A Colorizer for Use in Determining an Optimal Ophthalmic Tint

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Abstract: A colorizer for use in the provision of an ophthalmic tint is described. The design differs from that of an earlier model in that the spectral power distribution of the light in the instrument is very similar to the spectral power distribution obtained when tinted glasses are worn under typical lighting. The similarity in spectral power is obtained notwithstanding the fact that the instrument uses an additive mixture of filtered light, whereas tinted lenses use a subtractive mixture of dyes. The precision of color selection is high, and this precision is shown to be necessary to optimize reading fluency. Because of the similarity in spectral power distribution, it is possible to examine the effect of ophthalmic tints not only on reading fluency, but also on the perception and naming of colored surfaces, and the examination can be undertaken by patients who have color vision anomalies. Compared with the earlier design, the use of a diffuse source and seven colored filters reduces the requirement for precision in alignment of components; the variation in color from one instrument to another is, therefore, small, allowing a single calibration for all instruments. This calibration permits the matching of colored ophthalmic lenses to a given colorizer setting, using a computer algorithm which enables practitioners with color vision deficiencies to undertake ophthalmic colorimetry. © 2000 John Wiley & Sons, Inc. Col Res Appl, 26, 246–253, 2001

Key words: ophthalmic tints; colorizer; colorimeter; Meares–Irlen syndrome; metameric matches; spectral power distribution; additive and subtractive color mixture; reading speed

INTRODUCTION

The *Intuitive Colorimeter Mk 1** is an instrument now in widespread optometric use in the UK and overseas.[1,2] The instrument provides a patient and optometrist with the ability to vary the color of light incident upon a page of text in a simple and obvious way. The three intuitive dimensions of color: hue (h_{uv}), saturation (s_{uv}) and brightness (luminance), can be separately manipulated to obtain any desired shade of color (within a large gamut). (In this respect the instrument has an "intuitive interface"). The purpose of the instrument is to enable patients with Meares–Irlen syndrome[3] to obtain a color that reduces perceptual distortion and increases reading fluency. Because small changes in color can be made while the eyes remain color-adapted, the instrument provides a quick and efficient preliminary to the selection of the most appropriate ophthalmic tint.[4] The process of selection relies on subjective reports of improved clarity of vision, and reduced perceptual distortion, but can be corroborated by measurements of reading fluency.[5] Objective correlates of subjective benefits from ophthalmic tints have now been obtained in measurements of the dynamics of ocular accommodation.[6] The *Intuitive Colorimeter* has turned out to be useful in helping to select an ophthalmic tint that reduces headaches and eye strain,[7] and photosensitive seizures.[8]

The instrument was designed in 1992,[1,4] and became available commercially for the first time in 1993. The instrument is a *colorizer* (an instrument that produces color),

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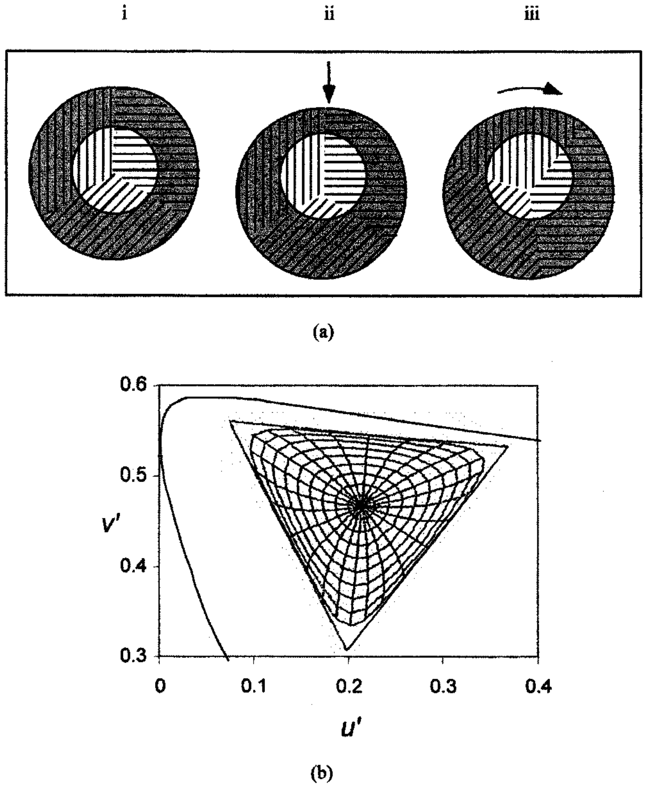


FIG. 1. (a) Geometry of the filter admixture giving the gamut shown by the outer perimeter in (b). The first panel shows a disc that is divided into three 120° sectors: (vertical hatching) red, (horizontal hatching) green, and (oblique hatching) blue. A cylindrical beam of collimated white light shines through the center of the disc and into a viewing chamber, where it is mixed by multiple reflection. The second panel shows movement of the disc eccentrically within the beam, and the change in the area of filters exposed. The third panel shows the change in exposed area as the disc is rotated from an eccentric position. The radial lines in (b) show how the chromaticity changes with eccentricity. The concentric curves plot the locus of chromaticities as the filter wheel is rotated at a constant eccentricity. The triangle shows the limits of the gamut when the center of the filter wheel is outside the aperture, and its apices show the chromaticities of the three filters.

but it measures a subjectively optimum tint and may, in this respect, be said to be a colorimeter. In this article, the term colorimeter is retained for historical reasons.

