of the defective eye was dichromatic; it might have been monochromatic. Reports of the subject in other sense fields (taste, temperature, smell, hearing) indicated a profound psychic disturbance.

The case of temporary cyanopsia reported by Brische has also been omitted; the visual system seems to have been monochromatism, black, gray, and white objects, and all parts of the spectrum, appearing blue.

In table 3 the indicated perceptions are specified in many cases simply by color name, and we see, as before, that unilateral defects of vision indicate that the protanopic and deuteranopic perception of white is normal, and those of hue are some kind of a yellow and some kind of a blue. In other cases these indications have been made more exact by direct comparison of the spectrum colors viewed by the defective eye with those of the same spectrum viewed by the normal eye. Orange, for example, is seen as yellow by the dichromatic eye, as is also yellow green; but the part of the spectrum whose hue is the same for both the normal and the defective eye serves as a specification for the particular kind of yellow sensed by the dichromatic eye; that is, we can say from such evidence that the dichromatic yellow is like that perceived at some certain portion of the spectrum by the normal eye. Five of the entries in table 3 are of this nature. Four out of five of these entries refer to subjects who had in the defective eye slight, rather than vanishing, ability to distinguish red from green, but reports of hue difference between the

two eyes could still be made and the spectral region yielding the same hue for both eyes determined. In general, it will be noted that for both the deuteranopic and protanopic forms the yellow is closely like that of the spectrum at 575 $m\mu$ to the normal eye, and the blue like that of 470 $m\mu$. This agrees with indications for the deuteranopic form obtained from the periphery of the normal retina and from acquired bilateral color-blindness.

The three exceptions to this generalization are, first, the wavelength 589 $m\mu$ found by Hippel for his unilaterally color-blind observer; second, the designation, orange-yellow, shown for Goldschmidt's case of unilateral protanomaly; and third, the contradictory report by Sloan's unilateral deuteranope. The first two exceptions suggest that some protanopes, at least, see orange-yellow instead of the slightly greenish yellow of 575 $m\mu$. Hippel, however, depended on the observation of flame spectra under the unfavorable condition of a dark background and did not report tests of any yellowish spectrum color other than 589 $m\mu$ (that is, none nearer than this to 575 $m\mu$), so his finding may merely be an imprecise check of 575 $m\mu$. Furthermore, the report of orange-yellow is rendered doubtful by the report by Holmgren of greenish yellow ("greenish yellow, or citron yellow, not golden yellow") for the same case [42] examined by means of dyed wools. In the second exception, it was stated [26] rather inexplicitly that for the defective eye, "the green appeared in the spectrum stretched out into the yellow, and the blue stretched out into the violet, . . ." Neither of these reports can be taken as established exceptions to the otherwise consistent indication that the yellow and blue of red-green confusers are, respectively, closely what the normal eye sees in the spectral regions near 575 and 470 $m\mu$.²

Some writers [28] have classified the Hering and Hess cases as probably protanomaly because of

² Since the indicated perceptions for both protanopic and deuteranopic vision are not significantly different, no extended discussion of discrepancies in classification of the unilateral defects shown in table 3 is required. For the same reason, it is unimportant for the present purpose to determine whether the defect is inherited or acquired. However, it may be remarked that the classification by Hippel of his patient as what we now call deuteranopic rests on his failure to find the spectrum shortened on the long-wave end relative to that for the normal eye, all of the various spectral emission lines used being either visible to both eyes or invisible to both. The classification of protanopia, however, is firmly grounded not only on Holmgren's finding based upon the Holmgren wool test, which includes a chromaticity method of diagnosing protanopia, but also on Hippel's own report that the brightest part of the spectrum for the defective eye was shifted considerably toward the short-wave end relative to that for the normal eye.

the statement that the long-wave end of the spectrum was shortened. This minor shortening is to be expected because of the partial impairment of the yellow-blue and light-dark senses, as well as the almost complete disappearance of the red-green sense. It is not to be confused [68, (p. 45)] with the much larger departure from normal characteristic of protanopia, designated by Hering as "blue-sighted red-green blindness."

The reclassification of Hayes' subject from protanopia to protanomaly is based upon the fact that the normal setting of a red plus a green by disk mixture to match a yellow plus black plus white was found by the subject's defective eye to be much too green. To satisfy the defective eye, she had to put by far more red in the first mixture. Hayes' conclusions are sound if translated into accepted terminology.

A further word is required regarding the apparently contradictory report by Sloan's unilateral deuteranope [87] that, on the one hand, the hues seen are like Munsell 5Y 5/5 (dominant wavelength 575 $m\mu$) and 3PB 5/5 (dominant wavelength 478 $m\mu$), and that, on the other they are like the spectrum at 584 and 452 $m\mu$. There are several possibilities to be explored, but it will be sufficient for the present to point out that if both eyes of this subject had an abnormally large amount of ocular pigmentation and so were provided with a permanent adaptation to reddish yellow, the discrepancy would be explained. The same explanation would also account for the discrepancy between the wavelength of neutral point estimated from the Munsell 5/5 locus (498 $m\mu$, which is typical of deuteranopia [50, 51]) and that estimated directly from the spectrum (503 $m\mu$, corresponding to reddish yellow adaptation). A more complete study of this observer might be worth while.

III. Agreement with Theories of Color Vision

The evidence just reviewed that red-green confusers see yellow and blue does not, of course, prove that all red-green confusers have those color perceptions, though the absence of reliable conflicting evidence renders such a conclusion highly probable. Thus, Parsons [79, p. 191] remarked in 1924, "Most observers think that the two sensations experienced (by protanopes and deuteranopes) correspond most closely to normal yellow and blue. Uncomplicated cases of uni-

lateral congenital colour blindness would afford valuable evidence . . .". Similarly, in 1927, Dieter [13, p. 79] said, "Only if still more cases of the same kind are completely analysed will there be sufficient ground for the alluring possibility of theoretical appraisal." Unilateral color-blindness, however, has already had an important influence on color theory.

During the period (1880-1920) when the experimental facts of protanopic and deuteranopic color perceptions were being established, the controversy between the three-components (Young-Helmholtz) theory of color vision and opponent-colors (Hering) theory reached its height [64].

According to the three-components theory, there are in the normal retina three independent photosensitive mechanisms, one sensitive preponderantly to the long-wave portion of the spectrum and yielding a red response, another sensitive preponderantly to the middle portion of the spectrum and yielding a green response, and the third sensitive preponderantly to the short-wave portion of the spectrum and yielding a blue or violet response.

According to the opponent-colors theory, there are in the normal visual mechanism three pairs of opposing processes, a black-white pair, which cancels to leave gray, and two chromatic pairs, blue-yellow, and red-green, which cancel to gray when both members of the pair are excited equally.

Red-green blindness according to the three-components theory comes from failure of either the red-component (protanopia) or the green-component (deuteranopia), leading to the indication that protanopes must see only mixtures of green and violet, and deuteranopes, only mixtures of red and violet. But, by the opponent-colors theory, only one type of red-green blindness is to be expected, that arising from elimination of the red-green process, leaving the perceptions white and black, blue and yellow.

The case of unilateral protanopia (Hippel, Holmgren, table 3) was a blow to the original form of three-components theory. It showed that one red-green blind eye, at least, saw yellow and blue, not green and violet. The three-components theory can be thrown into a form accounting both conveniently and precisely for the red-green confusions of protanopes and deuteranopes [51], but this single case of unilateral color-blindness showed that it is not a reliable guide to what they

TABLE 3. Cases of unilateral defect of vision-giving information regarding protanopic and deuteranopic color perceptions

Author	Date	Classification of the defect		Indicated perceptions	
		Author's own	Present		
Hippel [30]	1860	Deuteranopia	Protanopia	Yellow	Blue
Holmgren [42]	1881	Protanopia	do	Greenish yellow	Violet blue
Hippel [37]	1881	Deuteranopia	do	Like 589 μ	Blue
Hering [31]	1890	Approach to deuteranopia	Approach to deuteranopia	Yellow	Do
Hess [34]	1890	do	do	Like 575 μ	Like 471 m μ
Nagel [72]	1905	Deuteranopia	Deuteranopia	Yellow	Blue
Hayes [28]	1911	Protanopia	Protanomaly	do	Do
v. Kries [32]	1919	Deuteranomaly	Deuteranomaly	Like 573 μ	Like 464 to 480 m μ
Goldschmidt [25]	1919	Protanomaly	Protanomaly	Orange, yellow	Blue
Bloan [57]	1947	Deuteranopia	Deuteranopia	Like 5 Y 5/5, also 584 m μ	Like 3PB, 5/5, also 452 m μ

see. The opponent-colors theory, on the other hand, received dramatic support from the color perceptions reported for this case. This latter theory, however, does not account for two forms of red-green blindness, but only one, deuteranopia.

It may be said, therefore, that both of these simple visual theories received fatal blows from discovery of the facts of protanopia and deuteranopia. Some advocates of the three-components theory refused to be impressed by the Hippel-Holmgren case of unilateral protanopia. Holmgren, himself, continued to use the terms, "red blind", "green blind" and "violet blind", and offered a prize of 400 crowns to anyone who would bring to his attention a case of unilateral "green blindness" [45]. Some three-component advocates took refuge in Fick's [21, 22] suggestion that red-green blindness results, not from the complete failure of one of the three components, the red or the green, but from the receptors for red and green having identical photo-sensitive substances, either that normally used for red or that normally used for green. Other advocates of the three-components theory (König, v. Kries) eventually took up the very similar theoretical position [54a, 60 (p. 169)] originally proposed by Donders [15] that the three-components theory holds for processes in one stage or zone of the visual mechanism (perhaps the photosensitive substances), whereas the opponent-colors theory holds for processes in a later stage or zone (perhaps the optic nerve). This view is known as the zone or stage theory of vision. Furthermore, a very able advocate of the opponent-colors theory, G. E. Müller, adopted a theoretical view which, although divergent in detail and more elaborated, was essentially in

agreement with the zone theories favored by Donders, König, and v. Kries. All of these theories allow for protanopic and deuteranopic perception of yellow and blue, though that of Müller does not require it for protanopes. Müller remarks (p. 49), "If the color-blind is a deuteranope, his chromatic color sensations must therefore (by this theory) be pure yellow and pure blue It is otherwise with protanopes. If in an individual outer red-green sensitivity is absent, it makes no difference in his behavior, either in practical living or in any investigation, whether the remaining greenish-yellow and reddish-blue processes excite only yellow and blue in the optic nerve, or whether, . . . , they excite greenish-yellow or reddish-blue sensations, or whether, . . . they excite only green and red, or . . . even only green and blue, or . . . yellow and red. An individual lacking outer red-green sensitivity will give exactly the same color equations, exactly the same spectral positions of brightness maximum and neutral point regardless of whether his greenish yellow and reddish blue processes evoke nerve excitations corresponding to the like-named excitations (yellow and blue) or unlike-named excitations (green and red), or by simultaneous action of both sorts, excitations of exactly the same kind as the processes themselves. We would therefore not be particularly astonished if it were established definitely in a unilateral case of protanopia that the yellow sensation experienced actually was somewhat greenish and that the blue sensation experienced actually was somewhat reddish, and we would not believe that the ground was disappearing under our feet if sometime there should occur a (quite improbable) case establishing

the two chromatic color sensations of a protanopic eye as the pure-green sensation and the pure-red sensation."

Since all theories of vision with any pretense of being complete provide for the perception of yellow and blue by red-green confusers, and since a reasonable search of the literature has failed to uncover any reliable evidence against this indication, it is proposed to build a method of designating protanopic and deuteranopic perceptions of surface colors on the finding that such observers see a yellow and a blue like those seen by the normal observer in the spectrum near 575 and 470 m μ , respectively. The consequences of this choice of hues are bound to appear correct to binocular red-green confusers. These consequences can be contradicted only by observers having unilateral defects; and the probability of such contradiction arising may be estimated from the fact that the eight cases recorded so far (see table 3) fail to contradict it.

IV. Derivation of Deuteranopic and Protanopic Munsell Notations

Object-color perceptions by normal observers are most commonly described in terms of the attributes, hue, lightness, and saturation [78] defined [2] as follows:

"Hue is the attribute which determines whether the color perception is red, yellow, green, blue, purple, or the like.

"Lightness is the attribute which permits an object-color perception to be classified as equivalent to some member of the series of grays ranging between black and white.

"Saturation is the attribute of an object-color perception which determines the degree of its difference from the gray of the same lightness."

The Munsell color system is based upon this method of description. Munsell hue, value, and chroma are intended to correspond to hue, lightness, and saturation, respectively, and the samples in the Munsell Book of Color [70] when viewed in daylight by a normal observer under usual viewing conditions (daylight adapted eye, light to medium-gray surrounding field) yield color perceptions such that Munsell hue correlates closely with the perceived hue, Munsell value with the perceived lightness, and Munsell chroma with the perceived saturation. A method has been developed [49] by means of which readily understood color names

may be found for any color from its Munsell notation.

When the samples of the Munsell Book of Color are viewed by a protanopic or a deuteranopic observer, however, the color perceptions obtained are not even approximately indicated by the Munsell notation. It is proposed to develop a method of deriving protanopic and deuteranopic Munsell notations, analogous to the present normal Munsell notations, that will correlate with the color-perceptions that red-green-blind observers obtain from objects viewed in daylight under usual conditions. It has been shown [51] that the color confusions of red-green-blind observers can be found from three numbers (K , W_p , W_d) related to the tristimulus values (X , Y , Z) of the ICI standard observer by the transformation equations:

$$\left. \begin{aligned} K &= Z, \\ W_p &= -0.460 X + 1.359 Y + 0.101 Z, \\ W_d &= Y. \end{aligned} \right\} \quad (1)$$

Any two colors having identical values of K and W_p are identical to the average protanope; those having identical values of K and W_d are identical to the average deuteranope. Figure 1 shows in arbitrary units the values of K , W_p , and W_d for all parts of a spectrum of unit irradiance per unit wavelength.

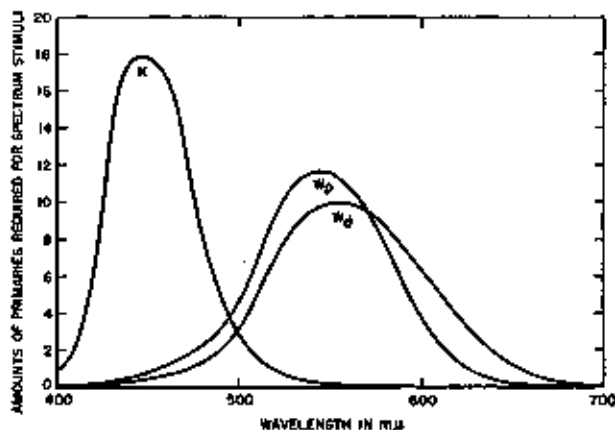


FIGURE 1

One of each of the two pairs of numbers (W_d , W_p), used in judging equivalence of colors for deuteranopic and protanopic observers, refers to the luminous aspect of the color (luminance for a self-luminous area, luminous directional reflect-

ance for a surface), the other number, K , of each pair taken relative to the first refers to the chromatic aspect. For the ICI observer, luminous directional reflectance is customarily expressed relative to that (Y_0) of magnesium oxide. By analogy we take $W_d/(W_d)_0 = Y/Y_0$ for deuteranopic luminous directional reflectance, and

$$\frac{W_p}{(W_p)_0} = \frac{-0.460X + 1.359Y + 0.101Z}{-0.460X_0 + 1.359Y_0 + 0.101Z_0}$$

for protanopic luminous directional reflectance. But since for magnesium oxide it is customary to take $X_0 = 0.9804$, $Y_0 = 1.0000$, and $Z_0 = 1.1512$, protanopic luminous directional reflectance may be written simply as $0.9733W_p$.

It is customary to specify the chromatic aspect of a color for the ICI standard observer by means of trichromatic coordinates, or chromaticity coordinates x , y , and z . By analogy with this practice, the chromaticity coordinates for deuteranopic and protanopic observers are the dichromatic coordinates (w_d , k_d ; w_p , k_p) defined as follows:

$$\left. \begin{aligned} w_d &= W_d/(W_d + K) = \frac{Y/(Y+Z)}{Y/(Y+Z) + Z/(Y+Z)} = \frac{y/(y+z)}{y/(y+z) + z/(y+z)} = \frac{y}{1-x}, \\ k_d &= K/(W_d + K) = \frac{Z/(Y+Z)}{Y/(Y+Z) + Z/(Y+Z)} = \frac{z/(y+z)}{y/(y+z) + z/(y+z)} = \frac{z}{1-x}. \end{aligned} \right\} (2d)$$

$$\left. \begin{aligned} w_p &= \frac{W_p}{W_p + K} = \frac{-0.460X + 1.359Y + 0.101Z}{-0.460X + 1.359Y + 1.101Z} \\ &= \frac{-0.561x + 1.258y + 0.101}{-1.561x + 0.258y + 1.101}, \\ k_p &= \frac{K}{W_p + K} = \frac{Z}{-0.460X + 1.359Y + 1.101Z} \\ &= \frac{1.000 - x - y}{-1.561x + 0.258y + 1.101}. \end{aligned} \right\} (2p)$$

From eq 2d and 2p it will be noted that w_p and k_p sum to unity; likewise, w_d and k_d . Hence only one of the dichromatic chromaticity coordinates need be used. We will use w_d and w_p , which may be taken as measures of the deuteranopic and protanopic "warm" quality, respectively. According to the data and views already summarized in sections II and III, it is legitimate to take them more precisely as indications of "yellowness."

