Effects of Luminance, Wavelength and Purity on the Color Attributes: Brief Review with New Data and Perspectives

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Abstract: A color stimulus may be characterized by three psychophysical dimensions (luminance, dominant wavelength, and purity), whose corresponding color attributes are lightness, hue, and chroma/colorfulness. The 3 × 3 matrix gives nine basic effects of the psychophysical dimensions on the color attributes (e.g. the effect of luminance on hue), but there are 49 possible combinations as more complex effects (e.g. the effect of luminance on hue and chroma, i.e. on chromaticity). Researching and quantifying such effects enables modelling of the underlying neural mechanisms and of color appearance. Using a simple nomenclature to identify the effects (e.g. Ph denotes the effect of Purity on hue), this paper briefly reviews and interrelates 15 of the commonest effects, giving new data or new graphical perspectives to clarify or fill gaps in the literature. Contrast and no-contrast effects (stimuli viewed simultaneously or singly, respectively) are differentiated. © 2007 Wiley Periodicals, Inc. Col Res Appl, 32, 208–222, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20312

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INTRODUCTION

Object color stimuli are characterized by three *psychophysical dimensions (luminance, dominant wavelength, and purity), whose corresponding color attributes are lightness/brightness, hue, and chroma/colorfulness. Variance of a physical or psychophysical dimension such as wavelength will normally influence the appearance of all three color attributes unless one dimension (or alternatively one attribute) is held constant. This is the correct method of measuring the specific effect on a specific attribute. Research and quantification of the effects of physical or psychophysical dimensions on color appearance, particularly the color attributes, enable modelling of the underlying neural mechanisms and of color appearance. As color appearance modeling attempts greater accuracy, better data are required together with a better understanding of the effects and how one relates to another. The value of data on two separate effects, say of purity on chroma and of purity on lightness, is multiplied if the two effects can be related, allowing a cross-check of the effects.

The 3 × 3 matrix of the psychophysical dimensions and the color attributes gives nine basic effects, as shown in Fig. 1, where each effect is shown as a line connecting each dimension with each color attribute. These nine basic effects together with six other common effects (see below) are studied in the present article, by briefly reviewing or updating previous data or in some cases giving new data or graphical perspectives. This is a wide-ranging study which aims to advance the understanding, quantification, and interrelationships, of the effects of the major psychophysical dimensions on color appearance, focusing on data rather than postulating the neural mechanisms. A fourth major psychophysical dimension is variable light source,[1,2] in terms of color temperature K, but in this article the focus is mainly on the effects for a given light source.

A given type of effect (e.g. the effect of luminance on hue) has various forms depending on experimental conditions, such as spatial, temporal, photometric, or chromatic parameters. For example, the effect of luminance on hue depends, inter alia, on the luminance of the sample and of

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*Psychophysical. These dimensions are conventionally labeled "psychophysical" though they are largely stated in physical terms. One purpose of the label here is to distinguish from physical or radiometric variables such as radiant flux and wavelength.

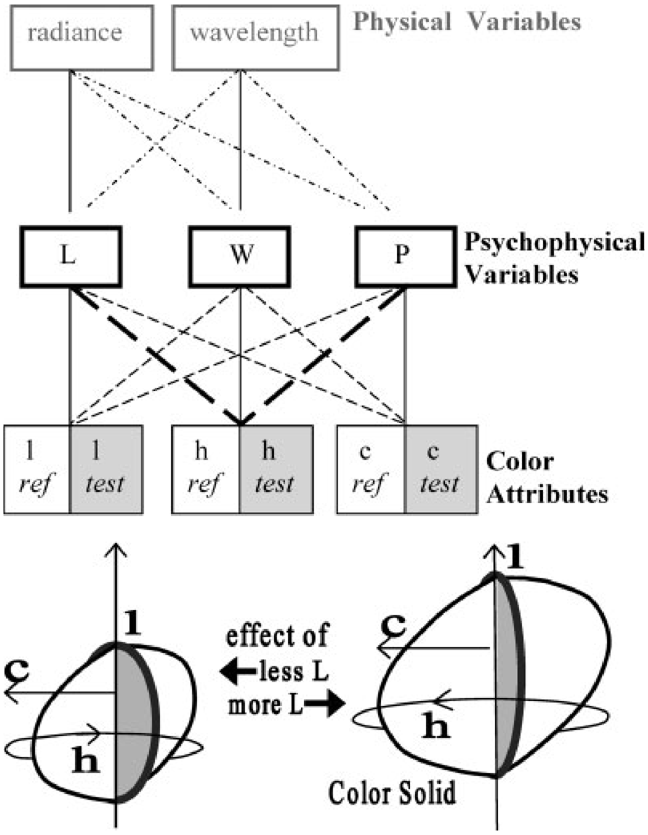

FIG. 1. Each psychophysical dimension (luminance, dominant wavelength, purity, as *L*, *W*, *P*) and each color attribute (lightness, hue, chroma, as *l*, *h*, *c*, for object colors) are connected by a line. The nine lines indicate the nine possible effects of single dimensions on single attributes, shown as adjacent reference and test samples. Sample pairs may be viewed singly (the no-contrast mode) or simultaneously (the contrast mode). Heavy dashed lines P-h and L-h indicate the well-known Abney and Bezold-Brucke effects. The top row shows the physical or radiometric dimensions (radiance and wavelength) of the radiant energy. Dominant wavelength derives from one or more physical wavelengths, and purity from admixture of two or more physical wavelengths of specific radiances. Bottom schema: the color solid *l*, *h*, *c* (lightness, hue, chroma, based on the Munsell solid) in a given surround luminance, illustrating how a single dimension effects all three attributes (unless one is held constant); e.g. the effect of increased sample luminance *L* (in either the contrast or no-contrast mode) is higher lightness and chroma and some hue shift (whose shift direction depends on the hue) as shown by the right hand color solid, relative to the left hand solid (only three planes of constant hue are shown) (see section Luminance Effects).

the surround, the sample's size or visual field, and the temporal mode of observation. The latter is of particular interest in this article and comprises two alternatives: the *contrast mode* where the reference and test samples are observed simultaneously (also known as contrast effects), and the *no-contrast mode* where samples are observed singly. The two modes are too-rarely differentiated in the literature on effects,[3,4] which usually assume the contrast mode.