The principle of the instrument is simple and has been described elsewhere.[1] A cylindrical beam of collimated light shines through a disc and into a viewing chamber, where the light is mixed by multiple reflection. The disc has a diameter at least twice that of the light beam, and is divided into three 120° sectors bearing filters colored red, green, and blue. When the beam is concentric with the disc, equal proportions of red, green, and blue light are mixed, giving white light. As the disc moves eccentrically, the saturation of the color increases [Fig. 1(a), (i) vs. (ii)]. As the disc rotates, the hue is altered [see Fig. 1(a), (ii) vs. (iii)]. Figure 1(b) shows how the chromaticity varies with rotation and eccentricity of the disc. When the saturation is modest, the variation of hue (CIE hue angle, h_{uv}) and saturation (CIE saturation, s_{uv}) is largely independent. As saturation increases, the two co-vary. At extreme eccentricity, where the center of the disc is no longer within the beam, the limit of the gamut is triangular.[1]

In clinical use, the hue and saturation are varied alternately, each by small amounts, to obtain the chromaticity for reducing perceptual distortion while the eyes are color adapted. Once the optimum has been reliably obtained, combinations of tinted trial lenses are used to match the color using a conventional *white* halophosphate fluorescent light source (CIE Type F3). The trial lenses have seven different dyes with five levels of saturation of each dye.[4] The spectral transmissions of the trial lenses are shown in Fig. 2, together with the extensive gamut of possible shades of color that can be obtained.

During the course of manufacture of the Intuitive Colorimeter Mk I, it has proved difficult to control the tolerances so that identical settings of each instrument give identical colors. It has, therefore, been impossible to provide a single calibration that applies to all machines. This does not invalidate the design of the instrument, because the calibration of color settings is held in the trial lenses. It does, however, mean that it has not been possible to provide a look-up table to enable practitioners to select appropriate combinations of trial lenses simply from the settings of the colorimeter. It is necessary for the practitioner to make a color match by eye. This is not, in practice, a great disadvantage unless the practitioner has a color vision anomaly. A visible match is obligatory in any event, because the patient's eyes need to confirm the match as acceptable, given that the match is metameric.

A greater disadvantage of the initial design is the fact that the spectral power distribution in the colorimeter differs from that obtained with the lenses. This means that the instrument cannot be used when the patient has a color vision anomaly. The patients can readily obtain a suitable color in the colorimeter, but the process of matching the trial lenses is too complex for the patient to undertake, and the patient does not usually accept the examiner's matches.

We describe a new design of colorimeter that circumvents these problems. The variation in color from one unit to another is small, allowing calibration figures to be published, together with look-up tables that relate colorimeter settings to trial lens combinations. The spectral power distribution of light in the instrument is virtually the same as that when combinations of tinted trial lenses or equivalent tinted spectacle lenses are worn under conventional fluorescent lighting.

REVISED INSTRUMENT (INTUITIVE COLORIMETER MK II)

The basis of the instrument is shown in Fig. 3. A cylinder is divided across its longitudinal axis into two halves. On one half are seven differently colored filters disposed evenly around the circumference, each with similar photopic transmission. The other half of the cylinder comprises a gray filter with photopic transmission similar to that of the col-