Since for the approximately 400 samples of the Munsell Book of Color, the tristimulus values, X , Y , Z , have already been evaluated from spectrophotometric measurements [23, 53], it is

a simple matter to compute $W_d/(W_d)_0$ and w_d from eq 1 and 2d, and so arrive at a specification of deuteranopic luminous directional reflectance and chromaticity. The results are shown in table 4. Similarly there have been computed for these 400 samples values of $W_p/(W_p)_0$ and w_p , which serve as specifications of protanopic luminous directional reflectance and chromaticity, respectively. These results are shown in table 5. In both tables 4 and 5, the samples have been arranged in a sequence, which would appear orderly to the average deuteranope (table 4) or protanope (table 5). The samples were first arranged according to reflectance, and, as expected, for deuteranopic vision were found to form seven groups of nearly constant reflectance (one for each of the Munsell values 2 to 8) with definite reflectance gaps separating them. The samples of each group are arranged according to yellowness, approximately as indicated by the chromaticity coordinate, w_d . Also, as expected, no such grouping was found after arranging the samples according to protanopic reflectance. However, the samples were arranged arbitrarily into 14 groups (one for each of the Munsell values 2.0, 2.5, . . . 8.5) so that the protanopic reflectance of each sample in one group is both lower than all of those in the group above and higher than all of those in the group below. Within each of these 14 groups the samples were arranged according to yellowness, approximately as indicated by the chromaticity coordinate w_p .

From the first three columns of tables 4 and 5, it may be seen that an arrangement that seems orderly to a deuteranope or protanope may contain outstanding irregularities to a normal observer. For example, the first four entries in table 4 are Y 8/12, Y 8/10, 10Y 8/8, Y 8/8. The second column indicates that these samples all have reflectances close to 0.58; that is, the colors of these surfaces appear to the average deuteranope as well as to the average normal observer to be about equally light. The third column indicates that the first sample is the yellowest and fourth the least yellow. With the exception of the third sample (10Y 8/8), this classification accords with that of the normal observer, which is indicated closely by the Munsell notation (Hue Value/Chroma) Y 8/12, Y 8/10, Y 8/8. The third sample, however, is a more greenish yellow than the others and for the normal observer does not

fit into the series. In this instance table 4 has served to indicate with some precision the kind of greenish yellow that the average deuteranope may be expected to confuse with a certain group of yellows. It indicates in general exactly the red-green confusions characteristic of deuteranopia. Table 5 indicates in a similar way the red-green confusions characteristic of protanopia.

TABLE 4. Deuteranopic arrangement—Continued

TABLE 4. Deuteranopic arrangement

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} = Y$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell notations	
			Deuteranopic	Normal
5Y 8/12	0.6706	0.6911	5Y 7.9/12.2	5.5Y 7.9/12.3
5Y 8/10	.6784	.6878	5Y 7.9/11.0	5.5Y 7.9/11.1
10Y 8/8	.6036	.7918	5Y 8.1/9.2	5.5GY 8.1/9.1
5Y 8/8	.6794	.7860	5Y 7.9/8.2	5.5Y 7.9/8.2
5Y 8/6	.6732	.7806	5Y 7.9/8.1	5.5Y 7.9/8.3
5GY 8/8	.6022	.7484	5Y 8.1/7.9	4.5GY 8.1/8.7
10YR 8/8	.6049	.7064	5Y 8.1/6.9	0.5Y 8.1/7.6
5Y 8/6	.6784	.6881	5Y 7.9/8.7	4.5Y 7.9/5.8
10Y 8/6	.6096	.6884	5Y 8.0/5.7	0.5GY 8.0/5.7
5GY 8/6	.6029	.6606	5Y 8.0/5.6	0.5GY 8.0/6.2
10YR 8/6	.6114	.6265	5Y 8.1/4.7	0.0YR 8.1/4.5
6Y 8/4	.6851	.6851	5Y 7.9/3.4	4.0Y 7.8/3.5
10Y 8/4	.6897	.6827	5Y 8.0/3.4	1.0GY 8.0/3.4
10GY 8/6	.6793	.6720	5Y 7.9/3.1	0.5GY 7.9/5.1
5GY 8/4	.6041	.6719	5Y 8.1/3.2	0.0GY 8.1/3.6
10YR 8/4	.6072	.6379	5Y 8.0/2.6	0.0YR 8.0/3.4
10GY 8/4	.6181	.6406	5Y 8.2/2.3	0.5G 8.2/4.0
6YR 8/4	.6070	.6311	5Y 8.0/2.0	4.0YR 8.0/3.8
10R 8/4	.6115	.6156	5Y 8.1/1.6	10.0R 8.1/3.7
5Y 8/2	.6870	.6141	5Y 7.8/1.5	8.5Y 7.8/1.6
5GY 8/2	.6881	.6107	5Y 8.0/1.5	6.0GY 8.0/1.6
5G 8/5	.6805	.4964	5Y 7.8/1.1	6.5G 7.8/4.7
5YR 8/2	.6917	.4949	5Y 8.0/1.0	4.0YR 8.0/2.0
5G 8/4	.6881	.4899	5Y 8.0/0.9	5.5G 8.0/3.3
5G 8/2	.6694	.4847	5Y 7.9/0.8	4.5G 7.9/2.1
5R 8/4	.6662	.4634	5Y 8.0/0.7	3.5R 8.0/3.6
10G 8/2	.6905	.4806	5Y 8.0/0.6	5.0G 8.0/2.0
N 8/	.6761	.4700	5Y 7.9/0.4	2.5GY 7.9/0.8
6R 8/2	.6021	.4699	5Y 8.1/0.4	2.0R 8.1/2.2
10RP 8/6	.6251	.4693	5Y 8.2/0.4	3.5RP 8.2/3.6
10R 8/4	.6107	.4678	5Y 8.1/0.3	6.5RP 8.1/2.7
5BG 8/2	.6082	.4656	5Y 8.1/0.3	1.0BG 8.1/2.0
5RP 8/2	.6436	.4633	5Y 8.3/0.2	6.0RP 8.2/1.9
5RP 8/6	.6068	.4611	5Y 8.1/0.1	6.5RP 8.1/3.4
5RP 8/4	.6030	.4588	5Y 8.1/0.1	6.5RP 8.1/2.8
10BG 8/2	.6258	.4587	5PB 8.2/0.4	5.0BG 8.2/1.9
6B 8/2	.6179	.4561	5PB 8.2/1.7	4.0B 8.2/2.2
5P 8/2	.6897	.4390	5PB 8.0/1.6	5.0P 8.0/2.5
10P 8/4	.6182	.4288	5PB 8.2/2.2	7.5P 8.2/3.5
6B 8/4	.6025	.4272	5PB 8.1/2.3	4.0B 8.1/2.9
10B 8/2	.6314	.4170	5PB 8.3/1.1	1.0PB 8.3/2.0
5PB 8/2	.6382	.4139	5PB 8.3/2.2	5.0PB 8.3/3.2
10PB 8/2	.6499	.4099	5PB 8.3/3.4	7.5PB 8.3/3.4
P 8/4	.6940	.4004	5PB 8.0/3.8	4.5P 8.0/4.8

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} = Y$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell notations	
			Deuteranopic	Normal
Y 7/10	0.4189	0.8302	5Y 6.9/9.7	5.0Y 8.9/9.7
Y 7/8	.4220	.8286	5Y 6.9/9.6	5.0Y 8.9/9.5
10YR 7/10	.4179	.8265	5Y 6.9/9.4	1.0Y 8.9/10.5
10Y 7/8	.4440	.8258	5Y 7.1/9.6	10.0Y 7.1/9.2
GY 7/10	.4263	.8160	5Y 7.0/9.0	4.0GY 7.0/9.5
YR 7/10	.4178	.7614	5Y 6.9/7.4	6.5YR 6.9/10.1
10YR 7/8	.4297	.7571	5Y 7.1/7.4	0.5Y 7.1/8.3
GY 7/8	.4612	.7487	5Y 7.1/7.1	5.0GY 7.1/8.9
10Y 7/6	.4334	.7406	5Y 7.0/7.0	0.5GY 7.0/8.9
Y 7/6	.4158	.7286	5Y 6.9/6.4	4.5Y 6.9/6.8
GY 7/6	.4599	.6967	5Y 7.1/5.7	5.0GY 7.1/6.4
YR 7/8	.4356	.6851	5Y 7.0/5.6	4.5YR 7.0/8.2
10YR 7/6	.4347	.6818	5Y 7.0/5.5	10.0YR 7.0/8.3
10GY 7/8	.4290	.6299	5Y 7.1/4.8	10.0GY 7.1/8.3
YR 7/6	.4262	.6143	5Y 7.0/2.9	3.5YR 7.0/6.0
YR 7/6	.4180	.6134	5Y 6.9/3.3	3.5YR 6.9/6.9
Y 7/4	.4282	.6084	5Y 7.0/3.7	4.0Y 7.0/3.8
10R 7/8	.4280	.6071	5Y 7.0/3.7	10.0R 7.0/7.5
10Y 7/4	.4429	.6053	5Y 7.1/3.6	1.0GY 7.1/3.6
10GY 7/6	.4507	.6046	5Y 7.1/3.6	10.0GY 7.1/6.6
GY 7/4	.4299	.6010	5Y 7.0/3.3	5.5GY 7.0/3.8
10YR 7/4	.4302	.6048	5Y 7.2/2.5	0.0YR 7.2/3.8
YR 7/4	.4376	.6067	5Y 7.0/2.5	3.0YR 7.0/4.1
10R 7/6	.4500	.6069	5Y 7.2/2.5	9.0R 7.2/5.7
10GY 7/4	.4571	.6488	5Y 7.2/2.3	10.0GY 7.2/4.1
10R 7/4	.4587	.6316	5Y 7.2/1.9	8.5R 7.2/4.7
Y 7/2	.4454	.6199	5Y 7.1/1.6	4.0Y 7.1/1.6
R 7/8	.4344	.6196	5Y 7.0/1.7	3.5R 7.0/7.0
GY 7/6	.4261	.6177	5Y 7.0/1.7	5.5GY 7.0/1.8
R 7/6	.4402	.6099	5Y 7.1/1.3	3.5R 7.1/5.7
YR 7/2	.4376	.6068	5Y 7.0/1.2	3.0YR 7.0/2.1
G 7/6	.4381	.6080	5Y 7.0/1.1	7.0G 7.0/6.1
R 7/4	.4402	.4973	5Y 7.1/1.0	3.0R 7.1/5.2
G 7/4	.4340	.4948	5Y 7.0/0.9	6.5G 7.0/4.3
10RP 7/8	.4412	.4601	5Y 7.1/0.6	9.0RP 7.1/5.8
G 7/2	.4321	.4777	5Y 7.0/0.5	6.5G 7.0/2.1
10RP 7/6	.4551	.4773	5Y 7.2/0.5	9.5RP 7.2/4.7
5R 7/2	.4521	.4766	5Y 7.2/0.5	2.5R 7.2/2.6
10G 7/4	.4572	.4784	5Y 7.2/0.4	0.5BG 7.2/3.9
10RP 7/4	.4597	.4782	5Y 7.1/0.4	9.0RP 7.1/3.5
RP 7/2	.4727	.4601	5Y 7.3/0.1	6.5RP 7.3/2.3
RP 7/4	.4835	.4690	N 7.4/	6.0RP 7.4/3.3
BG 7/2	.4728	.4589	N 7.3/	3.6BG 7.3/2.1
N 7/	.4433	.4562	5PB 7.1/0.2	7.5PB 7.1/0.1
RP 7/6	.4954	.4533	5PB 7.4/0.2	5.0RP 7.4/4.4
BG 7/4	.4634	.4522	5PB 7.2/0.3	4.5BG 7.2/3.4
RP 7/8	.4846	.4494	5PB 7.4/0.4	4.0RP 7.4/4.9
B 7/2	.4718	.4348	5PB 7.3/1.5	3.6B 7.3/2.2
10P 7/4	.4587	.4285	5PB 7.2/1.6	10.0P 7.2/4.0
10BG 7/4	.4655	.4244	5PB 7.2/2.2	0.6B 7.2/3.6
10P 7/6	.4675	.4228	5PB 7.2/2.3	9.5P 7.2/4.6
P 7/2	.4108	.4206	5PB 6.9/2.8	4.5P 6.9/2.7
10P 7/8	.4735	.4126	5PB 7.3/2.9	8.5P 7.3/8.0
PB 7/2	.4907	.4125	5PB 7.4/3.0	3.5PB 7.4/3.0
B 7/4	.4675	.4099	5PB 7.2/3.0	5.0B 7.2/3.7
10PB 7/4	.4498	.3982	5PB 7.1/3.7	10.0PB 7.1/4.0

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $R_{\lambda} = Y'$	Deuteranopic chromaticity coordinate, x'_d	Munsell notations	
			Deuteranopic	Normal
P 7/4	0.4457	0.3981	5PB 7.1/ 3.8	5.0P 7.1/ 4.8
B 7/6	.4438	.3936	5PB 7.1/ 3.8	5.0B 7.1/ 4.7
10B 7/4	.4596	.3994	5PB 7.2/ 3.8	5.0B 7.2/ 4.0
PB 7/4	.4743	.3886	5PB 7.3/ 4.4	4.0PB 7.3/ 4.5
P 7/6	.4381	.3766	5PB 7.0/ 4.9	5.5P 7.0/ 6.4
10PB 7/6	.4365	.3737	5PB 7.0/ 6.0	10.0PB 7.0/ 6.3
10B 7/6	.4578	.3709	5PB 7.2/ 5.2	9.5B 7.2/ 6.7
PB 7/6	.4556	.3687	5PB 7.2/ 5.4	4.0PB 7.2/ 5.6
10YR 6/10	.3596	.8249	5Y 6.5/ 8.6	10.0YR 6.5/ 9.8
5YR 6/12	.3241	.8401	5Y 6.2/ 8.6	6.0YR 6.2/11.5
Y 6/8	.3242	.8313	5Y 6.1/ 8.4	5.5Y 6.2/ 8.3
Y 6/8	.3145	.8289	5Y 6.1/ 8.2	6.5Y 6.1/ 8.1
10Y 6/6	.3278	.7890	5Y 6.2/ 7.7	9.5Y 6.2/ 7.4
YR 6/10	.3350	.7855	5Y 6.3/ 7.4	6.0YR 6.3/ 9.8
Y 6/6	.3179	.7817	5Y 6.2/ 7.2	5.0Y 6.2/ 7.2
10YR 6/8	.3457	.7683	5Y 6.4/ 7.0	9.5YR 6.4/ 8.0
GY 6/8	.3236	.7457	5Y 6.2/ 6.5	4.0GY 6.2/ 7.2
GY 6/6	.3200	.7248	5Y 6.2/ 6.9	5.0GY 6.2/ 6.7
YR 6/8	.3274	.7192	5Y 6.2/ 6.9	5.0YR 6.2/ 8.3
10YR 6/6	.3282	.7150	5Y 6.3/ 6.8	9.5YR 6.3/ 8.7
10R 6/10	.3243	.7068	5Y 6.2/ 6.8	9.5YR 6.2/10.1
10GY 6/10	.3092	.7025	5Y 6.0/ 5.4	9.0GY 6.0/ 8.7
10GY 6/8	.3224	.6862	5Y 6.2/ 4.8	9.0GY 6.2/ 7.7
10R 6/8	.3345	.6866	5Y 6.3/ 4.3	9.5YR 6.3/ 8.2
10Y 6/4	.3291	.6411	5Y 6.2/ 4.2	10.0Y 6.2/ 4.1
YR 6/6	.3221	.6410	5Y 6.2/ 4.2	4.5YR 6.2/ 6.0
Y 6/4	.3100	.6385	5Y 6.1/ 4.1	4.5Y 6.1/ 4.0
10GY 6/6	.3168	.6290	5Y 6.1/ 3.9	10.0GY 6.1/ 6.7
10YR 6/4	.3149	.6173	5Y 6.1/ 3.6	9.5Y 6.1/ 4.1
GY 6/4	.3217	.6151	5Y 6.2/ 3.6	5.0GY 6.2/ 4.0
10R 6/6	.3384	.6095	5Y 6.3/ 3.3	9.5YR 6.3/ 6.6
YR 6/4	.3113	.6751	5Y 6.2/ 2.8	4.0YR 6.1/ 4.0
R 6/10	.3236	.6628	5Y 6.2/ 2.4	4.0R 6.2/ 9.7
10GY 6/4	.3101	.5598	5Y 6.1/ 2.3	9.5GY 6.1/ 4.4
R 6/8	.3236	.5436	5Y 6.2/ 1.9	4.0R 6.2/ 8.1
10R 6/4	.3262	.5432	5Y 6.2/ 1.9	9.0R 6.2/ 4.2
Y 6/2	.3211	.5817	5Y 6.2/ 1.7	4.0Y 6.2/ 1.7
GY 6/2	.3245	.5239	5Y 6.2/ 1.7	5.0GY 6.2/ 1.7
G 6/6	.3040	.5237	5Y 6.0/ 1.5	8.0G 6.0/ 7.4
R 6/6	.3008	.5200	5Y 6.2/ 1.4	3.5R 6.2/ 6.3
YR 6/2	.3124	.5155	5Y 6.1/ 1.3	4.5YR 6.1/ 2.0
R 6/4	.3313	.5065	5Y 6.3/ 1.1	4.5R 6.3/ 4.5
G 6/4	.3154	.5018	5Y 6.1/ 1.0	6.0G 6.1/ 4.6
10RP 6/10	.3210	.4964	5Y 6.2/ 0.9	9.5RP 6.2/ 8.8
10RP 6/8	.3248	.4875	5Y 6.2/ 0.7	9.0RP 6.2/ 7.0
10G 6/2	.3032	.4838	5Y 6.0/ 0.6	6.0G 6.0/ 2.4
E 6/2	.3205	.4806	5Y 6.2/ 0.6	4.0R 6.2/ 2.3
10RP 6/6	.3260	.4792	5Y 6.2/ 0.6	9.0RP 6.2/ 6.5
10G 6/6	.3338	.4756	5Y 6.4/ 0.5	1.0BG 6.4/ 6.0
10RP 6/4	.3239	.4700	5Y 6.2/ 0.5	8.5RP 6.2/ 4.0
G 6/4	.3458	.4677	5Y 6.4/ 0.3	3.0BG 6.4/ 4.5
N 6/	.3033	.4588	N 6.0/	N 6.0/
6RP 6/2	.3169	.4549	6PB 6.1/ 0.2	4.0RP 6.1/ 2.3
5BG 6/2	.3429	.4524	6PB 6.4/ 0.2	5.0BG 6.4/ 2.4
5RP 6/4	.3454	.4504	6PB 6.4/ 0.3	4.5RP 6.4/ 4.2
5RP 6/6	.3345	.4503	6PB 6.2/ 0.3	4.5RP 6.2/ 6.6
5RP 6/8	.3349	.4438	5PB 6.2/ 0.7	5.0RP 6.2/ 7.3