TABLE I. Classification of the effects of the 3 psychophysical variables (luminance, dominant wavelength, purity) on the 3 color attributes (lightness, hue, chroma) by singles, pairs, or triplets.

		Psychophysical dimensions (3)		
		Singles	Pairs	Triplets
Color	Singles	Class I (9)	Class IV (9)	Class VII (3)
Appearance	Pairs	Class II (9)	Class V (9)	Class VIII (3)
Attributes (3)	Triplets	Class III (3)	Class VI (3)	Class IX (1)

Values in parentheses indicate mathematically possible combinations per class. The 9 classes give a total 49 types of effect.

Fairchild[3] gives a useful review of six of the effects in the present study (which expands, updates, or takes a different approach to, that review). Appendix A defines brightness, lightness, chroma, and some other terms for the interested but nonspecialist reader. To save space, wavelength will denote dominant wavelength.

Nomenclature

Before commmencing the study, a system of nomenclature is required to identify the effects, some of which have common names (e.g. the Abney effect, of purity on hue) and some of which have no common names, for example, the effects of wavelength on chroma and of purity on chroma. A nomenclature for the effects should be based on a logical classification of all possible types of effects, and an appropriate and simple system is outlined in Ref. 1 and detailed in Ref. 2 as shown at Table I. The table shows the possible combinations of singles, pairs, or triplets of psychophysical dimensions and singles, pairs, or triplets of color attributes, giving a total 49 possible types of effects.

Table II is a tabular version of Fig. 1 and shows the basic class of effects, in a 3×3 matrix of the psychophysical variables and the color attributes. As Table II shows, the effects may be simply and clearly named by using the initial letters of each psychophysical dimension (in upper case, as L, W, P) and each color attribute (in lower case, as l, h, c). This will be the nomenclature used here. For

TABLE II. The nine basic effects (Class I), named by readily understood terms using the initial letters of each psychophysical variable (*L*, *W*, *P*, in upper case) and color attribute (*l*, *h*, *c*, in lower case).

	Luminance (*L*)	Wavelength (*W*)	Purity (*P*)
Lightness	Ll	Wl	Pl
Hue	Lh	Wh	Ph
Chroma	Lc	Wc	Pc

Here, "*P*" denotes colorimetric purity unless otherwise specified, lower case "*l*" denotes lightness, or brightness if specified, and "*c*" denotes chroma, or colorfulness or saturation if specified. Effects associate with the following common names: Ll with Brightness/Luminance ratio; Lh with the Bezold-Brucke effect; Wl and Pl with the Helmholtz-Kohlrausch effect; and Ph with the Abney effect.

TABLE III. The effects of single dimensions on paired attributes[a] (Class II).

	L	*W*	*P*
Lightness and hue	Llh	Wlh	Plh
Lightness and chroma	Llc	Wlc	Plc
Hue and chroma	Lhc	Whc	Phc

[a] For example, Lhc is the well known effect of luminance on chromaticity, often shown as color difference ellipses.

example, the effect of wavelength (W) on lightness (l) is named Wl. This system, unlike the practice of naming effects after their discoverers (e.g. the Helmholtz-Kohlrausch effect),[3,4,5] offers admirable brevity and clarity; that is, the effect's name immediately indicates the variables involved (e.g. W and l).

Tables III lists the effects, by name, of a psychophysical dimension on paired color attributes, and Table IV lists the effects of a pair of dimensions on single color attributes. Whereas workers have tended to treat the various effects as special phenomena or even optical illusions, it may be seen from Tables I–IV that every effect has its proper and necessary place in the natural coherent gamut (or structure) of effects (Table I), and may be predicted (in outline) rather than discovered as if by surprise. This article introduces the practice of treating effects as categorical elements of the gamut, with logical relations between effects, rather than unusual phenomena with surprising or unpredictable characteristics.

A given type of effect may vary between the contrast and no-contrast modes. It is sometimes helpful therefore to add to the effect name (e.g. luminance on hue, Lh) an indication of the contrast (*C*) or no-contrast (*N*) mode by adding a subscript $_C$ or $_N$, for example, Lh_C. If required, further important parameters (e.g. 2° visual field, and illuminant D65) may be added to the effect name in parentheses,[2] e.g. Lh_C (2°, D65).

All nine basic effects will be studied, in one or both temporal modes (contrast or no-contrast), and in one or more perspectives, plus six other common but more complex effects: WPl (effect of wavelength and purity on lightness, i.e. the Helmholtz-Kohlrausch effect), LPh (effect of luminance and purity on hue, i.e. the combination of Bezold-Brucke and Abney effects), Lhc (effect of luminance on hue and chroma, i.e. chromaticity), Llhc (effect of luminance on 3-dimensional color), Wh [shadows] (effect of wavelength of the light source on hue), and Kh (effect of illuminant color temperature K on hue).

TABLE IV. The effects of paired psychophysical dimensions on single attributes[a] (Class IV).