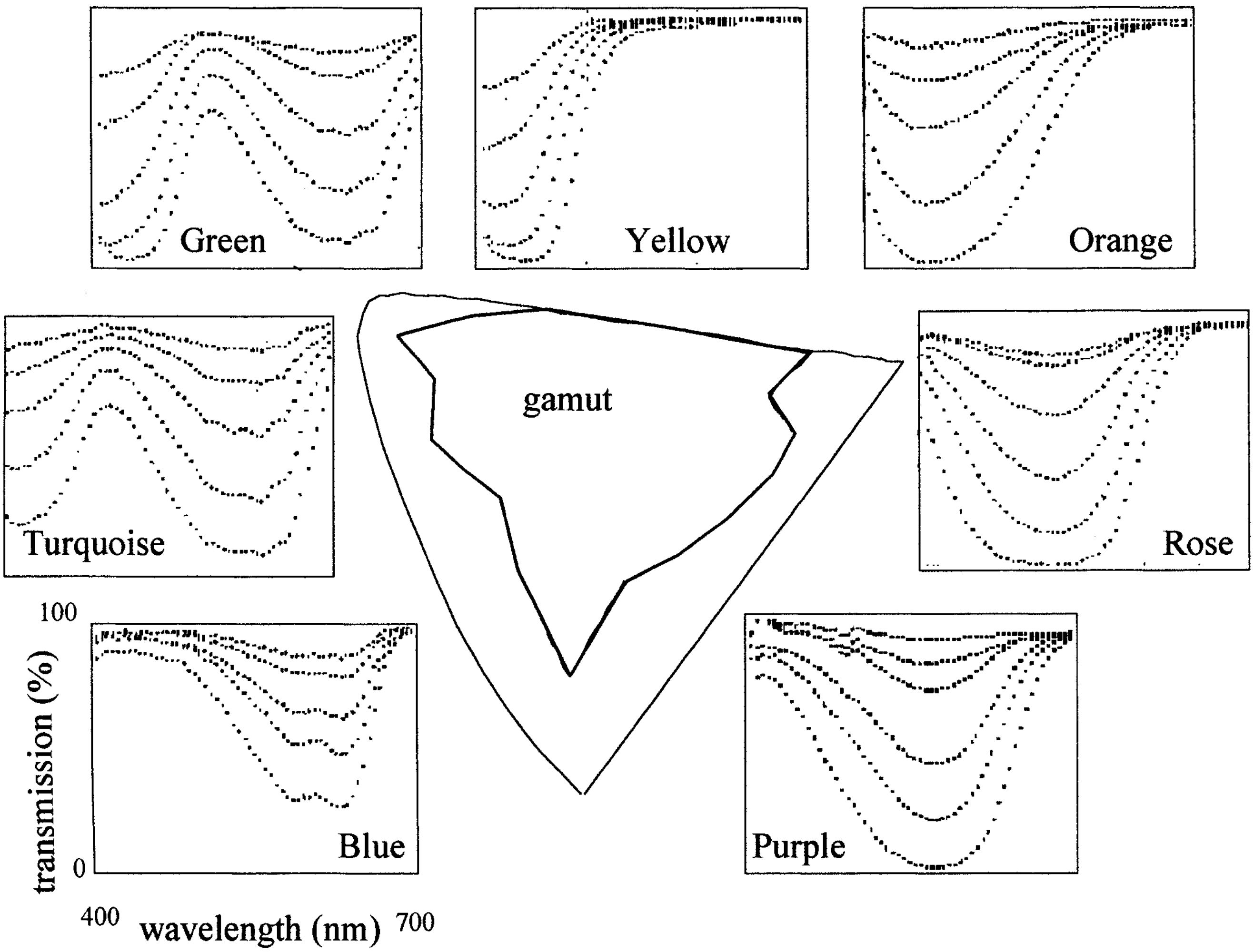


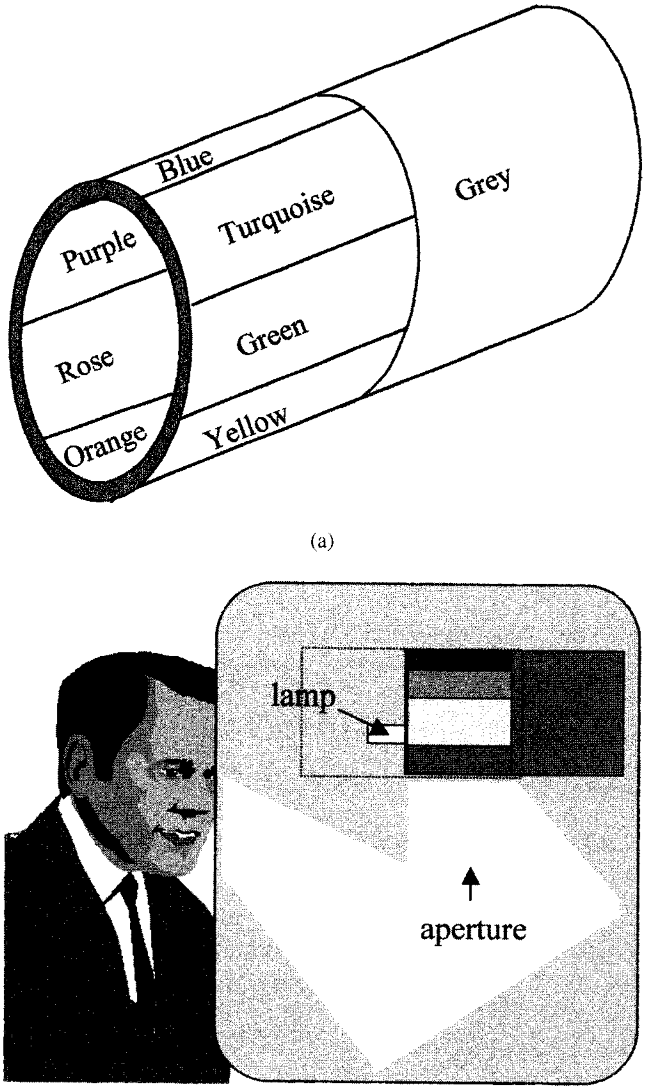
FIG. 2. Spectral transmission of trial lenses. There are five trial lenses for each of seven dyes, and these can be combined by superposition to give $2^5 = 32$ combinations. The combinations give 32 levels of dye deposition (31 with various lenses and one with no lenses). The 32 levels of each dye can be combined with the 32 levels of a dye with neighboring chromaticity to give $32 \times 32 = 1024$ combinations. There are seven pairs of dyes with neighboring chromaticity (rose-orange, orange-yellow, etc.) giving $7 \times 1024 = 7168$ combinations. The chromaticities of these combinations densely fill the gamut shown by shading, enabling any color within the gamut to be closely approximated.