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $R_{\lambda} = Y'$	Deuteranopic chromaticity coordinate, x'_d	Munsell notations	
			Deuteranopic	Normal
BG 6/4	0.3425	0.4421	5PB 6.4/ 0.8	5.6BG 6.4/ 4.1
BG 6/6	.3473	.4379	5PB 6.4/ 1.1	5.5BG 6.4/ 5.2
RP 6/10	.3389	.4358	5PB 6.3/ 1.1	4.5RP 6.3/ 8.5
10P 6/4	.3238	.4178	5PB 6.2/ 2.2	10.0P 6.2/ 4.6
10BG 6/4	.3316	.4163	5PB 6.3/ 2.3	10.0BG 6.3/ 4.1
P 6/2	.3236	.4126	6PB 6.2/ 2.5	4.5P 6.2/ 3.0
B 6/2	.3234	.4109	6PB 6.2/ 2.6	7.5B 6.2/ 3.0
PB 6/2	.3432	.4007	6PB 6.4/ 3.1	5.0PB 6.4/ 3.2
10P 6/6	.3307	.4005	6PB 6.2/ 3.1	9.5P 6.2/ 5.2
10BG 6/6	.3375	.3995	5PB 6.3/ 3.2	10.0BG 6.3/ 5.6
B 6/4	.3250	.3858	6PB 6.2/ 3.9	6.0B 6.2/ 4.5
P 6/4	.3301	.3849	6PB 6.2/ 4.0	4.0P 6.2/ 4.9
10P 6/8	.3245	.3820	6PB 6.3/ 4.1	9.0P 6.2/ 8.0
10B 6/4	.3415	.3777	5PB 6.3/ 4.6	10.0B 6.3/ 4.6
PB 6/4	.3589	.3733	5PB 6.5/ 4.6	5.0PB 6.5/ 4.7
10PB 6/4	.3394	.3729	5PB 6.3/ 4.6	9.5P 6.3/ 4.8
B 6/6	.3128	.3586	6PB 6.1/ 5.3	6.6B 6.1/ 8.4
10B 6/6	.3330	.3557	6PB 6.2/ 5.4	9.0P 6.2/ 8.3
P 6/6	.3179	.3545	5PB 6.2/ 5.4	4.5P 6.2/ 7.1
10PB 6/6	.3161	.3455	5PB 6.1/ 5.9	10.0PB 6.1/ 6.3
PB 6/6	.3494	.3447	5PB 6.3/ 6.1	5.0PB 6.3/ 6.2
P 6/6	.3157	.3216	5PB 6.1/ 6.7	5.0P 6.1/ 9.1
PB 6/8	.3329	.3200	6PB 6.3/ 7.4	8.0PB 6.3/ 7.4
10PB 6/8	.3200	.3210	5PY 6.2/ 7.4	9.5P 6.2/ 8.0
5YR 6/10	.3095	.3101	5Y 6.1/ 6.9	5.5YR 5.1/ 9.0
10YR 6/8	.3099	.3054	5Y 5.1/ 6.8	9.5Y 5.1/ 7.8
Y 5/6	.1984	.2817	5Y 5.0/ 6.1	6.0Y 5.0/ 6.0
GY 5/6	.2100	.2743	5Y 5.1/ 6.1	5.0GY 5.1/ 7.1
YR 5/6	.2081	.2637	6Y 5.1/ 5.7	6.0YR 5.1/ 7.7
10Y 5/6	.2250	.2635	6Y 5.3/ 5.8	10.0Y 5.3/ 6.6
10R 5/10	.1977	.2446	6Y 5.0/ 5.7	10.0R 5.0/ 9.9
10YR 5/6	.3121	.2132	6Y 5.2/ 5.0	10.0YR 5.2/ 6.7
10R 5/8	.2175	.1978	6Y 6.2/ 4.7	9.5YR 6.2/ 9.7
GY 6/6	.2066	.1881	6Y 6.1/ 4.6	5.0GY 6.1/ 5.4
10GY 5/8	.1910	.1893	5Y 4.9/ 4.4	9.5GY 4.9/ 7.8
YR 5/6	.1981	.1895	5Y 5.0/ 4.4	5.0YR 5.0/ 6.2
10Y 5/4	.2224	.1876	5Y 5.3/ 4.4	9.5GY 5.3/ 4.4
Y 5/4	.1987	.1867	5Y 5.0/ 4.0	5.0Y 5.0/ 3.9
10GY 5/6	.2141	.1845	6Y 5.2/ 4.0	9.5GY 6.2/ 7.1
R 6/12	.1939	.1808	5Y 5.0/ 3.8	5.5R 5.0/12.8
10YR 6/4	.2048	.1854	5Y 5.1/ 3.8	10.0YR 5.1/ 4.4
10R 5/6	.2073	.1872	5Y 5.1/ 3.6	10.0R 5.1/ 7.1
GY 5/4	.2070	.1839	5Y 5.1/ 3.4	5.0GY 5.1/ 4.1
R 5/10	.2128	.1824	5Y 5.2/ 3.3	3.0R 5.2/10.9
YR 5/4	.1904	.1873	5Y 4.9/ 3.1	4.5YR 4.9/ 4.6
R 5/8	.1903	.1828	5Y 5.0/ 2.7	4.5R 5.0/10.0
10R 5/4	.2028	.1874	5Y 5.1/ 2.3	9.5R 5.1/ 4.9
10GY 5/4	.2025	.1826	5Y 5.0/ 2.3	10.0GY 5.0/ 4.3
R 5/6	.1998	.1594	5Y 5.0/ 2.0	4.0R 5.0/ 8.0
G 5/6	.1875	.1591	5Y 4.9/ 1.6	5.0G 4.9/ 8.2
Y 5/2	.2117	.1612	5Y 5.2/ 1.7	4.5Y 5.2/ 1.7
GY 5/2	.2097	.1576	5Y 5.1/ 1.6	5.0GY 5.1/ 2.0
G 5/6	.1869	.1569	5Y 4.9/ 1.5	3.0G 4.9/ 8.6
R 5/4	.1916	.1575	5Y 4.9/ 1.4	4.0R 4.9/ 8.3
YR 5/2	.1927	.1524	5Y 4.9/ 1.3	4.0YR 4.9/ 2.1
G 5/4	.1856	.1515	5Y 4.9/ 1.2	5.0G 4.9/ 4.8

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} = Y'$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell rotations	
			Deuteranopic	Normal
10RP 6/10	.2180	.45166	5Y 5.2/ 1.2	10.0RP 5.2/10.3
10RP 6/ 8	.2111	.46866	6Y 5.2/ 1.0	10.0RP 5.2/ 8.6
10RP 6/ 6	.2101	.4692	6Y 5.2/ 0.7	10.0RP 5.2/ 6.0
R 5/ 2	.1354	.4291	5Y 5.0/ 0.0	4.0R 5.0/ 2.8
G 5/ 2	.1888	.4235	5Y 4.0/ 0.5	6.6G 4.0/ 2.4
10RP 5/ 4	.2200	.4814	5Y 5.3/ 0.5	10.0RP 6.3/ 4.2
10G 6/ 6	.2012	.4767	5Y 5.0/ 0.4	1.0BG 6.0/ 7.0
10G 6/ 4	.2047	.4707	5Y 5.1/ 0.2	0.5BG 5.1/ 4.6
RP 5/ 2	.2136	.4532	5PB 6.2/ 0.1	5.0RP 5.2/ 2.3
N 0/	.1206	.4560	5PB 4.2/ 0.2	5.0PB 4.2/ 0.1
BG 5/ 2	.2077	.4501	5PB 6.1/ 0.2	4.5BG 5.1/ 2.6
RP 5/ 4	.2110	.4488	5PB 5.2/ 0.4	5.0RP 6.2/ 4.3
RP 5/ 6	.2098	.4410	5PB 5.1/ 0.7	4.5RP 5.1/ 8.2
5RP 5/10	.2201	.4295	5PB 5.3/ 0.8	5.5RP 5.3/ 9.7
RP 6/ 8	.2206	.4356	5PB 5.2/ 1.0	4.5RP 5.2/ 8.0
BG 5/ 4	.2112	.4338	5PB 5.2/ 1.1	5.5BG 5.2/ 4.4
BG 6/ 6	.2097	.4280	5PB 5.1/ 1.4	5.0BG 5.1/ 6.4
P 6/ 2	.1259	.4101	5PB 5.0/ 2.0	5.0P 5.0/ 2.6
10P 5/ 4	.2143	.4089	5PB 5.2/ 2.2	1.0RP 6.2/ 4.9
P 5/ 2	.1517	.4037	5PB 4.0/ 2.2	6.5B 4.0/ 2.8
10BG 5/ 4	.2062	.3998	5PB 5.1/ 2.5	0.5B 5.1/ 4.4
10P 6/ 6	.2129	.3922	5PB 5.2/ 2.9	1.0RP 5.2/ 6.7
PB 5/ 2	.2087	.3891	5PB 5.1/ 3.0	5.0PB 5.1/ 3.1
10P 6/ 8	.2174	.3737	5PB 5.2/ 3.8	1.0RP 5.2/ 8.6
P 5/ 4	.1934	.3697	5PB 5.0/ 3.8	4.8P 5.0/ 4.7
10BG 6/ 6	.2160	.3687	5PB 5.2/ 4.0	1.0B 5.2/ 6.6
B 5/ 4	.1956	.3618	5PB 5.0/ 4.2	5.5B 5.0/ 5.1
10B 5/ 4	.2124	.3616	5PB 5.2/ 4.3	10.0B 5.2/ 4.5
PB 5/ 4	.2170	.3590	5PB 5.2/ 4.5	4.5PB 5.2/ 4.4
10P 6/10	.2226	.3576	5PB 5.2/ 4.6	0.5RP 5.2/10.4
10PB 6/ 4	.2180	.3528	5PB 6.2/ 4.7	10.0PB 5.2/ 4.0
P 6/ 6	.1906	.3424	5PB 6.0/ 5.1	5.0P 5.0/ 6.8
B 5/ 6	.1940	.3333	5PB 5.0/ 5.3	5.0B 5.0/ 6.8
10B 5/ 8	.2132	.3292	5PB 5.2/ 5.8	9.5B 5.2/ 6.3
PB 5/ 8	.2241	.3290	5PB 5.3/ 6.1	4.0PB 5.3/ 8.2
10PB 5/ 6	.2140	.3223	5PB 5.2/ 6.3	10.0PB 5.2/ 8.6
P 5/ 8	.2107	.3164	5PB 5.1/ 6.6	5.0P 5.1/ 8.9
PB 6/ 8	.2246	.3036	5PB 5.4/ 7.5	4.0PB 5.4/ 7.9
10PB 6/ 8	.2126	.2988	5PB 5.2/ 7.8	10.0PB 5.2/ 8.4
P 5/10	.2039	.2903	5PB 5.1/ 8.1	5.0P 5.1/10.9
PB 5/10	.2283	.2871	5PB 5.3/ 8.4	3.5PB 5.3/ 8.6
10PB 5/10	.2014	.2757	5PB 5.0/ 8.8	10.0PB 5.0/ 9.6
5YR 4/ 8	.1354	.7407	5Y 4.2/ 5.8	6.0YR 4.2/ 6.8
10R 4/10	.1493	.7234	6Y 4.4/ 4.6	9.5R 4.4/ 9.0
10R 4/ 8	.1428	.7112	6Y 4.3/ 4.3	10.0R 4.3/ 8.4
10YR 4/ 4	.1318	.7032	6Y 4.2/ 4.2	10.0YR 4.2/ 4.6
R 4/14	.1334	.7081	6Y 4.2/ 4.2	6.5R 4.2/13.2
R 4/14	.1335	.7034	6Y 4.2/ 4.2	6.5R 4.2/13.2
YR 4/ 8	.1445	.7032	5Y 4.4/ 4.2	5.0YR 4.4/ 5.8
Y 4/ 4	.1343	.6971	5Y 4.1/ 3.7	5.0Y 4.1/ 3.6
R 4/12	.1360	.6931	5Y 4.2/ 3.8	5.0R 4.2/12.6
10Y 4/ 4	.1385	.6733	5Y 4.2/ 3.7	10.0Y 4.2/ 3.7
10R 4/ 6	.1424	.6736	5Y 4.3/ 3.7	10.0R 4.3/ 7.3
GY 4/ 6	.1249	.6661	5Y 4.1/ 3.4	5.0GY 4.1/ 4.0
YR 4/ 4	.1416	.6666	5Y 4.2/ 3.4	5.0YR 4.2/ 4.6
R 4/10	.1306	.6307	5Y 4.2/ 3.0	4.5R 4.2/10.6