	L & W	L & P	W & P
Lightness	LWl	LPl	WPl
Hue	LWh	LPh	WPh
Chroma	LWc	LPc	WPc

[a] For example, WPl represents the well known Helmholtz-Kohlrausch effect.

Optimal Color Stimuli

Where possible, color stimuli will be 2–4 degrees visual field and optimal color stimuli,[6] i.e. object colors on the MacAdam limits and aperture color stimuli of optimal photometric efficiency in color mixture and in neutralizing their complementary colors. Optimal monochromatic or quasi-monochromatic stimuli are limited to the approximate range 442–613 nm and optimal compound stimuli (nonspectrals) comprise additive mixtures of 442 + 613 nm (approximately), in all CIE illuminants. Hence nonspectrals lie on or near the line 442-613 nm in the CIE diagram, rather than on the "purple line" often termed maximum purity but actually invisible due to no luminance.

To cover the whole hue cycle, nonspectrals will be represented in graphs' wavelength axes as complementary wavelengths, spaced similarly to nonspectrals in the Munsell hue circle.

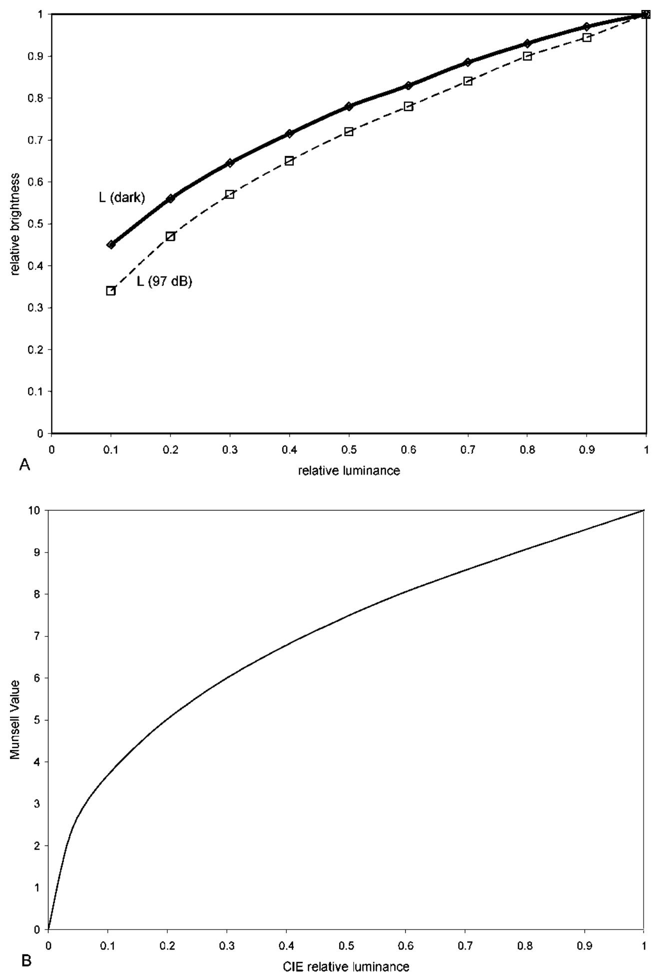

FIG. 2. Ll_C contrast effect of luminance on lightness (or brightness). A: Stevens' data[7] on relative brightness (his term, but *lightness* in modern useage) as a function of adapting luminance (i.e. contrast effect Ll_C). B: Relative lightness, in the form of Munsell Value, as a function of relative luminance, in the form of CIE luminous reflectance Y (i.e. contrast effect Ll_C).

LUMINANCE EFFECTS

Luminance Effect on Lightness/Brightness

The Ll effect, of varying luminance on lightness (or brightness, if "l" is so specified) is amply reported by experimental data in general agreement. Stimuli are achromatic of course; for chromatic samples, the effect would be that of luminance *and wavelength* on lightness (the LWl effect). In the no-contrast mode, perceived lightness is approximately constant with varying luminance, as Fairchild notes[4]; e.g. a white sample appears white at practically any level of photopic luminance.

The effect for the contrast mode (Ll_C) is more interesting, and is exemplified by the Stevens data (Fig. 2A),[4,7] the Munsell Value data (Fig. 2B),[4] and the Bartleson & Breneman data.[8] In all cases, if the luminance of the surround is increased, lightness (or brightness) of the sample increases not linearly but geometrically, and secondly, a lighter (or brighter) surround increases lightness (or brightness) contrast. Contrast denotes the rate of lightness change with respect to a given luminance. That is, in a higher adapting or surround luminance light colors will appear lighter and dark colors will appear darker, i.e. the image has more contrast. Some of the Stevens' data is shown in Fig. 2A; note that his term *brightness* today means *lightness*, and that effect Ll produces greater lightness contrast in the higher adapting luminance than in the lower luminance (labeled "dark").

Figure 2B shows effect Ll where lightness is in the form of Munsell Value, graphed as a function of CIE luminance Y (i.e. luminous reflectance factor). Munsell Value is a perceptually uniform 10-step scale from 0 (ideal black) to 10 (ideal white); for example, Value 5 is perceptually midway between Value 0 and Value 10. The curves in Figs. 2A and 2B are notably similar and approximate power law functions; these would plot approximately straight lines in log-log scale. To be precise, Fig. 2B's curve function is a 5th-order polynomial equation (see Ref. 4). This relationship between Munsell Value and relative luminance is true of any color, i.e. independent of hue or chroma.

Since Munsell Value is widely accepted as adequately representing lightness (e.g. the CIE lightness scale, L^*, is closely modeled on Munsell Value), effect Ll_C in the form of Fig. 2B is probably the most widely agreed and accurately formulated[4] of the nine basic effects.