ored filters. Inside the cylinder is a fluorescent light source: a set of three "white" halophosphate fluorescent lamps. The lamps approximate CIE type F3, correlated color temperature 3450 K. This lamp type was chosen, because it is one of the most commonly used in offices and schools and its spectral power distribution is relatively easily controlled. (Owing to ultraviolet and other filters, the color of the white light in the colorimeter differs from that of the lamps. The chromaticity coordinates are $u' = 0.217$, $v' = 0.521$. These coordinates lie further from the locus of the Plankian radiator than those of F3 lamps, and the correlated color temperature of the source and filter combination is closer to 3900 K than 3450 K).

Light from the source is directed through the cylinder and into a viewing chamber via a square aperture. In the viewing chamber the light is mixed by multiple reflection. The cylinder is mounted on an axle and can rotate around its longitudinal axis. It can also move to and fro (translate) along its axle. When it is at one extreme of the axle, the gray filter covers the entire aperture. When it is at the other extreme, two colored filters cover the square aperture, the proportion of each filter depending on the rotational position of the cylinder. At some positions, the proportion of the smaller filter reaches zero, i.e., just one filter covers the aperture.

Figure 4 shows how the hue and saturation of light mixed in the viewing chamber varies with rotation and translation of the cylinder. The luminance is varied separately by placing neutral density filters over the aperture. The luminance of the viewing surface is approximately 30 $cd.m^{-2}$. The luminance recommended for office work varies considerably from one country to another, but is generally between 60–100 $cd.m^{-2}$.[9] The colorimeter luminance thus allows for lenses that absorb just over half the light, and this absorbance is typical.[10]

Figure 5 shows the calibration curve for the instrument. Previous work has shown that blue is a commonly chosen color,[10] so the gamut has been deliberately extended into the blue (along the Plankian radiator locus). The effect of varying the saturation control (translating the cylinder) is shown



(b)

FIG. 3. (a) Cylinder bearing (hatched) colored filters and a gray filter. (b) Cross-section of colorimeter showing cylinder in a position to give maximally saturated color, and (dotted lines) in a position to give white light.

by the radial contours. The effect of varying hue (rotating the cylinder) is shown by the continuous curves. For small variations, hue and saturation can be changed independently.

The colored filters used in the colorimeter are made using dyes identical to those used to tint the trial lenses.[4] When just one colored filter covers the aperture, the spectral power distribution of the light in the viewing chamber is, therefore, the same as that obtained when the viewing chamber is illuminated with white light and the appropriate trial lens is worn. When two colored filters cover the aperture, the color of the light in the viewing chamber can still be matched metamerically by a combination of superimposed tinted trial lenses, but the spectral power distribution is not identical. This is because the spectral transmissions of the trial lenses are *multiplied*, whereas the light in the viewing chamber is the result of the *addition* of the spectral power from each

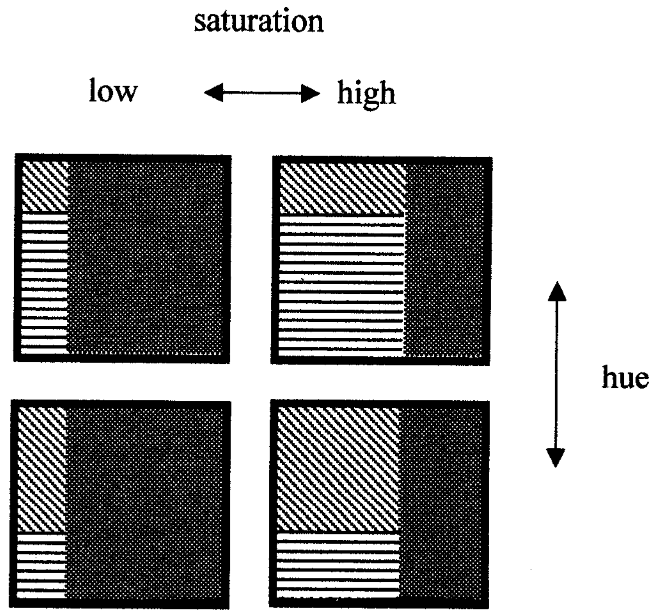


FIG. 4. Four views of the square aperture through which light enters the viewing chamber. The hatching shows colored filters and the tone the gray filter. Panels on the left-hand side show the disposition of filters necessary for a color of low saturation. The color of the upper panels differs from that of the lower panels.