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} = Y'$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell rotations	
			Deuteranopic	Normal
10GY 4/ 8	.0.1335	.6.6279	5Y 4.2/ 2.9	10.0GY 4.2/ 5.4
GY 4/ 4	.1313	.6173	5Y 4.2/ 2.7	5.0GY 4.2/ 3.2
R 4/ 8	.1306	.6111	5Y 4.2/ 2.6	4.5R 4.2/ 9.4
10R 4/ 4	.1348	.6007	5Y 4.2/ 2.6	0.5YR 4.2/ 4.7
10GY 4/ 4	.1337	.5716	5Y 4.2/ 2.0	1.0G 4.2/ 4.1
R 4/ 6	.1247	.5963	5Y 4.1/ 1.9	4.5R 4.1/ 6.8
Y 4/ 2	.1416	.5334	5Y 4.3/ 1.7	5.5Y 4.3/ 1.7
YR 4/ 2	.1268	.5494	5Y 4.1/ 1.5	4.0YR 4.1/ 2.3
GY 4/ 2	.1357	.5357	5Y 4.2/ 1.4	5.5GY 4.2/ 1.7
R 4/ 4	.1236	.5267	5Y 4.1/ 1.2	3.5R 4.1/ 4.7
G 4/ 4	.1291	.5218	6Y 4.1/ 1.1	5.0G 4.1/ 4.9
10RP 4/10	.1359	.5034	6Y 4.2/ 0.8	0.6RP 4.2/ 9.5
R 4/ 2	.1230	.4963	5Y 4.1/ 0.7	4.0R 4.1/ 2.6
10RP 4/ 6	.1262	.4903	5Y 4.1/ 0.6	0.5RP 4.1/ 6.4
G 4/ 2	.1242	.4834	5Y 4.1/ 0.6	6.0G 4.1/ 2.4
10RP 4/ 8	.1282	.4676	5Y 4.2/ 0.5	0.6RP 4.2/ 8.2
10RP 4/ 4	.1277	.4754	5Y 4.1/ 0.3	9.0RP 4.1/ 4.1
10J 4/ 4	.1293	.4731	6Y 4.1/ 0.3	0.5JG 4.1/ 4.5
N 4/	.1209	.4526	6PB 4.0/ 0.1	5.0PB 4.0/ 0.1
RP 4/ 2	.1445	.4474	5PB 4.4/ 0.3	4.0RP 4.4/ 2.1
BG 4/ 2	.1282	.4434	5PB 4.3/ 0.4	5.5BG 4.3/ 2.5
RP 4/ 4	.1418	.4332	5PB 4.3/ 0.8	4.0RP 4.3/ 4.4
BG 4/ 4	.1413	.4296	5PB 4.2/ 0.9	5.5BG 4.2/ 4.0
RP 4/ 6	.1406	.4230	5PB 4.2/ 1.1	4.5RP 4.2/ 6.4
RP 4/ 8	.1341	.4172	5PB 4.2/ 1.3	4.5RP 4.2/ 7.9
RP 4/10	.1359	.4127	5PB 4.2/ 1.5	4.6RP 4.2/ 9.4
BG 4/ 6	.1354	.4114	5PB 4.2/ 1.6	5.5BG 4.2/ 6.0
5RP 4/12	.1306	.4076	5PB 4.3/ 1.7	5.0RP 4.3/10.7
6P 4/ 2	.1248	.4025	5PB 4.1/ 1.8	5.0P 4.1/ 2.2
5B 4/ 2	.1274	.4005	5PB 4.3/ 1.9	5.0B 4.3/ 2.7
10BG 4/ 4	.1290	.4002	5PB 4.1/ 1.9	9.5BG 4.1/ 4.0
10P 4/ 4	.1428	.3989	6PB 4.3/ 2.1	0.5RP 4.3/ 4.6
PB 4/ 2	.1313	.3988	5PB 4.2/ 2.4	6.0PB 4.2/ 2.6
10BG 4/ 8	.1349	.3721	5PB 4.2/ 3.0	10.0BG 4.2/ 5.7
10P 4/ 6	.1407	.3718	5PB 4.3/ 3.1	0.5RP 4.3/ 6.6
P 4/ 4	.1289	.3653	5PB 4.1/ 3.2	5.0P 4.1/ 4.2
R 4/ 4	.1447	.3567	5PB 4.4/ 3.7	6.0B 4.4/ 4.6
10B 4/ 4	.1290	.3527	5PB 4.2/ 3.7	0.5PB 4.2/ 4.1
10P 4/ 8	.1406	.3519	5PB 4.3/ 3.9	0.5RP 4.3/ 8.5
PB 4/ 4	.1356	.3441	5PB 4.2/ 4.2	5.0PB 4.2/ 4.3
10PB 4/ 4	.1298	.3377	5PB 4.1/ 4.4	10.0PB 4.1/ 4.6
P 4/ 6	.1240	.3313	5PB 5.1/ 4.6	5.0P 4.1/ 6.1
10P 4/10	.1331	.3291	5PB 4.2/ 4.8	0.5RP 4.2/10.4
B 4/ 6	.1267	.3141	5PB 4.1/ 5.4	5.5B 4.1/ 6.4
PB 4/ 6	.1364	.3071	5PB 4.2/ 5.9	4.5PB 4.2/ 6.0
P 4/ 8	.1278	.3020	5PB 4.1/ 5.9	5.0P 4.1/ 8.2
10B 4/ 6	.1316	.3014	6PB 4.2/ 6.0	0.5PB 4.2/ 6.3
B 4/ 8	.1172	.2991	5PB 4.0/ 5.9	6.5B 4.0/ 8.9
10PB 4/ 6	.1321	.2985	5PB 4.2/ 6.2	10.0PB 4.2/ 8.6
10B 4, 8	.1292	.2831	5PB 4.1/ 7.0	10.0B 4.1/ 7.3
P 4/10	.1292	.2828	5PB 4.1/ 6.9	5.0P 4.1/10.1
PB 4/ 8	.1297	.2733	5PB 4.3/ 7.3	4.5PB 4.3/ 7.4
10PB 4/ 8	.1291	.2685	5PB 4.1/ 7.6	10.0PB 4.1/ 8.5
P 4/12	.1262	.2504	5PB 4.1/ 8.6	5.5P 4.1/12.6
10PB 4/10	.1234	.2492	5PB 4.0/ 8.6	10.0PB 4.0/ 9.7
PB 4/10	.1446	.2580	5PB 4.4/ 8.9	4.0PB 4.4/ 8.9

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} - Y'$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell notations	
			Deuteranopic	Normal
5YR 3/4	0.0783	0.6552	5Y 3.3/ 3.0	5.0YR 3.3/ 4.1
10R 3/6	.0786	.6380	5Y 3.3/ 2.8	10.0R 3.3/ 3.4
R 3/10	.0744	.6332	5Y 3.2/ 2.7	5.0R 3.2/ 3.3
10YR 3/2	.0696	.6231	5Y 3.1/ 2.5	10.0YR 3.1/ 2.7
10GY 3/4	.0736	.6102	5Y 3.2/ 3.3	10.0GY 3.2/ 4.5
R 2/8	.0748	.6005	5Y 2.2/ 2.2	5.0R 3.2/ 7.4
10R 3/4	.0741	.5961	5Y 2.2/ 2.1	10.0R 3.2/ 4.1
GY 3/4	.0739	.5900	5Y 2.2/ 2.1	5.0GY 3.2/ 2.6
10Y 3/2	.0738	.5885	5Y 2.3/ 1.7	0.5GY 3.3/ 1.8
R 3/6	.0839	.5647	5Y 2.4/ 1.7	4.5R 3.4/ 6.2
YR 3/2	.0698	.5602	5Y 3.1/ 1.6	5.0YR 3.1/ 2.0
YR 3/2	.0701	.5577	5Y 3.1/ 1.5	5.0YR 3.1/ 2.1
GY 3/2	.0748	.5533	5Y 3.2/ 1.4	4.5GY 3.2/ 1.9
R 3/4	.0724	.5506	5Y 3.2/ 1.4	5.0R 3.2/ 4.6
G 3/4	.0808	.5407	5Y 3.3/ 1.3	4.0G 3.2/ 4.8
Y 3/2	.0689	.5362	5Y 3.1/ 1.2	6.0Y 3.1/ 1.1
G 3/2	.0703	.4989	5Y 3.1/ 0.6	5.0G 3.1/ 3.7
R 3/2	.0716	.4979	5Y 3.1/ 0.6	5.5R 3.1/ 2.1
10RP 3/8	.0698	.4947	5Y 3.1/ 0.5	8.0RP 3.1/ 7.0
10RP 3/6	.0712	.4921	5Y 3.1/ 0.4	6.0RP 3.1/ 5.6
10G 3/4	.0704	.4736	5Y 3.2/ 0.3	10.0G 3.2/ 4.7
10RP 3/4	.0676	.4708	5Y 3.0/ 0.3	9.0RP 3.0/ 3.4
10RP 3/10	.0735	.4690	5Y 3.2/ 0.1	8.5RP 3.2/ 8.5
N 3/	.0851	.4511	5PB 3.0/ 0.1	2.5P 3.0/ 0.2
RP 3/2	.0654	.4464	5PB 3.0/ 0.3	4.5RP 3.0/ 1.9
BG 3/2	.0727	.4357	5PB 3.2/ 0.6	5.0BG 3.2/ 2.8
RP 3/4	.0675	.4359	5PB 3.0/ 0.6	5.0RP 3.0/ 8.7
RP 3/6	.0664	.4329	5PB 3.0/ 0.6	5.0RP 3.0/ 5.2
BG 3/4	.0716	.4180	5PB 3.1/ 0.9	5.0BG 3.1/ 4.1
RP 3/8	.0706	.4080	5PB 3.1/ 1.2	5.0RP 3.1/ 6.8
RP 3/10	.0743	.3975	5PB 3.2/ 1.5	5.0RP 3.2/ 8.4
BG 3/6	.0767	.3970	5PB 3.2/ 1.5	6.0BG 3.2/ 5.3
F 3/2	.0736	.3870	5PB 3.2/ 1.8	5.0F 3.2/ 2.2
B 3/2	.0715	.3854	5PB 3.1/ 1.8	5.5B 3.1/ 2.3
10BQ 3/4	.0778	.3788	5PB 3.3/ 2.0	9.5BQ 3.3/ 4.3
PB 3/2	.0689	.3710	5PB 3.1/ 2.2	5.0PB 3.1/ 2.1
10P 3/4	.0731	.3690	5PB 3.2/ 2.3	10.0P 3.2/ 4.5
10BG 3/6	.0727	.3475	5PB 3.2/ 2.9	9.5BG 3.2/ 3.8
B 3/4	.0700	.3393	5PB 3.1/ 3.1	4.5B 3.1/ 4.2
10P 3/8	.0722	.3327	5PB 3.2/ 3.4	9.0P 3.2/ 6.8
F 3/4	.0705	.3278	5PB 3.1/ 3.5	5.0F 3.1/ 4.5
10B 3/4	.0708	.3236	5PB 3.1/ 3.6	9.5B 3.1/ 3.9
5PB 3/4	.0699	.3179	5PB 3.1/ 3.8	5.0PB 3.1/ 3.9
10P 3/8	.0700	.3097	5PB 3.1/ 4.1	10.0P 3.1/ 8.3
B 3/6	.0802	.3047	5PB 2.3/ 4.5	5.0B 3.2/ 5.9
10PB 3/4	.0713	.3026	5PB 3.1/ 4.6	10.0PB 3.1/ 4.7
P 3/6	.0744	.2950	5PB 3.2/ 4.8	4.5P 3.2/ 6.4
10P 3/10	.0648	.2787	5PB 3.0/ 5.2	9.0P 3.0/ 9.8
10B 3/6	.0785	.2840	5PB 3.2/ 5.3	9.5B 3.2/ 5.6
PB 3/6	.0749	.2803	5PB 3.2/ 5.5	5.0PB 3.2/ 5.6
10PB 3/6	.0711	.2750	5PB 3.1/ 5.5	10.0PB 3.1/ 6.1
F 3/8	.0759	.2681	5PB 3.2/ 6.0	5.0F 3.2/ 8.4
10B 3/8	.0812	.2643	5PB 3.2/ 6.9	9.0B 3.2/ 7.1
10PB 3/8	.0724	.2625	5PB 3.2/ 6.8	10.0PB 3.2/ 7.4
PB 3/8	.0788	.2499	5PB 3.2/ 7.0	4.5PB 3.2/ 7.0
P 3/10	.0769	.2642	5PB 3.2/ 7.8	5.0P 3.2/ 11.2

TABLE 4. Deuteranopic arrangement—Continued

Munsell book notation	Deuteranopic reflectance, $W_{\lambda} - Y'$	Deuteranopic chromaticity coordinate, w_{λ}	Munsell notations	
			Deuteranopic	Normal
PB 3/10	0.0844	0.2323	5PB 3.4/ 8.4	4.5PB 3.4/ 8.5
PB 3/12	.0802	.2319	5PB 3.3/ 9.4	4.0PB 3.3/ 9.4
10PB 3/10	.0863	.1920	5PB 3.1/ 9.7	10.0PB 3.1/ 10.5
5GY 2/2	.0461	.5995	5Y 2.5/ 1.6	5.5GY 2.5/ 2.2
10Y 2/2	.0484	.5986	5Y 2.6/ 1.4	10.0Y 2.6/ 1.6
Y 2/2	.0472	.5979	5Y 2.5/ 1.4	5.0Y 2.5/ 1.4
10YR 2/2	.0505	.5519	5Y 2.6/ 1.3	7.5YR 2.6/ 1.5
YR 2/2	.0459	.5420	5Y 2.4/ 1.2	4.5YR 2.4/ 1.8
10GY 2/2	.0440	.5399	5Y 2.4/ 1.1	9.5GY 2.4/ 2.5
10R 2/2	.0458	.5344	5Y 2.5/ 1.0	8.5R 2.5/ 2.6
R 2/4	.0384	.5183	5Y 2.3/ 0.8	4.0R 2.5/ 3.8
R 2/6	.0461	.5151	5Y 2.5/ 0.8	3.0R 2.5/ 4.8
R 2/2	.0400	.4878	5Y 2.3/ 0.6	3.5R 2.3/ 2.2
G 2/2	.0373	.4850	5Y 2.2/ 0.4	7.0G 2.2/ 2.4
10G 2/2	.0407	.4678	5Y 2.3/ 0.2	10.0G 2.3/ 3.1
N 2/	.0300	.4505	5PB 2.0/ 0.1	5.0P 2.0/ 0.2
10RP 2/4	.0385	.4468	5PB 2.3/ 0.1	8.0RP 2.3/ 3.7
RP 2/2	.0386	.4362	5PB 2.3/ 0.2	6.0RP 2.3/ 2.3
BQ 2/2	.0379	.4361	5PB 2.2/ 0.3	4.6BQ 2.2/ 2.5
10RP 2/6	.0416	.4333	5PB 2.4/ 0.4	8.0RP 2.4/ 5.6
BQ 2/4	.0395	.4190	5PB 2.3/ 0.7	5.0BQ 2.3/ 3.7
10BQ 2/2	.0455	.4070	5PB 3.5/ 1.0	7.0BQ 3.5/ 3.1
RP 2/4	.0411	.4045	5PB 2.4/ 1.0	3.0RP 2.4/ 4.6
B 2/2	.0361	.3952	5PB 2.2/ 1.3	2.0B 2.2/ 2.2
RP 2/6	.0440	.3790	5PB 2.4/ 1.7	4.0RP 2.4/ 6.9
P 2/2	.0351	.3506	5PB 2.1/ 2.2	5.5P 2.1/ 2.9
PB 2/2	.0363	.3358	5PB 2.2/ 2.5	4.5PB 2.2/ 2.6
10B 2/2	.0390	.3353	5PB 2.3/ 2.7	8.5B 2.2/ 3.1
10P 2/4	.0370	.3220	5PB 3.2/ 3.0	9.0P 2.2/ 5.3
P 3/4	.0366	.3102	5PB 2.2/ 3.2	5.0P 2.2/ 4.6
10P 3/6	.0377	.2987	5PB 2.2/ 3.7	9.0P 2.2/ 6.8
10PB 2/4	.0380	.2770	5PB 2.2/ 4.6	10.0PB 2.2/ 4.8
PB 2/4	.0366	.2715	5PB 2.3/ 4.7	4.0PB 2.3/ 4.8
10PB 2/6	.0356	.2660	5PB 2.2/ 4.6	10.0PB 2.2/ 6.5
P 2/6	.0346	.2589	5PB 2.1/ 4.6	5.0P 2.1/ 4.8
PB 2/6	.0405	.2446	5PB 2.3/ 5.8	4.0PB 2.3/ 5.9

TABLE 5. Protanopic arrangement

Munsell book notation	Protanopic reflectance, 0.9753 W_{λ}	Protanopic chromaticity coordinate, w_{λ}	Munsell notations	
			Protanopic	Normal
N 9	0.7244	0.4706	5Y 8.7/ 0.2	7.5Y 8.7/ 0.1
10BQ 3/2	.6484	.4705	5Y 8.3/ 0.2	5.0BQ 8.2/ 1.9
5B 3/2	.6391	.4511	5PB 8.3/ 1.3	4.0B 8.2/ 2.2
10B 3/2	.6732	.4317	5PB 8.4/ 2.8	1.0PB 8.3/ 3.0
5PB 3/2	.6543	.4267	5PB 8.3/ 3.2	5.0PB 8.3/ 3.2
10PB 3/2	.6608	.4205	5PB 8.4/ 3.5	7.5PB 8.3/ 3.4
10Y 3/8	.5773	.7889	5Y 7.2/ 9.8	0.5GY 8.1/ 9.1
5GY 3/8	.5991	.7606	5Y 8.0/ 8.2	4.5GY 8.1/ 8.7
5GY 3/6	.5914	.6669	5Y 8.0/ 5.9	5.5GY 8.0/ 6.2
10Y 3/6	.5817	.6657	5Y 8.0/ 5.8	0.5GY 8.0/ 5.7
5Y 3/8	.5451	.6609	5Y 7.7/ 8.7	4.5Y 7.9/ 8.8