Luminance Effect on Hue

Luminance has a large influence on hue. The contrast form of the effect, Lh_C (or Bezold-Brucke effect) is well known.[9,10,11] The no-contrast form of the effect, for example on the unique hues,[12,13,14] has been generally confused with the contrast form. I have differentiated the two effects Lh_C and Lh_N for both aperture and object colors.[15] I found that Lh_N has a similar curve to the Lh_C effect but is shifted some 10–20 nm shorter wavelength (see Fig. 3). This subtle difference has drastic effects, in converting curve peaks to nulls and vice versa. Hence Lh_N has a quite different effect from the Bezold-Brucke effect. Reference 15 gives both spectral and nonspectral data for effects Lh_N and Lh_C, reproduced in Fig. 3. The

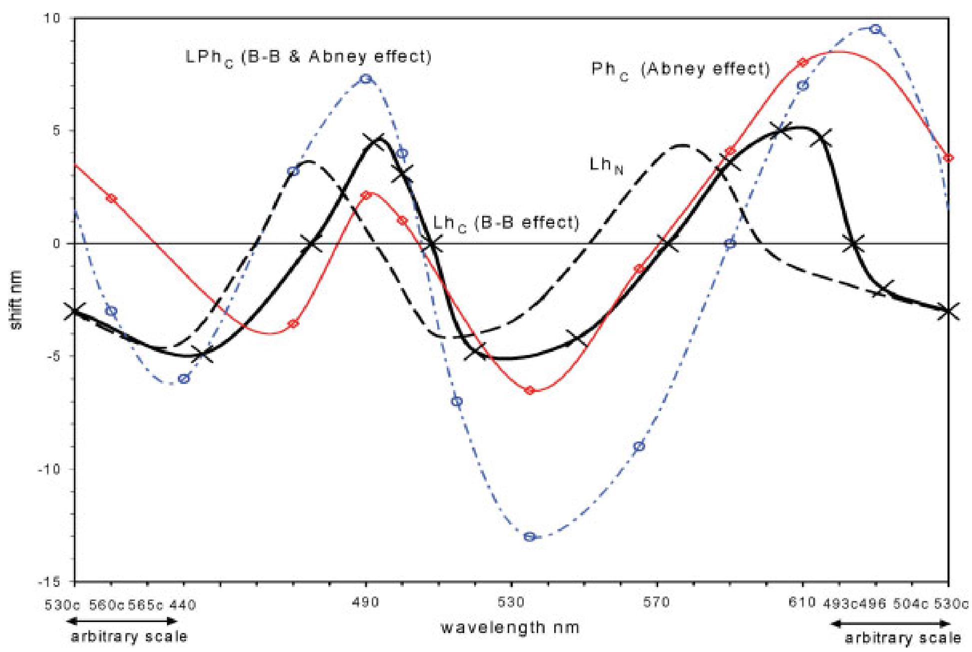

FIG. 3. Effect of luminance on hue, Lh, from Pridmore data.[15] Effects Lh_N (the no-contrast mode, dashed line) and Lh_C (the contrast mode, solid line) also known as the Bezold-Brucke effect, are significantly different: peak wavelengths of Lh_N tend to fall on null wavelengths of Lh_C. The two are compared with Ph_C (Abney effect, red line) from Pridmore.[33] Also shown is LPh_C (combined B-B & Abney effect, blue dash-dot line) for observers RP & IC, see section Six Other Common Effects. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

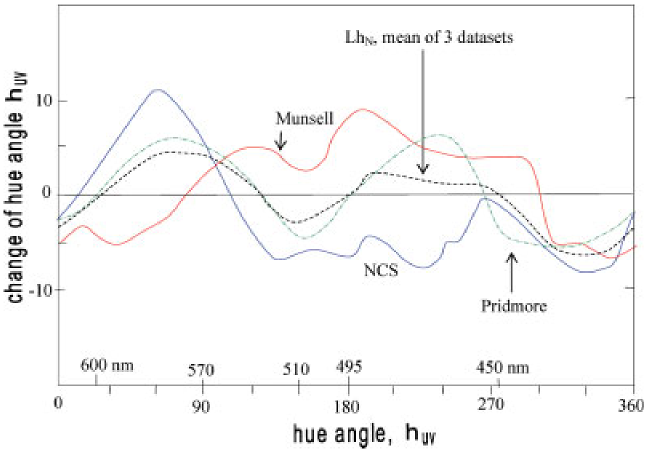

FIG. 4. Effect of luminance on hue, Lh_N (the no-contrast mode, as distinct from Lh_C, the Bezold-Brucke effect), from various data. Red line: Munsell data. Blue line: NCS data. Both adapted from Hunt (1989). Note the red and blue curves are generally opposed. Green dashed line: Pridmore data[15] for Lh_N (see also Fig. 3). Black dashed line: Mean of Pridmore, Munsell, and NCS curves. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

figure also includes the Ph (Abney) effect to show its similar curve shape to the Lh effect. A misconception that Bezold-Brucke effect does not apply to related colors was recently clarified.[16]

The Lh effect for object colors is reflected in Munsell and NCS data as loci of constant hue in different Values or blackness *s*. By numerical analysis of Munsell and NCS samples, Hunt has derived and graphed[17] data for the Lh effect. His analysis probably corresponds to viewing samples singly in a white surround, so his data probably represent the no-contrast mode. Hunt's curves for the Munsell and NCS data are reproduced in Fig. 4; their curves, though systematic, are opposed in most places. It would be difficult to model the effect from such conflicting data. Pridmore's data for Lh_N (averaged for aperture and object colors) are shown by green dashed line. A mean of the three data sets gives a bimodal curve similar to the Pridmore data.