filter on the cylinder. Nevertheless, by adjusting the combinations of trial lenses, allowing saturation to vary, it is possible to obtain spectral energy functions that are very similar to those of light in the chamber, despite the comparison of additive and subtractive color mixture. This is shown by example in Fig. 6 analytically for the abstract case

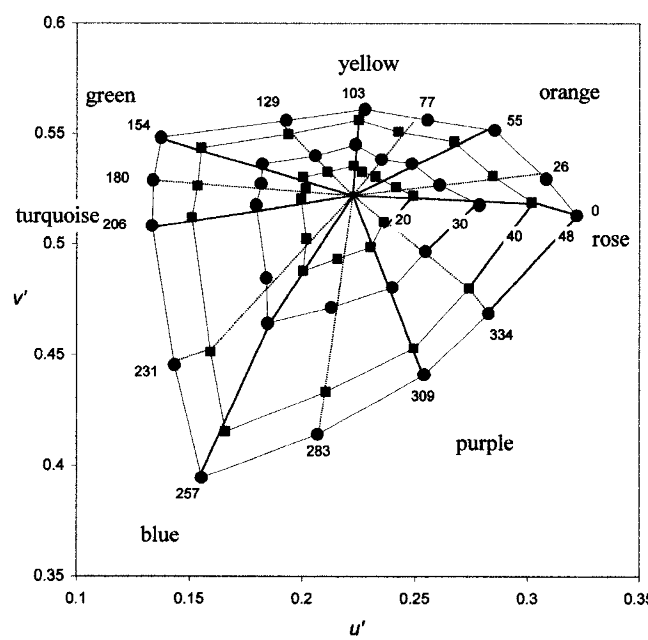


FIG. 5. Calibration of the colorimeter. The radial lines plot the loci of chromaticities as the cylinder is moved along its axle (labels show the displacement in cm). The concentric curves plot the loci as the cylinder is rotated (labels show the angle in degrees).