TABLE 5. Protanopic arrangement—Continued

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell notations	
			Protanopic	Normal
10YR 8/6	0.5632	0.6124	5Y 7.8/4.8	9.0YR 8.1/5.6
10GY 8/6	.5967	.5896	5Y 8.0/3.6	9.5GY 7.9/5.1
10Y 8/4	.5673	.5942	5Y 8.0/3.5	1.0GY 8.0/3.4
5GY 8/4	.6044	.5786	5Y 8.1/3.4	8.0GY 8.1/3.6
10GY 8/4	.6362	.6545	5Y 8.2/2.7	0.6G 8.2/4.0
10YR 8/4	.5656	.6312	5Y 7.9/2.5	9.0YR 8.0/3.4
5YR 8/4	.6014	.6225	5Y 7.8/1.6	4.0YR 8.0/3.5
5G 8/6	.5964	.5187	5Y 8.0/1.6	6.5G 7.8/4.7
5GY 8/2	.5851	.5174	5Y 8.0/1.6	6.0GY 8.0/1.6
5G 8/4	.6141	.5075	5Y 8.1/1.3	5.5G 8.0/2.3
10R 8/4	.5725	.5099	5Y 7.9/1.2	10.0R 8.1/3.7
5G 8/2	.5964	.4964	5Y 8.0/0.9	4.0G 7.9/2.1
10G 8/2	.6133	.4943	5Y 8.1/0.8	5.0G 8.0/2.0
5YR 8/2	.5731	.4937	5Y 7.9/0.8	4.0YR 8.0/2.0
5BG 8/2	.6281	.4803	5Y 8.2/0.8	1.0BG 8.1/2.0
5R 8/4	.5945	.4772	5Y 7.8/0.4	3.5R 8.0/3.5
N 8/	.5741	.4764	5Y 7.9/0.3	2.5GY 7.9/0.3
5R 8/2	.5857	.4698	5Y 8.0/0.2	2.0R 8.1/2.2
5RP 8/2	.6317	.4654	N 8.2/	5.0RP 8.2/1.9
10RP 8/4	.5905	.4662	N 8.0/	9.5RP 8.1/2.7
10RP 8/6	.5838	.4641	5PB 8.0/0.1	8.5RP 8.2/3.6
5RP 8/6	.5829	.4596	5PB 8.0/0.6	6.5RP 8.1/3.4
5RP 8/4	.5674	.4582	5PB 8.0/0.7	5.5RP 8.1/2.8
5B 8/4	.6310	.4452	5PB 8.2/1.3	4.0B 8.1/2.9
5P 8/2	.5877	.4388	5PB 8.0/2.2	5.0P 8.0/2.5
10P 8/4	.6081	.4316	5PB 8.1/2.8	7.6P 8.2/3.5
6P 8/4	.5903	.4004	5PB 8.0/4.5	4.6P 8.0/4.8
5Y 8/13	.5205	.3845	5Y 7.6/11.8	5.5Y 7.9/12.3
Y 8/10	.5292	.3801	5Y 7.6/10.8	5.5Y 7.9/11.1
Y 8/8	.5393	.3779	5Y 7.7/8.8	5.5Y 7.9/8.8
Y 8/6	.5539	.3735	5Y 7.7/8.2	5.5Y 7.9/8.2
10GY 7/6	.4726	.3222	5Y 7.3/4.3	10.0GY 7.1/8.5
Y 8/4	.6426	.3018	5Y 7.7/3.4	4.0Y 7.3/3.5
10GY 7/4	.4718	.3021	5Y 7.3/2.7	10.0Y 7.2/4.1
G 7/6	.4749	.3299	5Y 7.3/1.8	7.0G 7.0/6.1
Y 8/2	.5455	.5136	5Y 7.7/1.5	8.5Y 7.8/1.6
10G 7/4	.4960	.4851	5Y 7.4/0.8	0.5BG 7.2/3.9
BG 7/2	.4913	.4782	5Y 7.4/0.3	3.5BG 7.3/2.1
BG 7/4	.4906	.4733	5Y 7.4/0.2	4.5BG 7.2/3.4
RP 7/4	.4699	.4668	5PB 7.3/0.8	6.0RP 7.4/3.3
B 7/2	.4995	.4605	5PB 7.4/1.2	3.5B 7.3/2.2
10BG 7/4	.4883	.4471	5PB 7.4/1.4	0.5B 7.2/3.6
RP 7/6	.4687	.4463	5PB 7.3/1.6	5.0RP 7.4/4.4
B 7/4	.4875	.4313	5PB 7.4/2.6	6.0B 7.2/3.7
PB 7/2	.5048	.4200	5PB 7.5/2.9	3.5PB 7.4/3.0
B 7/6	.4798	.4213	5PB 7.3/3.1	5.0B 7.1/4.7
10B 7/4	.4794	.4158	5PB 7.3/3.5	0.0B 7.2/4.0
PB 7/4	.4942	.4048	5PB 7.4/4.3	4.0PB 7.3/4.5
10B 7/6	.4949	.3963	5PB 7.5/4.9	9.5B 7.2/5.7
PB 7/6	.4817	.3878	5PB 7.3/6.4	4.0PB 7.2/4.6
10Y 7/8	.4214	.3324	5Y 6.9/9.5	10.0Y 7.1/9.3
GY 7/10	.4235	.3191	5Y 7.0/9.2	4.0GY 7.0/9.5
GY 7/8	.4506	.7488	5Y 7.1/7.5	4.0GY 7.1/8.0
10Y 7/6	.4176	.7387	5Y 6.9/7.0	0.5GY 7.0/6.9
GY 7/6	.4502	.6922	5Y 7.1/6.1	5.0GY 7.1/6.4
10GY 7/8	.4655	.6097	5Y 7.2/5.5	10.0GY 7.1/8.3
10Y 7/4	.4340	.6054	5Y 7.0/3.8	1.0GY 7.1/3.6

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell notations	
			Protanopic	Normal
GY 7/4	0.4364	0.5973	5Y 7.0/3.6	5.5GY 7.0/3.8
Y 7/4	.4079	.6033	5Y 6.8/3.5	4.0Y 7.0/3.8
10YR 7/4	.4296	.5746	5Y 7.0/2.9	9.0YR 7.2/3.8
YR 7/4	.4016	.5422	5Y 6.3/2.0	3.0YR 7.0/4.1
10R 7/6	.4086	.5329	5Y 6.8/1.8	9.0R 7.2/5.7
GY 7/2	.4291	.5244	5Y 7.0/1.6	3.5GY 7.0/1.8
Y 7/2	.4359	.5213	5Y 7.0/1.6	4.0Y 7.1/1.6
G 7/4	.4613	.5163	5Y 7.2/1.4	6.5G 7.0/4.3
10R 7/4	.4122	.5145	5Y 6.9/1.3	8.5R 7.2/4.7
5YR 7/2	.4183	.5018	5Y 6.9/1.0	3.0YR 7.0/2.1
G 7/2	.4871	.4626	5Y 7.0/0.7	6.5G 7.0/2.1
R 7/6	.3999	.4899	5Y 6.8/0.6	2.5R 7.1/5.7
B 7/4	.4612	.4809	5Y 6.8/0.4	3.0R 7.1/5.2
R 7/2	.4336	.4739	5Y 7.0/0.2	2.5R 7.2/2.6
10BP 7/4	.4194	.4657	N 6.0/	9.5BP 7.1/3.5
10RP 7/6	.4213	.4649	N 6.9/	9.5RP 7.2/4.7
N 7/	.4441	.4633	5PB 7.1/0.1	7.5PB 7.1/0.1
10RP 7/8	.3999	.4625	5PB 6.8/0.2	9.0RP 7.1/5.3
RP 7/2	.4699	.4600	5PB 7.2/0.4	8.5RP 7.3/2.3
RP 7/8	.4643	.4490	5PB 7.2/1.9	4.5RP 7.4/4.9
10P 7/4	.4510	.4273	5PB 7.1/2.7	10.0P 7.2/4.0
P 7/2	.4695	.4259	5PB 6.8/2.7	4.6P 6.9/2.7
10P 7/6	.4505	.4204	5PB 7.1/3.1	9.5P 7.2/4.6
10PB 7/4	.4544	.4072	5PB 7.2/4.0	10.0PB 7.1/4.0
10P 7/8	.4489	.4061	5PB 7.1/4.2	9.5P 7.3/6.0
P 7/4	.4410	.4005	5PB 7.1/4.4	5.0P 7.1/4.8
10PB 7/6	.4435	.3808	5PB 7.1/5.6	10.0PB 7.0/5.3
P 7/6	.4283	.3775	5PB 7.0/5.8	8.5P 7.0/6.4
Y 7/10	.3814	.3415	5Y 6.8/9.5	5.0Y 6.9/9.7
Y 7/8	.3879	.3353	5Y 6.7/9.4	6.0Y 6.9/9.5
10YR 7/10	.3803	.3234	5Y 6.4/8.7	1.0Y 6.9/10.6
10YR 7/8	.3885	.7386	5Y 6.7/6.9	0.5Y 7.1/8.3
YR 7/10	.3443	.7299	5Y 6.4/6.4	5.5YR 6.9/10.1
Y 7/6	.3854	.7188	5Y 6.7/6.4	4.5Y 6.9/6.6
10GY 6/8	.3406	.6868	5Y 6.3/5.3	9.0GY 6.2/7.7
10YR 7/6	.3919	.6680	5Y 6.7/5.2	10.0YR 7.0/8.3
YR 7/8	.3926	.6648	5Y 6.6/4.7	4.5YR 7.0/8.2
10GY 6/6	.3343	.6486	5Y 6.2/4.5	10.0GY 6.1/8.7
YR 7/6	.3757	.5906	5Y 6.6/3.2	3.5YR 7.0/6.0
YR 7/8	.3682	.5824	5Y 6.6/3.2	3.5YR 6.9/5.9
10R 7/8	.3625	.5736	5Y 6.5/2.8	10.0R 7.0/7.5
G 6/8	.3378	.5366	5Y 6.3/2.3	6.0G 6.0/7.4
G 6/4	.3277	.5269	5Y 6.3/1.6	6.0G 6.1/4.8
10G 6/6	.3689	.5060	5Y 6.7/1.1	1.0G 6.4/6.0
10G 6/4	.3743	.4943	5Y 6.6/0.7	2.0G 6.4/4.5
R 7/8	.3628	.4911	5Y 6.6/0.7	3.5R 7.0/7.0
BG 6/2	.3563	.4706	5Y 6.5/0.2	5.0BG 6.4/2.4
BG 6/4	.3700	.4680	5Y 6.6/0.1	5.5BG 6.4/4.1
5BG 6/6	.3510	.4676	5Y 6.6/0.1	5.5BG 6.4/5.2
10BG 6/4	.3583	.4426	5PB 6.5/1.6	10.0BG 6.3/4.1
10BG 6/6	.3776	.4334	5PB 6.6/2.1	10.0BG 6.3/5.8
B 6/2	.3400	.4296	5PB 6.3/2.2	7.5B 6.2/3.0
PB 6/2	.3530	.4141	5PB 6.4/3.2	5.0PB 6.4/3.2
B 6/4	.3527	.4119	5PB 6.4/3.4	6.5B 6.2/4.5
10B 6/4	.3666	.4010	5PB 6.3/4.0	10.0B 6.3/4.6
B 6/6	.3827	.3931	5PB 6.4/4.5	5.5B 6.1/6.4
PB 6/4	.3789	.3927	5PB 6.6/4.7	5.0PB 6.6/4.7
10B 6/6	.3654	.3843	5PB 6.6/5.1	9.0B 6.3/6.3

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell notations	
			Protanopic	Normal
10PB 6/4	0.3438	0.3821	5PB 6.4/ 5.2	0.5P 6.3/ 4.8
PB 6/ 8	.3634	.3659	5PB 6.5/ 6.3	6.0PB 6.3/ 6.2
PB 6/ 8	.3576	.3024	5PB 6.5/ 6.4	5.0PB 6.3/ 7.4
10YR 6/10	.3090	.6170	6Y 6.1/ 8.2	10.0YR 6.5/ 9.8
Y 6/ 8	.2967	.6284	6Y 6.0/ 8.1	8.5Y 6.2/ 8.3
Y 6/ 8	.2978	.6199	6Y 5.9/ 8.0	6.8Y 6.1/ 8.1
10Y 6/ 6	.3115	.7940	5Y 8.1/ 7.7	9.8Y 6.2/ 7.4
Y 6/ 6	.2924	.7718	5Y 8.0/ 7.0	5.0Y 6.2/ 7.2
YR 6/10	.2735	.7544	6Y 5.8/ 6.5	8.0YR 6.3/ 9.8
OY 6/ 6	.3222	.7499	6Y 6.2/ 6.7	4.0OY 6.2/ 7.2
10YR 6/ 6	.3013	.7449	6Y 6.0/ 6.6	9.5YR 6.4/ 8.0
OY 6/ 6	.3196	.7269	5Y 8.2/ 6.2	6.0OY 6.2/ 6.7
10GY 6/10	.3224	.7206	5Y 8.2/ 6.1	9.0GY 6.0/ 8.7
10YR 6/ 8	.3003	.6958	5Y 8.0/ 5.4	9.5YR 6.3/ 6.7
YR 6/ 8	.2731	.6871	6Y 6.6/ 5.0	5.0YR 6.2/ 8.3
10Y 6/ 4	.3188	.6400	6Y 6.2/ 4.2	10.0Y 6.2/ 4.1
Y 6/ 4	.2980	.6317	6Y 6.0/ 3.9	4.5Y 6.1/ 4.0
GY 6/ 4	.3212	.6211	5Y 6.2/ 3.8	5.0GY 6.2/ 4.0
YR 6/ 6	.2806	.6153	5Y 5.8/ 3.5	4.5YR 6.2/ 6.0
10R 6/ 8	.2737	.6060	5Y 5.8/ 3.3	0.5YR 6.2/ 8.2
10YR 6/ 4	.2916	.6065	5Y 5.9/ 3.3	0.5Y 6.1/ 4.1
10GY 6/ 4	.2929	.5772	5Y 6.2/ 2.8	0.5G 6.1/ 4.4
10R 6/ 6	.2896	.5683	6Y 5.9/ 2.4	0.5YR 6.3/ 6.5
YR 6/ 4	.2828	.5580	5Y 5.8/ 2.2	4.0YR 6.1/ 4.6
Y 6/ 2	.3127	.5319	5Y 6.1/ 1.7	4.0Y 6.2/ 1.7
OY 6/ 2	.3343	.5306	5Y 6.2/ 1.7	3.0GY 6.2/ 1.7
10R 6/ 4	.2944	.5244	5Y 5.9/ 1.4	9.0R 6.2/ 4.2
5YR 6/ 2	.2977	.5106	5Y 6.0/ 1.1	4.5YR 6.1/ 2.0
5G 6/ 2	.3158	.5006	5Y 6.1/ 0.9	8.0G 6.0/ 2.4
R 6/ 6	.2879	.4921	5Y 5.9/ 0.6	3.5R 6.2/ 6.3
R 6/ 4	.3004	.4888	6Y 6.0/ 0.6	4.5R 6.3/ 4.5
R 6/ 2	.3060	.4758	6Y 6.0/ 0.2	4.0R 6.2/ 2.3
N 6/ 6	.3032	.4653	N 6.0/	N 6.0/
10RP 6/ 8	.2815	.4596	5PB 6.9/ 0.4	9.0RP 6.2/ 5.5
10RP 6/ 4	.3019	.4593	5PB 6.0/ 0.3	8.5RP 6.2/ 4.0
10RP 6/ 8	.2811	.4583	5PB 5.9/ 0.4	9.0RP 6.2/ 7.0
RP 6/ 2	.3072	.4636	5PB 6.1/ 0.6	4.0RP 6.1/ 2.2
RP 6/ 4	.3260	.4428	5PB 6.2/ 1.4	4.5RP 6.4/ 4.2
RP 6/ 6	.3057	.4347	5PB 6.0/ 1.8	4.5RP 6.3/ 5.6
RP 6/ 8	.2968	.4208	5PB 6.0/ 3.6	5.0RP 6.3/ 7.3
P 6/ 2	.3218	.4176	5PB 6.2/ 2.9	4.5P 6.2/ 3.0
10P 6/ 4	.3098	.4135	5PB 6.1/ 3.1	10.0P 6.2/ 4.6
RP 6/10	.2951	.4066	5PB 6.0/ 3.3	4.5RP 6.3/ 8.3
10P 6/ 6	.3121	.3981	5PB 6.1/ 4.4	9.5P 6.2/ 6.2
P 6/ 4	.3270	.3882	5PB 6.3/ 4.7	4.0P 6.2/ 4.9
10P 6/ 8	.3013	.3710	5PB 6.0/ 5.6	9.0P 6.2/ 8.0
P 6/ 6	.3126	.3569	5PB 6.1/ 6.7	4.5P 6.2/ 7.1
10PB 6/ 6	.3227	.3564	5PB 6.2/ 6.7	10.0PB 6.1/ 6.3
P 6/ 8	.3080	.3322	5PB 6.1/ 8.4	5.0P 6.1/ 9.1
10PB 6/ 8	.3277	.3322	5PB 6.2/ 8.4	0.5P 6.2/ 8.0
YR 6/12	.2872	.6107	5Y 6.6/ 7.6	8.0YR 6.2/11.5
10GY 6/ 6	.2272	.6625	5Y 5.3/ 4.6	9.6GY 5.2/ 7.1
10R 6/10	.2609	.6672	4Y 5.6/ 4.2	0.5YR 6.2/10.1
10G 6/ 8	.2282	.6139	4Y 5.3/ 1.2	1.0BG 5.0/ 7.0
R 6/10	.2571	.6124	5Y 5.9/ 1.1	4.0R 6.2/ 9.7
R 6/ 8	.2692	.6043	5Y 5.7/ 0.9	4.0R 6.2/ 8.1