Luminance Effect on Chroma/Colorfulness

The Hunt effect[4] predicts that higher luminance increases colorfulness and increases chromatic contrast. This is particularly true of colorfulness (mostly an attribute of aperture colors) but is also, to lesser extent, true of chroma. Chroma is defined by the CIE as "the amount of pure chromatic color present regardless of the amount of achromatic color''. Munsell chroma loci in the CIE 1931 diagram indicate that a given sample increases chroma when its lightness increases, restricted of course by the limits to optimal object color stimuli. Munsell data presumably represent the no-contrast mode, so the effect Lc_N is that chroma increases with sample luminance. One may expect Lc_C (contrast mode) to be similar.

The Lc effect is illustrated in Figs. 5A and B. Readers may observe the effects for themselves. The effects for subject RP are graphed in Fig. 5C, and agree generally with definitions of chroma. Chroma of a given sample is constant when surround luminance increases, though colorfulness (dashed line, in left panel) rises. If the sample's luminance is increased while the surround luminance is held constant the chroma increases in the no-contrast mode (center panel, C). The slope increases slightly for Lc_C (the contrast mode, in right panel) because the chroma of the darker sample (N in B) is reduced while that of the lighter sample M is hardly affected. The effect on the darker sample is explained[18,19] by the induced complementary color (or after image) of the adjacent lighter sample, which overlays the darker sample and shifts its color towards neutral. There is less induction from the darker desaturated sample so the effect on the lighter sample is trivial. In summary, the luminance effect Lc_C is similar to but slightly greater than the effect Lc_N.

The effects of luminance on lightness and chroma are also shown in Fig. 1 (see color solids).

WAVELENGTH EFFECTS

Effect of Wavelength on Lightness/Brightness

Brightness is a color attribute of aperture colors and (less commonly) object colors, for which the more common attribute is lightness; see Appendix A. The Wl effect, of varying wavelength on lightness, is part of the important and complex effect known as Helmholtz-Kohlrausch effect or the Brightness/Luminance (B/L) ratio. The ratio depends on luminance, purity, and wavelength; only the latter is considered here. Data are generally for the contrast mode (effect Wl_C) due to the experimental method of comparing test samples with a reference sample of constant luminance.[3] For equal luminance stimuli of constant purity, the apparent brightness of aperture colors or the lightness of object colors varies widely with wavelength.[20] The Inset over Fig. 6 shows B/L ratio for monochromatic aperture colors according to the CIE data.[21] The base line ($B/L = 1$) represents the CIE luminance function Y.[22] Note this B/L curve (which peaks in violet) does not represent perceived brightness (which of course peaks in the yellowish hues) but only the relation between luminance and brightness. Burns *et al.*[23] give higher B/L ratios than the CIE data.[21]

In Fig. 6 proper, the solid curve represents data on aperture colors, so the relevant attribute is brightness rather than lightness (see Appendix A). The solid curve is labeled Wl(U) and represents the effect of wavelength on brightness, for both observers in Uchikawa et alia[24] for equally bright monochromatic lights and four nonspectral lights. (As already mentioned, "l" refers to lightness or to brightness if specified.) This curve is fairly typical of perceived brightness or lightness, and is roughly the inverse of perceived chroma (see Wc, on next page).