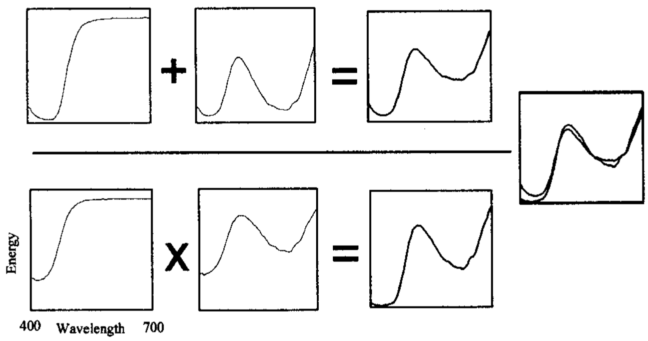


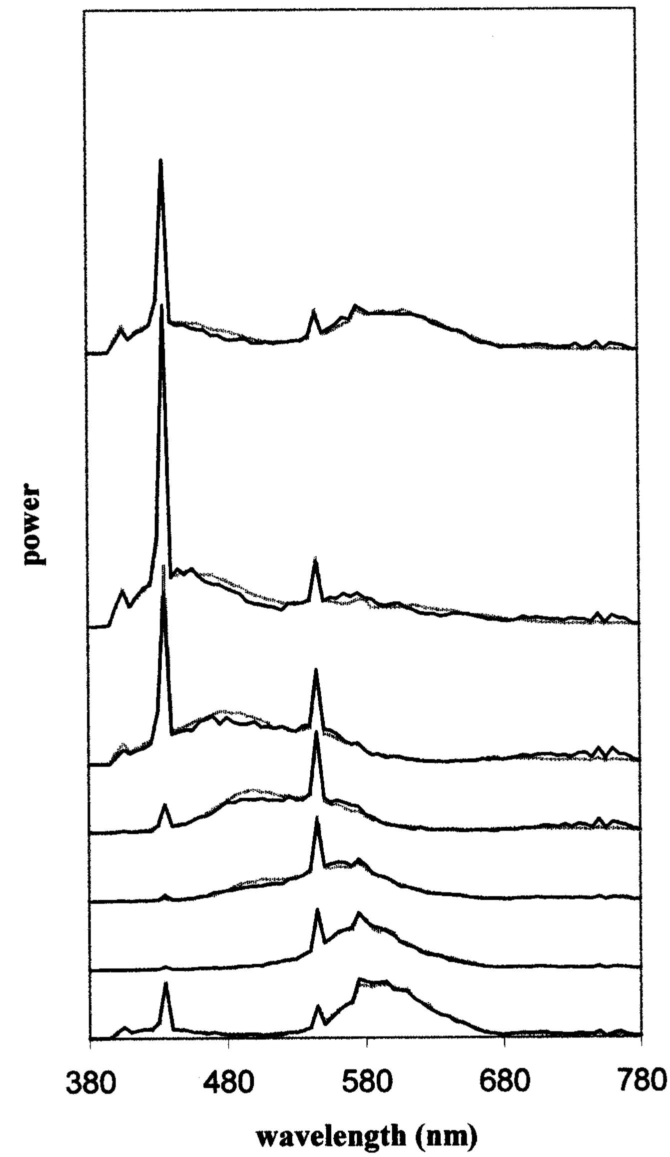
FIG. 6. *Upper row*: The first panel shows the spectral power distribution for light from a yellow filter, and the second panel the distribution for light from a green filter. The third panel shows the spectral power distribution of the sum. *Lower row*: The first panel shows the spectral power distribution of light passing through a yellow filter made from the same yellow dye as that used in the upper row, though less saturated. The second curve shows the corresponding transmission of the green filter. The third curve shows the product. The curves for the sum and the product have been superimposed in the rightmost panel.

where the illuminating light is not a fluorescent lamp but the equal energy illuminant (i.e., an illuminant with equal energy throughout the visible spectrum).

RESULTS: SPECTRAL POWER DISTRIBUTION OF COLORIMETER SETTINGS AND METAMERIC MATCHES OF COMBINATIONS OF TRIAL LENSES

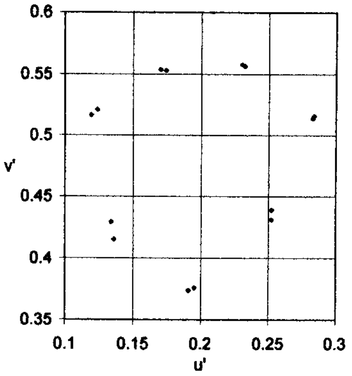
Depending on the position of the cylinder, the aperture may be covered by one, two, or three filters (one or two colored filters with or without a gray filter). As mentioned above, when one filter covers the aperture, the spectral power distribution should be identical to that from a similarly colored tinted trial lens: the dyes used for the colorimeter filters are the same as those from the trial lenses. The spectral power distribution is expected to be maximally different when the aperture is covered in equal proportion by two differently colored filters. The spectral power distribution of light in the colorimeter was measured under these conditions. The measurements were made using a Monolite system based on a rotating diffraction grating. The data were independently corroborated by a Minolta CF1000 spectroradiometer, courtesy of the Color and Imaging Institute at the University of Derby, UK. Measurements were then made of the spectral power distribution of the white light filtered by combinations of superimposed trial lenses. The white light source used was that of the colorimeter with the neutral filter covering the entire aperture. The combination of trial lenses chosen was that combination calculated to have the closest available match to the chromaticity of the light in the colorimeter. (The latter was calculated from the measured spectral power.) The distributions are shown in Fig. 7. As can be seen, the distributions for added light in the colorimeter and for white light filtered by trial lenses are closely similar.

The spectral energy was measured every 5 nm between 380–780 nm, resulting in 81 measurements. To assess how similar the distributions were, two calculations were undertaken. (1) The Pearson product moment correlation coefficient between the 81 measurements for each pair of spectral power distributions shown in Fig. 8 was obtained. The coefficients are given in Table I. (2) The chromaticities for the eight surfaces used to calculate the CIE 1965 color rendering index were calculated for the spectral power distributions shown in Fig. 8. The spectral power distribution of light from the colorimeter was used as the reference and with one exception; the light from the corresponding combination of trial lenses gave a color rendering index greater than 80 (see Table I).



(a)

FIG. 7. (a) Spectral power distributions of colored light in (solid curves) the colorimeter and (broken curves) white light in the colorimeter filtered by combinations of tinted trial lenses. Each pair of curves has been normalized so that both spectral power distributions have the same luminance, and the origins have been separated vertically for clarity.



(b)

FIG. 7. (b) Chromaticities of the spectral power distributions shown in (a). The lowest pair of curves in (a) correspond to the rightmost points in (b), and the progression upwards in (a) is counterclockwise in (b).