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell notations	
			Protanopic	Normal
10G 5/ 4	0.2235	0.4993	6Y 5.3/ 0.6	0.5BG 5.1/ 4.6
BG 6/ 6	.2593	.4643	8PB 5.4/ 0.1	5.0BG 5.1/ 6.4
BG 5/ 4	.2320	.4623	5PB 5.4/ 0.2	5.5BG 5.2/ 4.4
10RP 6/10	.2660	.4563	5PB 5.7/ 0.6	9.5RP 6.2/ 8.6
10BG 5/ 4	.2276	.4203	5PB 5.2/ 1.8	0.5B 5.1/ 4.4
10BG 5/ 6	.2463	.4081	5PB 5.5/ 2.9	1.0B 5.2/ 6.5
10B 5/ 4	.2316	.3869	5PB 5.4/ 4.2	10.0B 5.2/ 4.6
PB 5/ 4	.2294	.3792	6PB 5.3/ 4.5	4.5PB 5.4/ 4.4
B 6/ 6	.2262	.3735	6PB 5.3/ 4.8	6.0B 6.0/ 6.8
10PB 5/ 4	.2219	.3631	6PB 6.3/ 6.3	10.0PB 6.2/ 5.0
10B 5/ 6	.2353	.3615	6PB 5.4/ 5.5	9.5B 5.2/ 6.2
5PB 5/ 6	.2438	.3539	6PB 5.6/ 8.0	4.0PB 5.3/ 6.2
PB 5/ 8	.2606	.3323	6PB 5.6/ 7.6	4.0PB 5.4/ 7.9
PB 5/10	.2567	.3194	5PB 5.6/ 8.5	3.5PB 5.3/ 8.6
OY 5/ 8	.2112	.7800	5Y 5.2/ 6.4	5.0OY 5.1/ 7.1
10YR 5/ 8	.1811	.7890	6Y 4.8/ 6.2	0.5Y 6.1/ 7.6
Y 5/ 6	.1831	.7728	6Y 4.9/ 6.9	6.0Y 5.0/ 8.0
10Y 5/ 6	.2155	.7606	6Y 6.2/ 5.9	10.0Y 5.3/ 5.8
10OY 5/ 8	.2044	.7160	6Y 6.1/ 5.2	9.5OY 4.9/ 7.6
OY 5/ 8	.2076	.6998	5Y 5.1/ 4.8	5.0OY 5.1/ 5.4
10YR 5/ 6	.1873	.6928	5Y 4.9/ 4.5	10.0YR 5.2/ 5.7
10Y 5/ 4	.2164	.6766	5Y 5.2/ 4.4	6.5OY 5.3/ 4.4
Y 6/ 4	.1871	.6582	6Y 4.9/ 3.9	10.0Y 5.3/ 3.9
OY 5/ 4	.2089	.6500	6Y 6.1/ 3.7	5.0OY 6.1/ 4.1
10YR 5/ 4	.1854	.6398	5Y 4.9/ 3.5	10.0YR 5.1/ 4.4
10OY 5/ 4	.2111	.5933	5Y 6.2/ 2.9	10.0OY 5.0/ 4.3
G 5/ 8	.2122	.5890	5Y 5.2/ 2.7	5.0G 4.9/ 6.2
G 5/ 6	.2075	.5673	5Y 5.1/ 2.3	5.0G 4.9/ 6.6
G 5/ 4	.2008	.5458	5Y 5.0/ 1.8	5.0G 4.9/ 4.8
OY 5/ 2	.2097	.5443	5Y 5.1/ 1.8	5.0OY 5.1/ 2.0
Y 5/ 2	.2056	.5406	6Y 6.1/ 1.7	4.5Y 6.2/ 1.7
YR 5/ 2	.1813	.6149	6Y 4.8/ 1.6	4.0YR 4.9/ 2.1
G 5/ 2	.1971	.6010	6Y 4.9/ 0.8	6.5G 4.9/ 2.4
R 5/ 2	.1819	.4780	6Y 4.8/ 0.3	4.0R 5.0/ 2.8
BG 5/ 2	.2220	.4710	5Y 5.2/ 0.1	4.5BG 5.1/ 2.5
10RP 5/ 4	.2050	.4638	5PB 5.1/ 0.1	10.1RP 5.3/ 4.2
N 5/ 6	.1908	.4610	6PB 4.9/ 0.2	5.0PB 4.9/ 0.1
10RP 5/ 6	.1867	.4588	5PB 4.9/ 0.3	10.0RP 5.2/ 6.8
RP 5/ 2	.2048	.4512	5PB 6.1/ 0.7	5.0RP 5.2/ 2.8
RP 5/ 4	.1943	.4321	5PB 6.0/ 1.5	5.0RP 5.2/ 4.3
B 5/ 2	.2031	.4244	6PB 5.1/ 2.0	6.5B 4.9/ 2.6
RP 5/ 6	.1843	.4158	5PB 4.8/ 2.2	4.5RP 5.1/ 6.2
P 5/ 2	.1941	.4144	5PB 5.0/ 2.4	5.0P 5.0/ 2.3
RP 5/ 8	.1863	.4011	5PB 4.9/ 2.9	4.5RP 5.2/ 8.0
PB 5/ 2	.2164	.4042	5PB 5.2/ 3.0	5.0PB 5.1/ 3.1
10P 5/ 4	.2005	.3904	6PB 5.0/ 3.2	1.0RP 6.2/ 4.9
RP 6/10	.1882	.3647	6PB 4.9/ 3.3	6.5RP 5.3/ 9.7
B 5/ 4	.2187	.3641	6PB 6.2/ 3.6	5.5B 5.0/ 5.1
10P 5/ 6	.1937	.3703	5PB 5.0/ 4.4	1.0RP 5.2/ 6.7
5P 5/ 4	.1993	.3722	5PB 4.9/ 4.5	4.5P 5.0/ 4.7
10P 5/ 6	.1933	.3528	5PB 5.0/ 5.6	1.0RP 5.2/ 8.6
P 5/ 6	.1910	.3420	5PB 4.9/ 6.2	5.0P 5.0/ 6.8
10P 6/10	.1922	.3206	5PB 4.9/ 7.0	0.5RP 5.3/10.4
10PB 6/ 6	.2213	.3348	6PB 5.3/ 7.2	10.0PB 6.2/ 6.8
P 5/ 8	.2033	.3137	5PB 5.1/ 8.5	5.0P 5.1/ 8.9
10PB 5/ 8	.2206	.3073	5PB 6.2/ 9.1	10.0PB 5.2/ 8.4
10PB 5/10	.2104	.2991	5PB 5.1/10.3	10.0PB 5.0/ 9.6

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell rotations	
			Protanopic	Normal
P 5/10	0.1950	0.2858	6PB 5.0/10.4	5.0P 5.1/10.9
YR 5/10	.1634	.7770	5Y 4.6/ 5.8	5.5YR 5.1/ 9.0
YR 4/ 8	.1898	.7196	5Y 4.7/ 4.9	5.5YR 5.1/ 7.7
10R 5/10	.1445	.9866	5Y 4.4/ 4.1	10.0R 5.0/ 9.9
YR 3/ 6	.1869	.8577	5Y 4.8/ 3.7	5.0YR 5.0/ 6.2
10GY 4/ 6	.1443	.9487	5Y 4.4/ 2.4	10.0GY 4.2/ 5.4
10R 5/ 8	.1678	.9464	5Y 4.7/ 2.5	0.5YR 5.2/ 8.7
10R 5/ 6	.1605	.9023	5Y 4.6/ 2.7	10.0R 5.1/ 7.1
YR 3/ 4	.1671	.8925	5Y 4.6/ 2.6	4.5YR 4.9/ 4.6
10GY 4/ 4	.1412	.8915	5Y 4.3/ 2.4	1.0G 4.2/ 4.1
Y 4/ 2	.1376	.8525	5Y 4.3/ 1.7	5.5Y 4.3/ 1.7
G 4/ 4	.1414	.8512	5Y 4.3/ 1.7	5.0G 4.1/ 4.9
10R 5/ 4	.1749	.8477	5Y 4.7/ 1.7	9.5R 5.1/ 4.9
R 5/10	.1497	.8437	5Y 4.4/ 1.6	5.0R 5.2/10.9
R 5/ 8	.1427	.8271	5Y 4.3/ 1.2	4.5R 5.0/10.0
R 5/ 6	.1572	.8064	5Y 4.6/ 0.9	4.0R 5.0/ 8.0
10G 4/ 4	.1421	.8064	5Y 4.3/ 0.8	0.5BG 4.1/ 4.5
R 4/ 4	.1836	.4930	5Y 4.6/ 0.6	4.0R 4.2/ 5.3
BG 4/ 2	.1475	.4652	N 4.4/	5.5BG 4.3/ 2.5
BG 4/ 4	.1561	.4909	5PB 4.5/ 0.1	5.5BG 4.3/ 4.0
10RP 5/ 6	.1365	.4561	5PB 4.6/ 0.4	10.0RP 5.2/ 8.6
BG 4/ 8	.1593	.4532	5PB 4.6/ 0.5	5.5BG 4.2/ 6.0
10RP 5/10	.1349	.4626	5PB 4.6/ 0.5	10.0RP 5.2/10.2
RP 4/ 2	.1379	.4425	5PB 4.3/ 0.9	4.0RP 4.4/ 2.1
10BG 4/ 4	.1437	.4330	5PB 4.3/ 1.2	9.5BG 4.1/ 4.0
B 4/ 2	.1468	.4330	5PB 4.4/ 1.6	5.0B 4.3/ 2.7
10BG 4/ 6	.1594	.4139	5PB 4.3/ 2.0	10.0BG 4.2/ 5.7
B 4/ 4	.1619	.3882	5PB 4.6/ 3.2	6.0B 4.4/ 4.6
10B 4/ 4	.1416	.3790	5PB 4.3/ 3.6	0.5PB 4.2/ 4.1
PB 4/ 4	.1444	.3849	5PB 4.4/ 4.3	5.0PB 4.2/ 4.3
B 4/ 6	.1511	.3661	5PB 4.4/ 4.9	4.5B 4.1/ 6.4
5B 4/ 8	.1398	.3433	5PB 4.3/ 6.3	6.5B 4.0/ 6.9
10B 4/ 6	.1505	.3383	5PB 4.4/ 5.9	0.5PB 4.2/ 6.3
PB 3/ 6	.1502	.3339	5PB 4.4/ 5.9	4.5PB 4.2/ 8.0
10B 4/ 8	.1574	.3226	5PB 4.5/ 6.7	10.0B 4.1/ 7.3
PB 4/ 8	.1569	.3066	5PB 4.5/ 7.6	4.5PB 4.3/ 7.4
PB 4/10	.1681	.2913	5PB 4.7/ 9.3	4.0PB 4.4/ 8.9
YR 4/ 8	.1114	.7072	5Y 3.9/ 4.1	6.0YR 4.2/ 6.3
10YR 4/ 4	.1165	.6960	5Y 3.9/ 3.8	10.0YR 4.2/ 4.6
10Y 4/ 4	.1240	.6720	5Y 4.2/ 3.8	10.0Y 4.3/ 3.7
Y 4/ 4	.1162	.6784	5Y 3.9/ 3.7	5.0Y 4.1/ 3.6
GY 4/ 6	.1251	.6724	5Y 4.1/ 3.7	5.0GY 4.1/ 4.0
YR 4/ 6	.1203	.6696	5Y 4.0/ 3.6	6.0YR 4.4/ 5.8
10R 4/10	.1078	.6699	5Y 3.8/ 3.4	9.5R 4.4/ 9.0
10R 4/ 8	.1045	.6514	5Y 3.8/ 3.2	10.0R 4.3/ 8.4
YR 4/ 4	.1215	.6285	5Y 4.0/ 2.9	5.0YR 4.3/ 4.6
GY 4/ 4	.1318	.6242	5Y 4.2/ 2.9	5.0GY 4.2/ 3.2
10R 4/ 6	.1102	.6202	5Y 3.9/ 2.7	10.0R 4.3/ 7.3
10R 4/ 4	.1138	.6061	5Y 3.9/ 1.9	0.5YR 4.2/ 4.7
R 5/12	.1302	.5823	5Y 4.1/ 1.8	5.5R 5.0/12.8
GY 4/ 2	.1360	.5429	5Y 4.2/ 1.5	5.5GY 4.2/ 1.7
YR 4/ 2	.1166	.5343	5Y 3.9/ 1.2	4.0YR 4.1/ 2.8
G 4/ 2	.1247	.5075	5Y 4.2/ 0.8	6.0G 4.1/ 2.4
R 4/ 4	.1046	.4909	6Y 3.8/ 0.5	3.5R 4.1/ 4.7
R 4/ 2	.1160	.4827	6Y 4.0/ 0.3	4.0R 4.1/ 2.6
N 4/	.1211	.4597	5PB 4.0/ 0.1	5.0PB 4.0/ 0.1
10RP 4/ 4	.1128	.4513	5PB 3.9/ 0.4	9.0RP 4.1/ 4.1

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.9733 W _p	Protanopic chromaticity coordinate, w _p	Munsell rotations	
			Protanopic	Normal
RP 4/ 4	0.1288	0.4152	6PB 4.1/ 1.8	4.0RP 4.3/ 4.4
P 4/ 2	.1234	.4067	6PB 4.1/ 2.2	5.0P 4.1/ 2.2
PB 4/ 2	.1359	.4035	5PB 4.2/ 2.4	5.0PB 4.2/ 2.5
RP 4/ 6	.1206	.3925	5PB 4.0/ 2.7	4.5RP 4.3/ 6.4
10P 4/ 4	.1329	.3861	5PB 4.2/ 3.1	0.5RP 4.3/ 4.3
RP 4/ 8	.1068	.3759	5PB 3.8/ 3.1	4.5RP 4.2/ 7.9
RP 4/10	.1060	.3602	5PB 3.8/ 3.8	4.5RP 4.2/ 9.4
P 4/ 4	.1258	.3854	6PB 4.1/ 4.0	5.0P 4.1/ 4.2
RP 4/12	.1047	.3465	6PB 3.8/ 4.5	5.0RP 4.3/10.7
10P 4/ 6	.1292	.3530	6PB 4.1/ 4.6	0.5RP 4.3/ 6.6
10PB 4/ 4	.1314	.3455	6PB 4.2/ 5.0	10.0PB 4.1/ 4.6
P 4/ 6	.1198	.3267	5BP 4.0/ 4.9	5.0P 4.1/ 6.1
10P 4/ 8	.1236	.3274	5PB 4.0/ 5.9	0.5RP 4.3/ 8.5
10PB 4/ 6	.1295	.3111	5PB 4.2/ 7.1	10.0PB 4.2/ 6.6
P 4/ 8	.1219	.2977	5PB 4.0/ 7.8	5.0P 4.1/ 8.2
10P 4/10	.1112	.2964	5PB 3.9/ 7.5	0.5RP 4.2/10.4
10PB 4/ 8	.1347	.2824	5PB 4.2/ 9.2	10.0PB 4.1/ 8.5
5P 4/10	.1212	.2754	5PB 4.0/ 9.3	5.0P 4.1/10.1
10PB 4/10	.1283	.2633	5PB 4.1/10.2	10.0PB 4.0/ 9.7
P 4/12	.1145	.2688	5PB 3.9/12.1	5.5P 4.1/12.6
10GY 3/ 4	.0904	.6910	5Y 3.3/ 2.8	10.0GY 3.2/ 4.5
G 3/ 4	.0885	.6713	5Y 3.5/ 1.8	4.0G 3.3/ 4.8
10Y 3/ 2	.0778	.6710	5Y 3.3/ 1.8	0.5GY 3.3/ 1.8
R 4/12	.0812	.6693	5Y 3.3/ 1.8	5.0R 4.2/12.6
R 4/10	.0851	.6539	5Y 3.4/ 1.2	4.6R 3.2/10.8
R 4/ 8	.0912	.6300	5Y 3.5/ 1.1	4.6R 4.2/ 9.4
R 4/ 6	.0967	.6100	5Y 3.6/ 0.6	4.6R 4.1/ 6.8
10G 3/ 4	.0849	.5999	6Y 3.4/ 0.6	10.0G 3.2/ 4.7
5BG 3/ 2	.0791	.4604	6PB 3.3/ 0.1	5.0BG 3.2/ 2.8
BG 3/ 4	.0909	.4546	5PB 3.3/ 0.3	5.0BG 3.1/ 4.1
10RP 4/ 6	.1010	.4439	5PB 3.7/ 0.6	9.5RP 4.1/ 6.4
BG 3/ 6	.0683	.4497	5PB 3.5/ 0.7	6.0BG 3.2/ 5.3
10RP 4/ 8	.1027	.4297	5PB 3.7/ 1.1	9.0RP 4.2/ 8.2
10RP 4/10	.0980	.4281	5PB 3.6/ 1.1	5.5RP 4.2/ 9.5
10BG 3/ 4	.0688	.4168	5PB 3.5/ 1.4	6.5BG 3.3/ 4.3
B 3/ 2	.0774	.4109	5PB 3.3/ 1.5	5.6B 3.1/ 2.3
10BG 3/ 6	.0870	.3958	6PB 2.4/ 2.1	9.5BG 3.2/ 5.8
B 3/ 4	.0803	.3771	5PB 3.3/ 2.6	4.5B 3.1/ 4.2
10B 3/ 4	.0794	.3544	5PB 3.3/ 3.4	9.5B 3.1/ 3.9
B 3/ 6	.0681	.3604	5PB 3.3/ 3.9	5.0B 2.3/ 5.9
10B 3/ 6	.0600	.3241	5PB 2.5/ 5.2	9.5B 3.2/ 5.6
PB 3/ 6	.0629	.3026	5PB 2.4/ 5.8	5.0PB 3.2/ 5.6
10B 3/ 8	.0697	.3006	5PB 2.7/ 8.7	9.0B 3.3/ 7.1
PB 2/ 8	.0692	.2843	5PB 3.5/ 7.3	4.5PB 3.2/ 7.0
PB 2/10	.1002	.2694	5PB 3.7/ 9.0	4.5PB 3.4/ 8.6
PB 2/12	.0992	.2528	5PB 3.6/ 9.5	4.0PB 3.3/ 9.4
YR 3/ 4	.0665	.6217	5Y 3.0/ 2.6	5.0YR 3.3/ 4.1
10YR 3/ 2	.0636	.6060	5Y 3.0/ 2.3	10.0YR 3.1/ 2.7
GY 3/ 4	.0741	.6030	5Y 3.2/ 2.3	5.0GY 3.2/ 2.8
R 4/14	.0782	.6074	5Y 3.2/ 2.1	5.6R 4.2/13.2
R 4/12	.0783	.6020	5Y 3.2/ 2.1	5.6R 4.3/13.2
10R 3/ 6	.0614	.5859	5Y 2.9/ 2.0	10.0R 3.3/ 5.4
5GY 3/ 2	.0747	.5598	5Y 3.2/ 1.6	4.5GY 3.2/ 1.9
10R 3/ 4	.0611	.5568	5Y 2.9/ 1.4	10.0R 3.2/ 4.1
YR 3/ 2	.0636	.5437	5Y 3.0/ 1.3	5.0YR 3.1/ 2.1
YR 3/ 2	.0641	.5424	5Y 3.0/ 1.3	5.0YR 3.1/ 2.0
Y 3/ 2	.0671	.5362	5Y 2.9/ 1.2	6.0Y 3.1/ 1.1
G 3/ 2	.0747	.5207	5Y 3.2/ 1.0	6.0G 3.1/ 2.7
R 3/ 4	.0693	.5041	5Y 2.9/ 0.6	6.0R 3.2/ 4.6
R 3/ 6	.0630	.5031	5Y 2.9/ 0.8	4.5R 3.4/ 6.2
R 3/ 8	.0649	.4892	5Y 2.9/ 0.2	3.5R 2.1/ 2.1
N 3/	.0651	.4679	5PB 3.6/ 0.2	2.5P 3.0/ 0.2