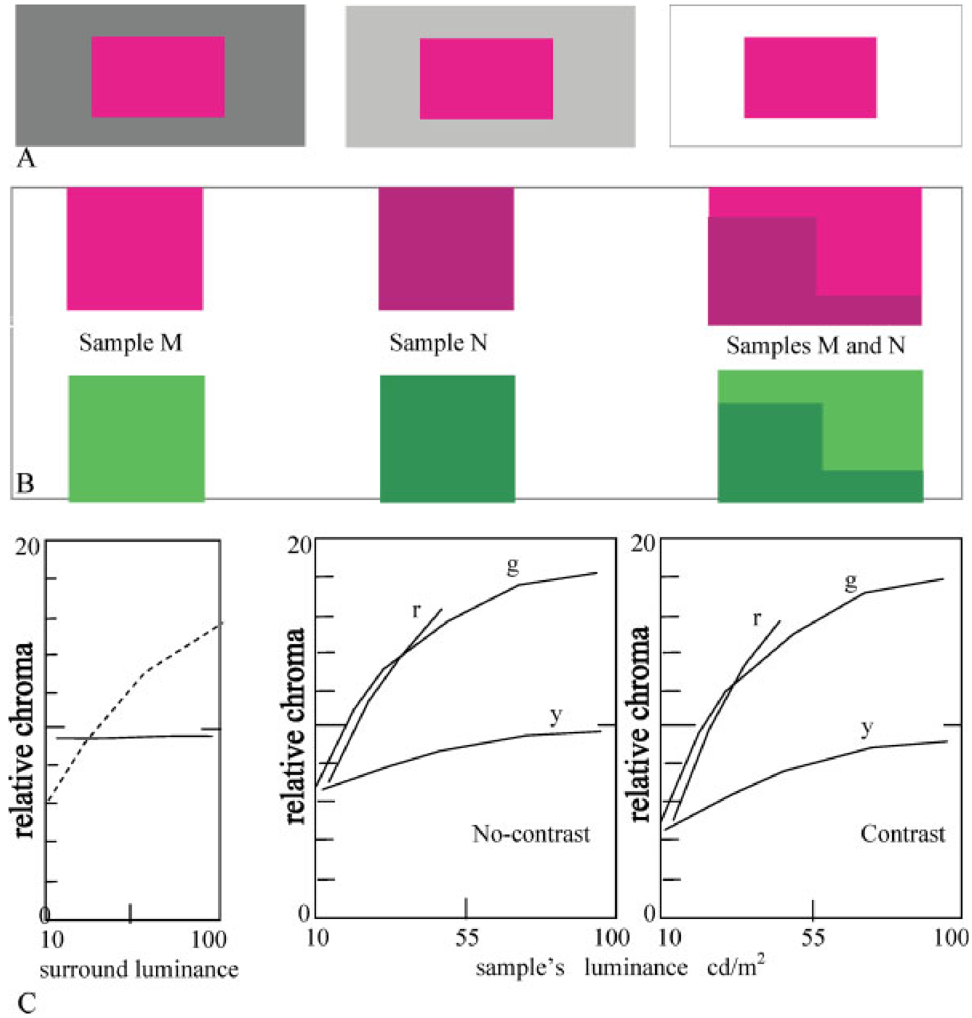

FIG. 5. Effects of luminance on chroma, Lc_N and Lc_C, for varying surround luminance or varying sample luminance. A: Effect Lc_N for a red sample of constant luminance factor in grey surrounds of varying luminance levels. Note chroma stays constant while colorfulness (dashed line in C) rises. B: Effects Lc_N and Lc_C in a constant luminance level (the white page as surround and background). The (red or green) sample N is darker and lower chroma than sample M of the same wavelength when seen singly. The difference in chroma is increased when juxtaposed samples M and N (at right) are seen simultaneously; i.e. sample N appears even greyer and lower chroma. C: Left panel: For a sample of constant reflectance or luminance factor, chroma is almost constant with increasing surround luminance [though colorfulness (dashed line) rises], as in A. Center panel: In a constant luminance surround, for the labeled red (630 nm), green (510 nm), and yellow (575 nm) (*r, g, y*) samples of constant CIE *x, y* chromaticity, chroma rises with sample luminance in the no-contrast mode; amounts represent RP data and approximately Munsell data. Yellow rises least. Right panel: Same but for contrast mode; RP data. The difference in chroma (and the slope) increases since the darker sample's chroma is reduced but the lighter sample's chroma remains almost the same, as in B.

Effect of Wavelength on Chroma /Colorfulness/ Saturation

Wc, the effect of wavelength on chroma (or colorfulness) is shown in Fig. 6 also. The dotted curve labelled Wc(U) represents perceived saturation (almost the same curve as colorfulness) for observer KU in Ref. 24 for equally bright monochromatic lights and four nonspectral lights. Note it is inversely-related to the brightness curve Wl(U). The same inverse relationship with brightness is shown by the dashed curve labelled Wc (Munsell), which relates to the right ordinate and represents chroma or colorfulness derived from Munsell chroma data for Value 5 and aperture or object colors of 0.9 colorimetic purity (p_c); the latter, for violet-blue hues, lies outside the boundary of optimal object colors so Munsell chroma data are extrapolated as colorfulness for aperture colors. Both Wc curves resemble previous data on chroma.[24,25]

The general reciprocity of lightness and saturation was first noted by Helmholtz and was later modeled by Pridmore.[26] Rather than resembling lightness, the B/L ratio curve (Inset to Fig. 6) resembles chroma: wavelengths of relatively high chroma have relatively high B/L.

Figure 7 shows the Wc effect for a constant 50% purity across the hue cycle, in terms of Munsell chroma, Value 5, and no-contrast (i.e. effect Wc_N, for samples in a white surround, viewed singly). The figure discriminates between excitation and colorimetric purity. The two functions are quite dif-