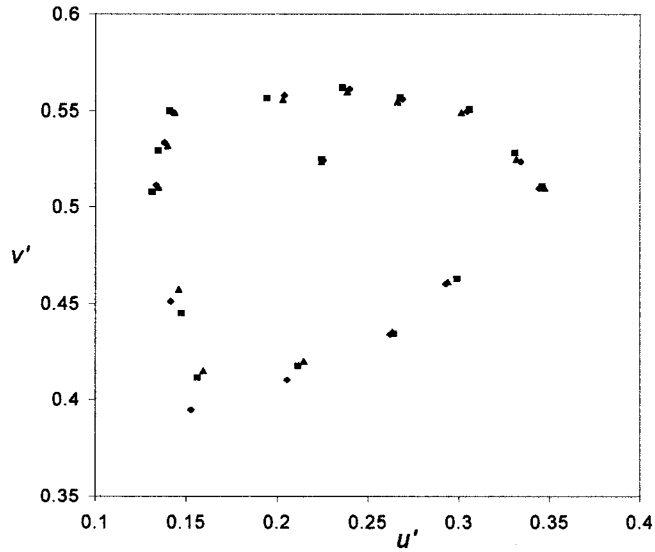


FIG. 8. Chromaticities at each of several settings of three instruments. The settings have extreme saturations and show the similarity of calibration from one instrument to another. Each of the instruments is represented by a different symbol. Using the average "white" setting as a reference, the color difference (CIE 1976 $L^*u^*v^*$) between corresponding settings for the three instruments was calculated. The average value of all the pairwise combinations was 6.54 (s.d. 3.54).

The luminance decreased by a factor of 2 as saturation increased to maximum, to simulate the change normally obtained with lenses. Measurements of luminance at maximum saturation gave a standard deviation across filters of only 12%.

RESULTS: REPLICABILITY OF CALIBRATION IN MANUFACTURE

The first design of the colorimeter used a point light source and a collimated beam of light. The distribution of energy within the beam was responsible for the color mixture. It was critically dependent on the alignment of the optics and, therefore, difficult to maintain from one instrument to another. The new design is based on a distributed and diffused light source. Seven filters are used rather than three, decreasing the precision of alignment required of each filter. The geometry of the filter arrangement is simple to engineer with sufficient precision. As a result, the chromaticity obtained at a given colorimeter setting is closely similar from one instrument to another. See Fig. 8 for a comparison of three instruments The measurements in Fig. 8 were made using a Minolta TV Color Analyzer II. A value of ΔE was calculated for the differences between instruments, using the "white" setting as the reference. The average value for all the settings shown determined for all the pairwise combinations of instruments was 6.54 (s.d. 3.54).

PRECISION OF COLOR REQUIRED FOR OPTIMAL READING FLUENCY

A series of patients was assessed in a clinical evaluation of the new design. Some had previously been assessed (using the original design of the *Intuitive Colorimeter*) and were now wearing precision filters for reading. One patient had not previously been tested and was assessed entirely using the new design. Assessment involved increasing and then decreasing saturation at each of 12 hue angles spaced about 30° apart. Those hues reported to improve clarity were then compared, and the saturation optimized at the best hue. At this best saturation, the hue angle was then again revised and saturation optimized once again at the revised hue. Using successive approximations, hue and saturation were thereby optimized, using only small changes in chromaticity to maintain color adaptation. Reading speed was measured at the optimal chromaticity and at other chromaticities selected to be of increasing color difference. Reading speed

TABLE I. For each setting in which the Colorimeter aperture was covered by two filters, each having identical area, the spectral energy was measured every 5 nm and compared with that obtained when white light was filtered by a combination of tinted trial lenses matching the chromaticity as closely as possible. Pearson product moment correlation coefficients (rho) express the association between the two spectral power distributions, and color rendering indices (CRI) express the similarity of the chromaticity of colored surfaces rendered by each spectral power distribution. The pythagorean distance (*pd*) separating the CIE 1976 UCS chromaticities obtained under each condition is also shown.

Component filters	rho	CRI	*pd*
a. rose-orange	0.9956	92.6	0.00223
b. orange-yellow	0.9969	91.1	0.00252
c. yellow-green	0.9897	84.9	0.00413
d. green-turquoise	0.9808	81.4	0.00614
e. turquoise-blue	0.9883	68.6	0.01403
f. blue-purple	0.9915	83.1	0.00483
g. purple-rose	0.9908	80.8	0.00806