TABLE 5. Protanopic arrangement—Continued

Munsell book notation	Protanopic reflectance, 0.5723 W ₀	Protanopic chromaticity coordinate, w _p	Munsell notations	
			Protanopic	Normal
10RP 3/4	0.0508	0.4412	5PB 2.8/ 0.5	9.0RP 3.0/ 3.4
RP 3/2	.0611	.4204	5PB 2.0/ 0.8	4.0RP 3.0/ 1.9
10RP 3/6	.0502	.4300	5PB 2.8/ 0.8	9.0RP 3.1/ 5.6
RP 3/4	.0596	.4037	5PB 2.8/ 1.4	5.0RP 3.0/ 2.7
P 3/2	.0722	.3889	5PB 3.1/ 2.1	5.0P 2.2/ 2.2
FP 3/2	.0719	.3975	5PB 3.1/ 2.1	5.0PB 3.1/ 2.1
RP 3/8	.0551	.3540	5PB 2.7/ 3.0	5.0RP 3.1/ 6.8
10P 3/4	.0685	.3542	5PB 3.0/ 3.2	10.0P 3.2/ 4.6
RP 3/10	.0653	.3353	5PB 2.8/ 3.7	5.0RP 3.2/ 8.4
PB 3/4	.0757	.3410	5PB 3.2/ 3.8	5.0PB 3.1/ 3.0
P 3/4	.0679	.3256	5PB 3.1/ 4.2	5.0P 3.1/ 4.5
10P 3/6	.0645	.3141	5PB 3.0/ 4.0	9.0P 3.2/ 6.3
10PB 3/4	.0728	.3128	5PB 3.2/ 5.3	10.0PB 3.1/ 4.7
P 3/6	.0711	.2914	5PB 3.1/ 5.2	4.5P 3.2/ 6.4
10PB 3/6	.0730	.2868	5PB 3.2/ 6.7	10.0PB 3.1/ 6.1
10P 3/8	.0599	.2794	5PB 2.8/ 6.5	10.0P 3.1/ 8.3
P 3/8	.0713	.2611	5PB 3.1/ 8.1	5.0P 3.2/ 8.4
10PB 3/8	.0743	.2643	5PB 3.2/ 8.2	10.0PB 3.2/ 7.4
P 3/10	.0700	.2224	5PB 3.1/11.0	5.0P 3.3/11.2
10PB 3/10	.0735	.2008	5PB 3.2/11.8	10.0PB 3.1/10.6
GY 2/2	.0403	.5884	5Y 2.5/ 1.6	5.0GY 2.5/ 2.2
10Y 2/2	.0475	.5800	5Y 2.5/ 1.6	10.0Y 2.6/ 1.6
Y 2/2	.0455	.5583	5Y 2.5/ 1.4	5.0Y 2.5/ 1.4
10GY 2/2	.0456	.5582	5Y 2.5/ 1.4	9.0GY 2.4/ 2.5
10YR 2/2	.0472	.5419	5Y 2.5/ 1.2	7.4YR 2.6/ 1.5
R 3/10	.0487	.5371	5Y 2.6/ 1.1	5.0R 3.2/ 8.3
YR 2/2	.0403	.5274	5Y 2.3/ 0.9	4.5YR 2.4/ 1.8
R 3/8	.0519	.5291	5Y 2.7/ 0.9	5.0R 3.2/ 7.4
G 2/2	.0396	.5061	5Y 2.3/ 0.6	7.0G 2.2/ 2.4
10R 2/2	.0397	.5056	5Y 2.3/ 0.6	8.3R 2.5/ 2.8
10G 2/2	.0445	.4967	5Y 2.5/ 0.4	10.0G 2.3/ 3.1
5BG 2/2	.0412	.4623	5PB 2.3/ 0.1	4.5BG 2.2/ 2.5
BG 2/4	.0446	.4644	5PB 2.5/ 0.2	5.0BG 2.3/ 3.7
10BG 2/2	.0307	.4400	5PB 2.6/ 0.5	7.0BG 2.5/ 3.1
B 2/2	.0414	.4215	5PB 2.4/ 0.9	2.0B 2.2/ 2.2
10RP 3/8	.0615	.4167	5PB 2.7/ 1.0	9.0RP 3.1/ 7.0
RP 3/6	.0549	.3837	5PB 2.7/ 2.0	5.0RP 3.0/ 6.2
10RP 3/10	.0505	.3507	5PB 2.8/ 2.0	3.5RP 3.2/ 8.5
10B 2/2	.0455	.3654	5PB 2.4/ 2.4	8.5B 3.2/ 3.1
PB 2/4	.0437	.3080	5PB 2.4/ 4.7	4.0PB 2.3/ 4.9
10PB 2/4	.0391	.2884	5PB 2.3/ 5.1	10.0PB 2.2/ 4.9
PB 2/6	.0474	.2802	5PB 2.6/ 6.8	4.0PB 2.3/ 5.9
10P 3/10	.0531	.2438	5PB 2.7/ 8.3	9.0P 3.0/ 9.5
R 2/4	.0311	.4713	5Y 2.0/ 0.1	4.0R 2.3/ 3.8
R 2/2	.0397	.4693	5Y 2.2/0.05	3.5R 2.3/ 2.2
R 2/6	.0359	.4565	5PB 2.0/ 0.1	3.0R 2.5/ 4.8
N 2/	.0300	.4570	5PB 2.0/ 0.1	5.0P 2.0/ 0.2
RP 2/2	.0352	.4204	5PB 2.1/ 0.9	4.0RP 2.3/ 2.3
10RF 2/4	.0336	.4127	5PB 2.1/ 1.1	6.0RP 2.3/ 3.7
10RF 2/6	.0323	.3700	5PB 2.0/ 1.9	8.0RP 2.4/ 5.6
RF 2/4	.0345	.3691	5PB 2.1/ 2.2	5.0RP 2.4/ 4.6
PB 2/2	.0375	.3603	5PB 2.2/ 2.5	4.5PB 2.2/ 2.6
P 2/2	.0340	.3493	5PB 2.1/ 2.8	5.5P 2.1/ 2.9
RP 2/6	.0359	.3385	5PB 2.2/ 3.1	4.0RP 2.4/ 5.9
P 2/4	.0344	.3072	5PB 2.1/ 4.2	5.0P 2.2/ 4.6
10P 2/4	.0333	.3061	5PB 2.1/ 4.3	9.0P 2.2/ 5.3
10PB 2/6	.0368	.2767	5PB 2.2/ 5.6	10.0PB 2.2/ 5.5
10P 2/6	.0327	.2723	5PB 2.1/ 5.6	9.0P 2.2/ 6.8
P 2/6	.0323	.2590	5PB 2.0/ 6.2	5.0P 2.1/ 6.8

Thus far no precise indication has been given of the color perceptions of deuteranopes and protanopes corresponding to the 400 samples in the Munsell Book of Color; we have only grouped together those samples that differ least and that are therefore most likely to be confused. We know, however, that deuteranopes and protanopes in all probability perceive black, gray, and white normally; furthermore, we know (see table 3) that their yellow corresponds closely to what the normal observer sees in the spectrum at 575m μ , and their blue corresponds closely to 470m μ . These facts may be conveniently expressed in the Munsell color system by giving for each set of values of W/W_0 and w the Munsell equivalent of the purple-blue (PB) or yellow (Y) hue; see master hue chart, figure 13 of the OSA Subcommittee on the Spacing of the Munsell Colors [76]. These Munsell hues correspond closely to those of the spectrum at 470 and 575m μ , respectively, and since the exact hues corresponding to these portions of the spectrum depend somewhat on the observing conditions [14, 17, 96] more precise fitting (as by 6PB and 7Y) is probably not warranted.

The deuteranopic and protanopic Munsell notations based in this way resulted from the following steps: (a) from table 1 of the OSA Subcommittee Report [76] (pp. 399 and 402) were read the chromaticity coordinates (x, y) for enough colors of the hues 5Y and 5PB to cover the range of the Munsell papers; (b) from these chromaticity coordinates were computed the dichromatic coordinates w_x and w_p , according to eq 2d and 2p and these coordinates were tabulated in table 6; (c) from the data of table 6 families of curves were plotted on each of two graphs, one with w_x as the abscissa, the other with w_p as the abscissa, the ordinate being Munsell chroma and each curve showed the variation of Munsell chroma for hue 5Y or 5PB with dichromatic coordinate (w_x or w_p) for some one Munsell value; (d) from the reflectance relative to magnesium oxide, W/W_0 , (second col of tables 4 and 5), the Munsell value was read from table 2 of the subcommittee report [76]; and (e) by interpolation among the curves of the corresponding family according to this Munsell value, the Munsell hue (whether 5Y or 5PB) was determined, and the Munsell chroma corresponding to the dichromatic coordinate, w_x or w_p , was read with an uncertainty of about 0.1 chroma step. The Munsell di-

chromatic rennotations (Hue Value/Chroma) so found are given in the fourth column of tables 4 and 5. The fifth column is the normal Munsell rennotation copied from table 3 of the subcommittee report [76].

Comparison of these two columns (dichromatic Munsell rennotation with normal Munsell rennotation) indicates in a precise and detailed way the difference between the surface-color perceptions of the normal observer and those of the average deuteranope and average protanope, respectively.

TABLE 6. Deuteranopic and protanopic chromaticity coordinates for Munsell rennotations of hues 5Y and 5PB

Munsell rennotation	Chromaticity coordinates		Munsell rennotation	Chromaticity coordinates	
	w_x	w_y		w_x	w_y
5Y 9/12	0.8510	0.8433	5PB 8/ 6	0.2615	0.3810
5Y 9/10	.7911	.7827	5PB 8/ 4	.3973	.4119
5Y 9/ 8	.7296	.7219	5PB 8/ 2	.4925	.4423
5Y 8/ 6	.6628	.6569			
5Y 8/ 4	.6055	.6028	5PB 7/10	.2927	.3214
5Y 8/ 2	.6291	.6305	5PB 7/ 8	.3246	.3469
			5PB 7/ 6	.3670	.3798
5Y 8/12	.8905	.8731	5PB 7/ 4	.3913	.4065
5Y 8/10	.8181	.8093	5PB 7/ 2	.4272	.4377
5Y 8/ 8	.7494	.7408			
5Y 8/ 6	.6764	.6696	5PB 6/12	.2507	.2836
5Y 8/ 4	.6028	.5993	5PB 6/10	.2804	.3107
5Y 8/ 2	.5326	.5335	5PB 6/ 8	.3096	.3354
			5PB 6/ 6	.3426	.3636
5Y 7/12	.9125	.9061	5PB 6/ 4	.3623	.3684
5Y 7/10	.8552	.8466	5PB 6/ 2	.4308	.4319
5Y 7/ 8	.7788	.7693			
5Y 7/ 6	.7007	.6927	5PB 5/12	.3299	.3675
5Y 7/ 4	.6184	.6139	5PB 5/10	.3577	.3909
5Y 7/ 2	.5379	.5369	5PB 5/ 8	.3891	.4176
			5PB 5/ 6	.4242	.4470
5Y 6/12	.9436	.9377	5PB 5/ 4	.4662	.4829
5Y 6/10	.8935	.8858	5PB 5/ 2	.4166	.4326
5Y 6/ 8	.8231	.8134			
5Y 6/ 6	.7546	.7351	5PB 4/12	.3017	.3426
5Y 6/ 4	.6873	.6814	5PB 4/10	.3282	.3653
5Y 6/ 2	.6471	.6468	5PB 4/ 8	.3596	.3919
			5PB 4/ 6	.3907	.4261
5Y 5/12	.9903	.9894	5PB 4/ 4	.4442	.4642
5Y 5/10	.9326	.9279	5PB 4/ 2	.4656	.4691
5Y 5/ 8	.8665	.8662			
5Y 5/ 6	.7783	.7677	5PB 3/12	.1606	.2065
5Y 5/ 4	.6867	.6868	5PB 3/10	.1896	.2305
5Y 5/ 2	.5569	.5558	5PB 3/ 8	.2228	.2594
			5PB 3/ 6	.2605	.2919
5Y 4/ 8	.9168	.9061	5PB 3/ 4	.3104	.3346
5Y 4/ 6	.8200	.8092	5PB 3/ 2	.3729	.3890
5Y 4/ 4	.7061	.6962			
5Y 4/ 2	.5774	.5741	5PB 2/12	.1313	.1709
			5PB 2/10	.1469	.1925
5Y 3/ 6	.8839	.8748	5PB 2/ 8	.1798	.2215
5Y 3/ 4	.7873	.7861	5PB 2/ 6	.2207	.2604
5Y 3/ 2	.6999	.6964	5PB 2/ 4	.2633	.3107
			5PB 2/ 2	.3564	.3790
5Y 2/ 4	.8330	.8266			
5Y 2/ 2	.6149	.6182	5PB 1/10	.0996	.1508
			5PB 1/ 8	.1214	.1785
5Y 1/ 2	.7392	.7267	5PB 1/ 6	.1739	.2157
			5PB 1/ 4	.2337	.2671
N 1/ 10 9/	.4655	.4652	5PB 1/ 2	.3127	.3335
5PB 9/ 2	.4322	.4467			

It will be noted, of course, first that the normal observer perceives a multiplicity of hues (red, yellow-red, yellow, green-yellow, green, and so on), while the deuteranope and protanope perceive but two—Munsell yellow and Munsell purple-blue. Second, it will be noted from table 4 that the Munsell value of each sample for the deuteranope is the same as that for the normal observer, but from table 5 the protanopic and normal Munsell value differs except for hues near to yellow-green (3GY) and bluish purple (2P). The reddish colors have lower protanopic values, and the greenish have higher; the amount of the difference from the normal values varying from one value step for R 4/14 to zero for nearly neutral colors.

Table 5 also serves to indicate the degree to which protanopic vision leads to confusions between colors easily distinguishable by a normal observer. For samples of small size, such as those that yield ideal protanopic vision, a difference of 0.1-value step or 0.2-chroma step is so small as to be easily confusable with zero difference. From table 5 it may be seen therefore, that Munsell samples GY 8/6 and 10Y 8/6 would be confusable to a typical dichromat if viewed in small size, though to the normal observer, of course, these two samples are distinctly different. By proceeding along the fourth column of table 5 and noting the samples whose protanopic rennotations differ by 0.1 or less in value and at the same time by 0.2 or less in chroma, we may make an estimate of the frequency with which a protanope will be troubled to distinguish colors that to the normal observer are separated by at least 10 just noticeable steps. It is found that there are 97 such pairs among the 410 different colors listed; that is, in a group of colors chosen in such a way as to be unrelated to the characteristic protanopic confusions, still about one-fourth of the colors are by chance confusable with another of the group.³ This result may explain, on the one hand, why dichromatic observers often reach maturity without having become convinced that there is anything abnormal about them other than unusual unfamiliarity with the meaning of color terms, since in about three-fourths of the pairs that they are called upon to

³ A similar count of pairs confusable by the deuteranope can be made from the fourth column of table 4, and about 200 will be found, roughly twice as many, as from table 5. This is ascribable to the fact that the samples are not unrelated to deuteranopic confusions, being divisible into seven groups, each composed of samples differing but slightly in deuteranopic Munsell value.

compare, they see a difference but describe it in terms not used by the normal observer. On the other hand, since one-fourth of the differences that the normal observer sees plainly are so slight to the red-green confusing dichromat that he must look long and closely to decide about them, and occasionally fails completely, it is easy to understand that a characteristic by which the dichromat is marked is his tendency to hesitate before making a decision, to wait for someone else to speak up, and then to agree with him.