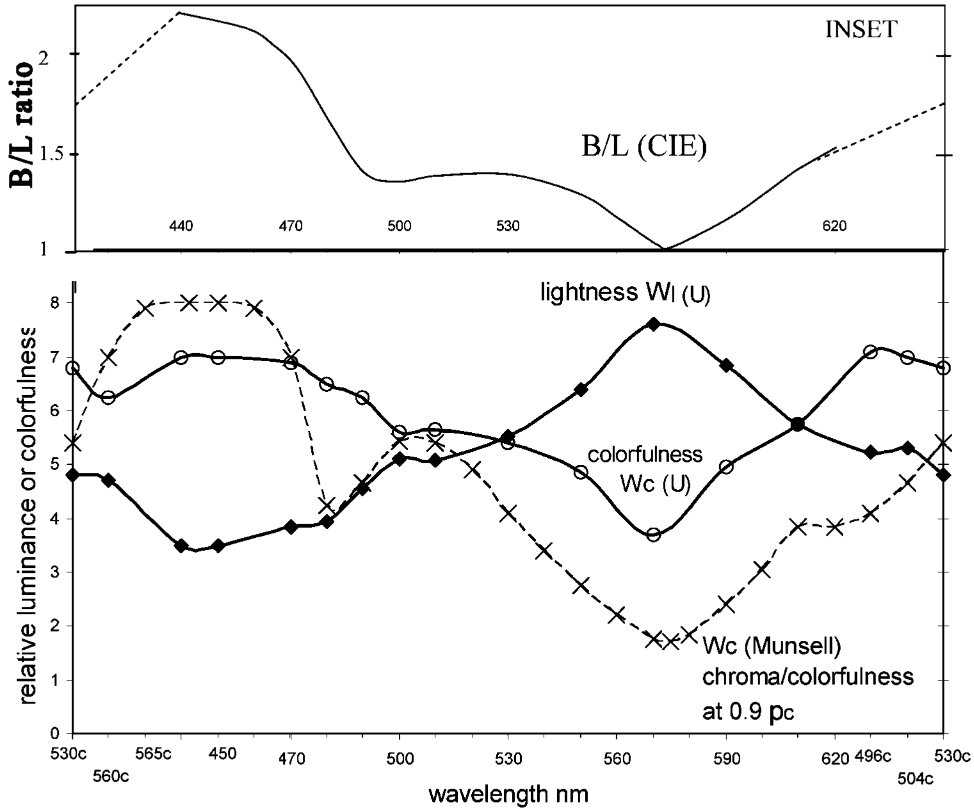

FIG. 6. Inversely-related effects Wl (wavelength on lightness) and Wc (wavelength on chroma, see also Fig. 7), for the contrast mode. The Inset over main graph shows CIE (1988) 2 degree data for the Brightness/Luminance ratio of monochromatic colors; dashed line approximates compound stimuli (nonspectrals). Main graph: Curve Wl (U) (solid line with filled diamond data points) represents perceived lightness measured as relative luminance for equally bright monochromatic lights and four nonspectrals, for mean of two subjects in Uchikawa,[24] normalised at 7.6 units as max. Curve Wc (U) (solid line, data points "o") represents perceived colorfulness for subject KU of Ref. 24, normalised at 7.2 units as max. Note this curve and Wl (U) are broadly inverse. Curve labelled "Wc (Munsell)" (dashed line, data points "*x*") shows Munsell chroma data for Value 5 for near-monochromatic colors (0.9 colorimetic purity) employed to represent colorfulness of aperture colors; the curve is extrapolated over the short wavelengths (where the boundary of optimal object colors limits Munsell chroma) where colorfulness rises steeply to 40 units (an arbitrary limit) at least; colorfulness is divided by 5 at the ordinate to normalise with the other curves. Note similarity of Wc functions to *B/L* ratio in the top Inset.

ferent, and that for colorimetric purity is much closer to the Wc functions in Fig. 6. Effect Wc is further described later.

Effect of Wavelength on Hue

The effect of wavelength on hue, Wh_N (no-contrast mode), is the well known phenomenon that hue varies nonuniformly with wavelength. In principle, the effect may best be determined as the variation of hue as a function of wavelength, e.g. as x-axis of a graph. This first requires a scale of uniform hue difference. The Munsell hue circle and its wavelengths (from Munsell hue data in the CIE 1931 diagram)[3] for Value 5 and maximum chroma is shown in Fig. 8A, together with the hue circle derived from OSA-USC data for $L = 0$ and maximum chroma. OSA-UCS relates to the CIE 10 deg observer, so its wavelengths are converted[†] to CIE 2 deg observer so it may be compared directly with the Munsell hue circle.

[†] To convert from one diagram to another, one reads the x, y coordinates for a given wavelength, and then looks up the wavelength nearest the same coordinates in the other diagram.

Since uniform polar angle represents uniform hue difference in these hue circles, the variation of hue with wavelength may be plotted as angle per uniform wavelength interval, as shown in Fig. 8B for both Munsell and OSA-UCS. The result indicates the Wh_N effect is a trimodal curve (three RGB troughs and three implied CMY peaks), which resembles various functions such as relative radiance of complementary colors[3,6] and (unsurprisingly) data on hue discrimination.[3] Interestingly, wavelength distribution around the CIELUV diagram (heavy dashed curve) is very similar to Munsell and OSA-UCS wavelength distribution, implying that complementary wavelength distribution in CIELUV, and CIE LUV hue angle, represent uniform hue difference quite well.

The no-contrast Wh_N effect, above, may be expected to be different from, and much simpler than, the contrast effect Wh_C due to chromatic induction in the latter. Presently there seems no experimental data on the Wh_C effect of wavelength on hue, as distinct from the effect of hue on (adjacent) hue, which is reported in the literature. Both the latter types of effect may be termed simultaneous con-

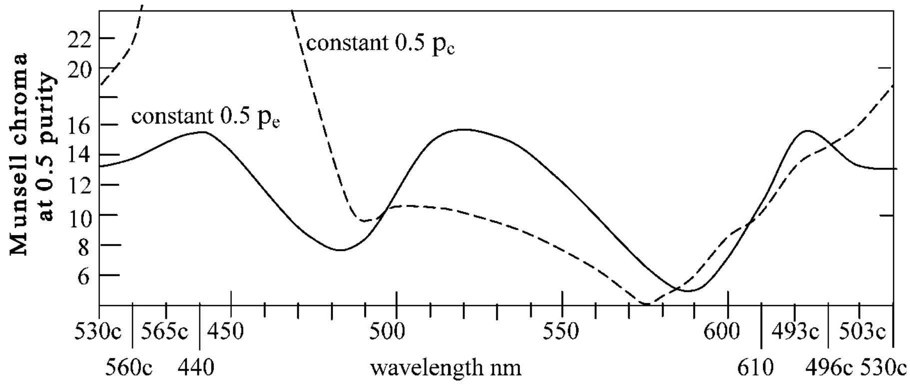

FIG. 7. The effect Wc, of wavelength on chroma, is discriminated between 0.5 excitation purity (p_e, solid line) and 0.5 colorimetric purity (p_c, dashed line), for Munsell chroma at Value 5, and the no-contrast mode (effect Wc_N). The 0.5 p_c curve rises drastically in blue and purple where it applies only to aperture colors, because it (but not 0.5 p_e) lies outside the MacAdam limits to optimal object colors.