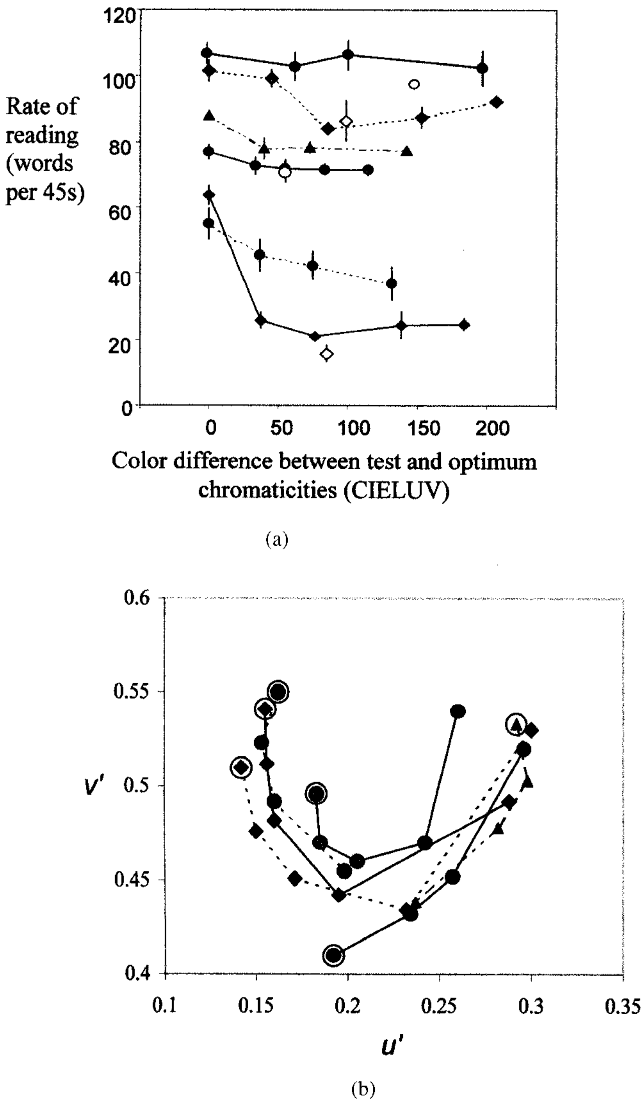


FIG. 9. (a) Number of randomly ordered common words read aloud in 45 s, with light of various chromaticities, luminance 30 cd.m^{-2}. The reading rate is shown as a function of the difference in color (CIE 1976 $L^*u^*v^*$ color difference, with L^* set at a nominal 100) between the test color and the color of light optimum for subjective clarity. The curves are for six consecutive patients, and the linear trend analyzed separately for each patient by Page's L using the ranked data was significant for all patients except the fourth from the top. In three patients data were obtained for white light (u' = 0.215, v' = 0.521) and these data are shown by separate open symbols of corresponding shape. The data for the first and third patient (numbered from the top) have been displaced upward by five for clarity. (b) The chromaticities of the light used in the examination of the patients. The optimal chromaticities (obtained by subjective methods) are shown encircled. Each continuous curve joins the chromaticities used, and symbols and connecting lines correspond with those used in (a) to distinguish the six patients. The patients were four male and two female, aged 12–20 (average 14.8 years). All except one [the second from the top in (a)] had previously been wearing tinted spectacles, and the average duration of use was 2.1 years, range 1.5–3 years.

was measured using the Rate of Reading Test, a passage of randomly ordered common words that are read aloud.[5] This test emphasizes the visual aspects of the task of reading. It shows improvements in reading fluency with colored lenses,[11,12] and has prognostic value in predicting benefits from colored overlays.[13] The text was illuminated in the colorimeter and patients were simply required to read the passage aloud as rapidly as possible. (The patients did not wear any colored filters for this test.) The test was given repeatedly at different chromaticities, randomly ordered. (The effects of practice have previously been shown to be negligible after initial familiarization with the reading task, and placebo effects are generally minimal[13].) Figure 9 summarizes the way in which reading speed varied with the chromaticity of the illuminating light, and demonstrates just how precise a chromaticity is necessary for optimizing reading speed, confirming earlier reports.[7] Note that the speed with white light is generally lower than that under the optimal color, and similar to that with colored light having an equivalent color difference.

DISCUSSION

The new design of colorimeter (colorizer) is similar to the previous design in that (1) the color can be varied continuously within a large gamut, and (2) the effects of colored light on visual perception can be examined by varying hue (h_{uv}), saturation (s_{uv}) and luminance (V_λ) independently. Precise selection of color is necessary to optimize the improvement in reading fluency (see Fig. 9). The new colorimeter design differs from the earlier design in that the spectral power distribution of the light is very similar to the spectral power distribution obtained under conventional lighting with conventional ophthalmic CR39 lenses tinted with conventional dyes. The following advantages accrue: (1) the effect of an ophthalmic tint on the perception and naming of colored surfaces can be examined in the colorimeter; (2) the examination can be undertaken by patients who have color vision anomalies. The use of a diffuse source and seven colored filters reduces the requirement for precision in alignment of components; the variation in color from one instrument to another is, therefore, small, allowing a single calibration for all instruments. This calibration permits the matching of colored lenses to a given colorimeter setting, using a look-up table or a computer algorithm. The latter enables optometric practitioners with color vision deficiencies to undertake ophthalmic colorimetry.

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