It is suggested that persons who have been found to have either protanopic or deuteranopic vision by the usual tests might find it interesting and possibly instructive to lay out the Munsell papers in the order given in table 4 or table 5, as the case may be, and see to what degree the Munsell dichromatic notation accords with their own perceptions. To the extent that the accord is good, the person will discover how well his type of vision is known; and he may be encouraged to study the basis of the Munsell dichromatic notation, and so gain an additional insight into the relation of his own vision to that possessed by the majority. If the Munsell dichromatic notation fails to accord with his perceptions in ways not to be corrected by viewing the papers through bluish or brownish goggles, it is likely that the observer will find that he has been mistyped by careless administration or interpretation of a routine test, and a retest would be in order. Should the observer find that he is indeed a red-green confusing dichromat, he would have a chance to contribute to the knowledge of color perceptions by studying and reporting the nature and degree of any contradictions.

V. Analysis of Color-Blindness Tests in Terms of Dichromatic Munsell Notations

To show how tables 4 and 5 make available the color perceptions of deuteranopes and protanopes, respectively, it will be sufficient to analyse a few of the color-blindness tests based upon light-reflecting objects whose colors are fairly well established.

1. Holmgren Wool Test

Probably the oldest color-blindness test still in fairly common use is the famous wool test developed by Holmgren [38]. In this test a considerable

number (50 to 200) of small skeins of differently colored yarns are placed in a pile on a flat surface sufficiently spacious and illuminated with full daylight. The skein having the trial color is taken from the pile by the examiner and placed to the side far enough from the others not to be confused with them during the test. The examiner requests the subject to pick out the other skeins that come closest to the test skein in color and to place them beside it. Three tests are recommended by Holmgren, one with a green trial skein, one with a purple or rose colored skein, and a third with a red skein. The color chart (p. 120) "serves to guide the examiner in the choice of colors for the test skeins and in appreciating the mistakes of the deficient. We have tried to render there the colors mentioned in this chapter. We divide them into two classes:

"1. The test colors, that is to say, those which the examiner offers to the subject, and

"2. The confusion colors, that is to say, those which the deficient picks from the pile because he confuses them with that of the specimen."

Table 7 gives the Munsell book notations found in April 1942 for the colors of the chart that forms the frontispiece of a book [38] sent by Holmgren personally to the Smithsonian Institution from which it was turned over on October 10, 1884, to the Library of Congress as volume 150530. Some of the colors were found to be obviously faded; for example color I, supposed to be a green (neither yellow green nor blue green), was found to be a weak greenish yellow, and color IIa, supposed to be a purple, was found to be a light brown. However, the colors relating to the third test seem not to have faded seriously and will serve as an example of how to analyse a color-blindness test by means of dichromatic Munsell notations.

Of the third test Holmgren says, "The red skein is presented to the subject. It should have a vivid red color like the red flag serving as a signal for the railroads. This color corresponds to IIb of the chart, which ought perhaps to incline a little more definitely toward yellowish red. The test, which is to be made only with subjects that are completely defective, ought to be continued until the subject has placed with the test skein all of the skeins having that hue, or until he has selected one or more of the confusion colors (10 to 13). The red-blind (protanope, by present-day terminology) chooses in addition to red some

shades of green and brown (10 and 11) that for the normal sense appear darker than the red. But the green-blind (deuteranope) chooses contrasting hues which appear lighter than the red."

The analysis of this test consists in finding the dichromatic Munsell notations of the confusion colors (10 to 13) and comparing them to the dichromatic Munsell notation of the trial color (IIb). From tables 4 and 5, the dichromatic Munsell notations of these five colors have been obtained by reading the notations for neighboring colors and interpolating among them. For example, color IIb was found to have a Munsell book notation of 5.5R 4.8/10. The two closest colors in table 5 are R 5/10 and 10R 5/10, from which we read protanopic equivalents of Y 4.4/1.5 and Y 4.4/4.1, from which in turn by interpolation we would get a protanopic equivalent of Y 4.4/1.8 for 5.5R 5.0/10, and Y 4.2/1.8 for the required book notation 5.5R 4.8/10. This equivalent is given in table 7, together with deuteranopic and protanopic equivalents similarly found for colors IIb, 10, 11, 12, and 13.

TABLE 7. Munsell book notations of the color chart published by Holmgren to indicate how to administer and interpret his wool test; also dichromatic Munsell renotations of five of the colors

Holmgren's—		Munsell book notation	Dichromatic Munsell renotation	
Description	Number		Protanopic	Deuteranopic
Green.....	1	5Y 7/4		
Colors confused with green.	1	6Y 6/2		
	2	1Y 6/2.5		
	3	4Y 8/5		
Purple.....	4	7YR 3/5		
	5	7YR 7/3		
Protanopic confusions with purple.	IIa	6YR 6.5/3		
	6	5PB 3.0/8		
Deuteranopic confusions with purple.	7	6P 4.0/5		
	8	6Y 5.6/1		
Red.....	9	7G 4.3/8		
	IIb	5.5R 4.8/10	Y 4.2/1.8	Y 4.9/3.5
Protanopic confusions with red.	10	7GY 3.5/2	Y 3.8/1.5	Y 3.7/1.3
	11	10YR 3.8/2	Y 3.6/2.1	Y 3.7/2.3
Deuteranopic confusions with red.	12	5GY 6.0/8	Y 6.2/5.2	Y 6.2/5.9
	13	5YR 4.0/8	Y 4.0/3.6	Y 4.4/4.2

It is evident from an examination of table 7 why the protanope would be expected to confuse colors 10 and 11 with the red color IIb. The protanopic renotations of these colors differ from

that of the red by 0.6 of a value step or less and by only 0.3-chroma step. Similarly, color 13 would be expected to be moderately confusable by deuteranopes with the red color IIb, because the deuteranopic Munsell renotations of these two colors differ by only 0.5 of a value step and 0.7-chroma step; but color 12 should be distinct from the red color IIb to deuteranopes because it is lighter by 1.3 value steps and higher in chroma by 2.4 steps (compare Y 6.2/5.9 with Y 4.9/3.5). This analysis shows that the colors in Holmgren's book conform to his statements regarding the test with the red skein except for color 12, which was probably not correctly rendered originally by the lithographer. The other discrepancies are too small to be significant in view of Holmgren's statement: "The resemblance need not be perfect in all respects; there are no two skeins that are exactly alike. The question is particularly on resemblance in hue, and on this account the subject ought to look for those that are similar and belong to the same hue, that which is paler or deeper but of the same color, and so on. . . . Not too much attention should be paid to lightness nor to slight shades of off-gray color."

Similar analyses of tests by means of green and purple skeins give similar corroboration of Holmgren's interpretation of his tests, but these analyses have to be carried out with reference to the actual colors of the green and purple skeins used instead of the faded colors I and IIa of the color chart.

2. Stilling Pseudo-Isochromatic Plates

The plates developed by Stilling in 1878 [91] are still used [71, 93], and copies and developments of them are widely distributed in this country [1, 41]. The subject is shown a series of printed pages in succession, each page covered with a pattern of irregularly shaped spots. The spots are so colored and so arranged that numbers can be read on the plates by many observers of normal vision, but to observers having various types of abnormal vision certain of the plates seem to have uniform colors or a uniform mixture of colors, so that no number can be read. Because of this, they are called pseudo-isochromatic plates.

The analysis of a pseudo-isochromatic plate designed to detect protanopia or deuteranopia can be carried out by obtaining the Munsell book notations of typical background spots and typical spots making up the number, reading their pro-

tanopic and deuteranopic Munsell notations by interpolation in tables 4 and 5, and comparing them. These charts were designed, however, to accord with a view of the color perceptions of dichromatic observers developed by Stilling and described by him in detail by means of a color chart printed in 1909 [92]. It will suffice for illustration of the method to confine our analysis to these printing-ink reproductions of the colors.

Table 8 gives the Munsell book notations of most of the colors found in 1944 on the color chart in the Library of Congress copy of Stilling's paper, *Über Entstehung und Wesen der Anomalien des Farbensinnes* [92]. The colors dealing with Stilling's view of the color perceptions of tritanopes have been omitted. Table 8 also shows the protanopic and deuteranopic Munsell renotations corresponding to these book notations read by interpolation from tables 4 and 5.

From the Munsell book notations of the brown, light brown, and gray colors representing Stilling's view of what the red-green confuser's color perceptions are, it may be seen that his idea of the hue of these perceptions is close to that taken in the present paper; in no case does his estimate depart from the present one (5Y) by as much as five Munsell hue steps. The value and chroma estimates are also fairly close, particularly those for the color-blind equivalent of blue green; compare Y 6.9/4.3 with Y 5.8/3.6 and Y 6.7/3.6 with Y 6.0/3.8. The light brown chosen is only slightly darker (0.9 of a value step) than that which would represent an average confusion color for protanope and deuteranope. The yellowish gray shown as an estimate of the color-blind perception of violet is very close to the present estimate of the deuteranopic perception of the violet shown (compare Y 5.7/0.6 with Y 6.2/0.9); but since the name given to this sample was gray, the agreement may signify only that there has been a yellowing of the printing-ink representation of gray since its preparation in 1909. Actually the average of the protanopic (PB 5.4/0.4) and deuteranopic (Y 5.7/0.6) Munsell renotations for the violet shown on the chart is very close to a neutral gray.

The protanopic and deuteranopic confusion colors for red (7R 4.5/8), also shown in table 8 are not in very striking agreement; in each case the green is too light and of too high a chroma to be confused by an average protanope or deuteranope. Since the difference between the two colors cor-

responds well with the difference between the present estimate of the protanope and deuteranope color perceptions, it is reasonable to suppose that the greenish printing-ink specimens, like the gray, have yellowed with age by one chroma step since 1909. Note that the protanopic equivalent of the red is lower in chroma by $3.4 - 2.0 = 1.4$ chroma steps than the deuteranopic equivalent. The green chosen by Stilling as a protanope confusion for red also gives a dichromatic equivalent of lower chroma ($6.0 - 3.5 = 2.5$, $5.8 - 3.2 = 2.6$) than that chosen as the deuteranope confusion for the same red. The two printing-ink specimens thus give the correct idea of the difference between the greens that are confused with red by red-green confusers, but the amount of chroma difference is exaggerated. Similarly, the correct idea of the lightness difference is given ($4.6 - 4.0 = 0.6$), but the amount is in this case too small ($5.6 - 5.4 = 0.2$, $5.7 - 5.4 = 0.3$). Stilling was perfectly well aware of the direction of this difference, because he refers to the protanope confusion green as a "somewhat darker green"; whether he had very precise quantitative information cannot be told from this illustrative example because of the uncertainties

TABLE 8. Munsell book notations of the color chart published by Stilling [92] to indicate his view of the color perceptions and confusions of red-green confusers; also protanopic and deuteranopic Munsell renotations of them

Stilling's description	Munsell book notation	Dichromatic Munsell renotations	
		Protanopic	Deuteranopic
Red	7.4R 4.5/8	Y 4.2/2.6	Y 4.0/4.1
Brown seen by color-blind instead.	0.2Y 5.9/8	Y 5.2/5.4	Y 5.2/5.3
Pink	7.4R 6.2/8	Y 5.9/2.1	Y 6.4/3.1
Light brown seen instead	2.5Y 5.0/4	Y 5.8/3.6	Y 6.0/3.8
Violet	9RP 5.6/8	PB 5.4/0.4	Y 5.7/0.6
Gray seen by color-blind instead.	7.6Y 6.0/1	Y 6.2/0.9	Y 6.2/0.9
Blue-green	2G 6.8/8	Y 6.9/4.3	Y 6.7/3.6
Light brown seen instead	2.6Y 5.9/4	Y 5.8/3.6	Y 6.0/3.8
Yellow-green	8GY 7.3/4.8	Y 7.5/3.7	Y 7.4/3.2
Brown seen by color-blind instead.	0.2Y 5.9/8	Y 5.2/5.4	Y 5.2/5.3
Red	7R 4.5/8	Y 4.0/2.0	Y 4.6/3.4
Yellow-green confused with red by deuteranope.	3GY 6.6/8.0	Y 5.6/6.0	Y 5.7/5.8
Green confused with red by protanope.	6GY 5.3/4	Y 6.4/3.5	Y 6.4/3.2

introduced by possible failure of the lithographic process to render the colors correctly, and because of possible changes of the colors with time.

3. Farnsworth Dichotomous Test (B-20)

The serial order test devised by Farnsworth [20] at the beginning of the war for screening observers into two groups is particularly easy to analyse in terms of dichromatic Munsell notations, because it is based upon Munsell papers whose color characteristics are known through spectrophotometry [28, 53]. Table 9 shows the protanopic renotations of these papers arranged in the order given by Farnsworth for a typical protanope; and it also shows the deuteranopic renotations of the papers arranged in the order given by Farnsworth for a typical deuteranope. The values of W_p , w_p , W_d , and w_d are taken from a previous publication [51].

It will be noted that the arrangement of these papers made by the observer chosen by Farnsworth as a typical protanope is closely, but not perfectly, given by the protanopic Munsell renotation ranging from a yellow of chroma 2.2 through a near neutral (Y 5.2/0.1) to a purple blue of chroma 3.3. A similar correspondence may also be noted between the Farnsworth deuteranopic arrangement and deuteranopic Munsell renotation. Possible causes for the failure of the cor-

relation to be perfect are the same as those previously discussed with reference to the chromaticity coordinates, w_p and w_d [51]. The chief cause of the discrepancies seems to be a slight but consistent difference between the hypothetical average observers defined by eq 1, on the one hand, and the actual observers chosen by Farnsworth as typical on the other. The discrepancies may thus be taken as indicating about the degree of agreement to be expected between an average red-green confuser and some one observer of the same type chosen at random.

VI. Summary

A review of the literature on color perceptions mediated by dichromatic, red-green-confusing, visual mechanisms for an observer capable of relating them to normal color perceptions has been carried out, and it shows that both types of such mechanisms (protanopia and deuteranopia) yield color perceptions of two hues, and two hues only, yellow and blue. A review of the chief theories of vision shows that they also all provide for this kind of color perception. A method of deriving protanopic and deuteranopic Munsell notations of colors from their specification in the standard ICI colorimetric coordinate system has

TABLE 9. Protanopic and deuteranopic Munsell renotations of the chips of the Farnsworth dichotomous test [20] arranged in the order found by Farnsworth for a typical protanope and a typical deuteranope, respectively

Protanopic arrangement	Normal serial number	$0.0733 W_p$	w_p	Protanopic Munsell renotation	Deuteranopic arrangement	Normal serial number	W_d	w_d	Deuteranopic Munsell renotation
1.....	8	0.2283	0.5628	Y 5.3/2.2	1	10	0.2143	0.5493	Y 5.2/1.8
2.....	10	.2038	.5405	Y 5.1/1.7	2	9	.2117	.5412	Y 5.2/1.7
3.....	7	.2066	.5442	Y 5.1/1.8	3	8	.2292	.5504	Y 5.3/2.1
4.....	6	.2061	.5307	Y 5.1/1.5	4	7	.2087	.5376	Y 5.1/1.6
5.....	9	.2056	.5406	Y 5.1/1.7	5	11	.1927	.5234	Y 4.9/1.8
6.....	11	.1813	.5149	Y 4.8/1.0	6	12	.2185	.5153	Y 5.2/1.2
7.....	5	.1972	.5011	Y 5.0/0.8	7	6	.2017	.5183	Y 5.0/1.2
8.....	12	.2034	.5042	Y 5.1/0.9	8	13	.1954	.4891	Y 5.0/0.6
9.....	13	.1816	.4779	Y 4.8/0.5	9	14	.2228	.4791	Y 5.3/0.4
10.....	4	.2180	.4709	Y 5.2/0.1	10	5	.1898	.4835	Y 4.9/0.6
11.....	3	.2152	.4432	PB 5.2/1.0	11	15	.2159	.4552	PB 5.2/0.1
12.....	15	.2049	.4512	PB 5.1/0.7	12	16	.2082	.4320	PB 5.1/1.1
13.....	14	.2103	.4684	Y 5.1/0.1	13	4	.2077	.4691	PB 5.1/0.3
14.....	2	.2080	.4242	PB 5.1/2.0	14	17	.1950	.4101	PB 5.0/2.0
15.....	16	.2027	.4509	PB 5.1/1.6	15	3	.2043	.4227	PB 5.1/1.6
16.....	17	.1942	.4145	PB 5.0/2.4	16	2	.1917	.4037	PB 4.9/2.2
17.....	1	.2321	.4301	PB 5.4/2.3	17	18	.2118	.3906	PB 5.2/3.0
18.....	19	.2071	.4121	PB 5.1/2.5	18	20	.2087	.3891	PB 5.1/3.0
19.....	20	.2164	.4042	PB 5.2/3.0	19	19	.2035	.4013	PB 5.1/2.5
20.....	18	.2140	.3908	PB 5.2/3.3	20	1	.2229	.4037	PB 5.3/2.5

been worked out on the basis of this kind of color perception. It is concluded that these notations of colors conform to the usual perceptions of them by protanopic and deuteranopic observers in the sense that the chance of any protanope or deuteranope of average ocular pigmentation having valid ground for objecting to them is remote. These protanopic and deuteranopic Munsell notations therefore serve to relate in a complete and detailed way the color perceptions of red-green-confusing dichromats with those of normal vision. It is expected that this detailed information will assist in the design of color-blindness tests, and will help color-blind persons to understand the relation of their own visual systems to the normal system and so give them a better chance to avoid the embarrassments and dangers of living in a tridimensional color world with a two-dimensional color detector.

VII. References

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