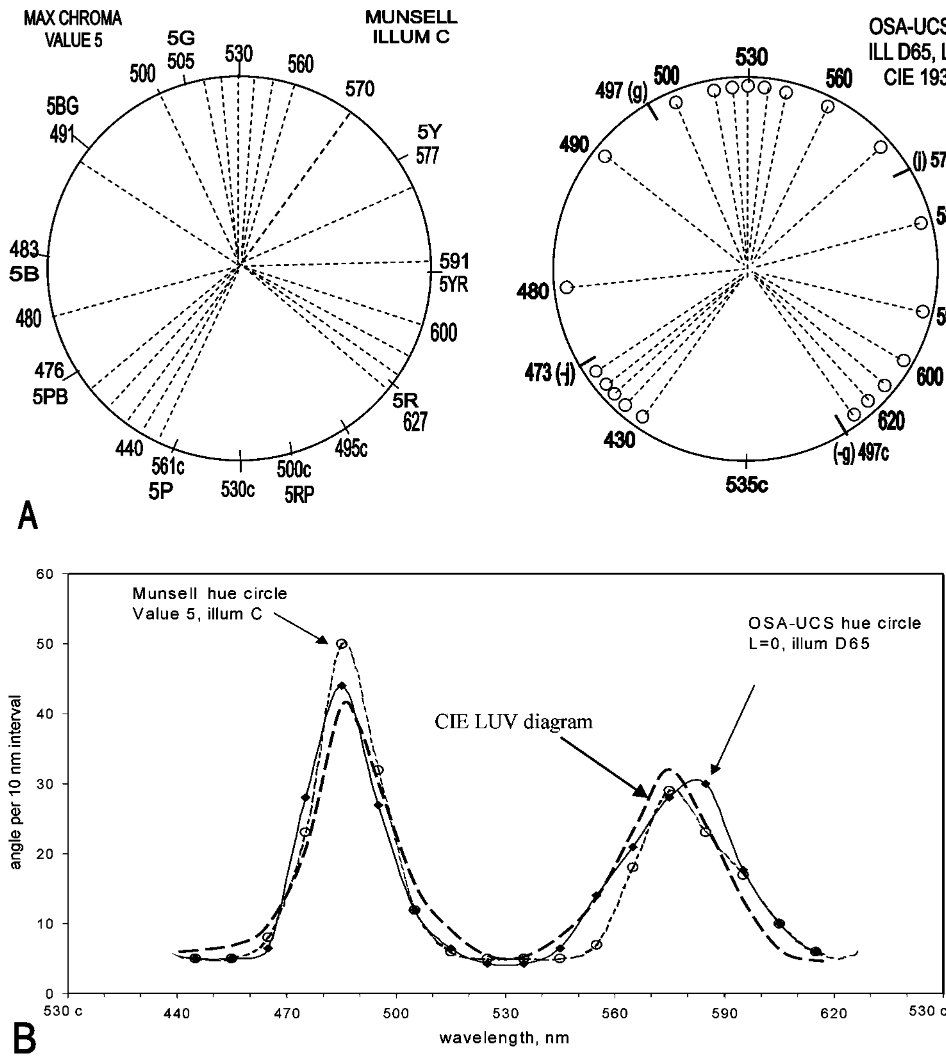

FIG. 8. Effect Wh_N, of wavelength on hue. A: Uniform hue difference as a function of circle angle, for two color order systems. Munsell hue circle showing wavelengths for illuminant C, max chroma, Value 5 and CIE 2° observer, and OSA-UCS data rendered as hue circle, for illuminant D65, max chroma, $L = 0$ and wavelengths converted to CIE 2° observer. Dashed radii show 10 nm intervals. Both hue circles are arranged with 530 nm at top of circle (the vertical radius), with increasing wavelength ordered clockwise. B: Effect Wh_N shown as change of uniform hue (in A hue circles) with wavelength. Ordinate shows angle per 10 nm interval for UCS hue circle (solid line, filled diamonds) and Munsell hue circle (dashed line, open circles). Note high rate of change for CMY hues, indicating greater visual sensitivity at these wavelengths. Heavy dashed line is wavelength distribution in CIE LUV diagram, representing complementary wavelength pairs as opposites through the neutral point.

trast or chromatic induction (see Fairchild[4] for examples). The Wh_C effect may be investigated by an experiment employing adjacent, simultaneously observed, samples where one is the reference hue and the other represents one of several test hues of known dominant wavelength. The aim is to measure how the test wavelengths affect the appearance of the reference hue. Next I describe simultaneously the effects Wh_C and Wc_C (effect of wavelength on chroma) since they appear to be directly related.

Figure 9 represents hue shift of a reference sample (of labeled wavelength) when seen adjacent to (without any gap) test samples of equal luminance, equally high chroma, and varying wavelength, in a neutral surround of thrice the lightness, for two observers RP (author) and IC. It shows effect Wh_C for only six reference hues over the hue cycle but in a manner that indicates the systematic pattern of hue shifts over the cycle. The peaks and troughs of hue shift (left ordinate) vary across the hue cycle and the variations appear to be, as shown, about equal in positive and negative portions of curve.

The effect of adjacent colors (including complementaries) on a sample has been well researched by Chevreul and others.[18,19] Consider reference sample 470 nm in Fig. 9, for both hue shift (left ordinate, Wh_C effect) and chroma shift (right ordinate, Wc_C effect). The wavelengths of the hue shift nulls are shown as the same as those of the maximum positive and negative chroma shifts, as may be argued in theory and demonstrated in practice. First, note that after-images are, or are close to, complementary colors.[19,27] So, when the test sample adjacent to the reference sample (blue 470 nm, labeled) is the latter's complementary hue (about 573 nm, yellow), its after-image will be practically the same hue as the reference sample. Hence the after-image's

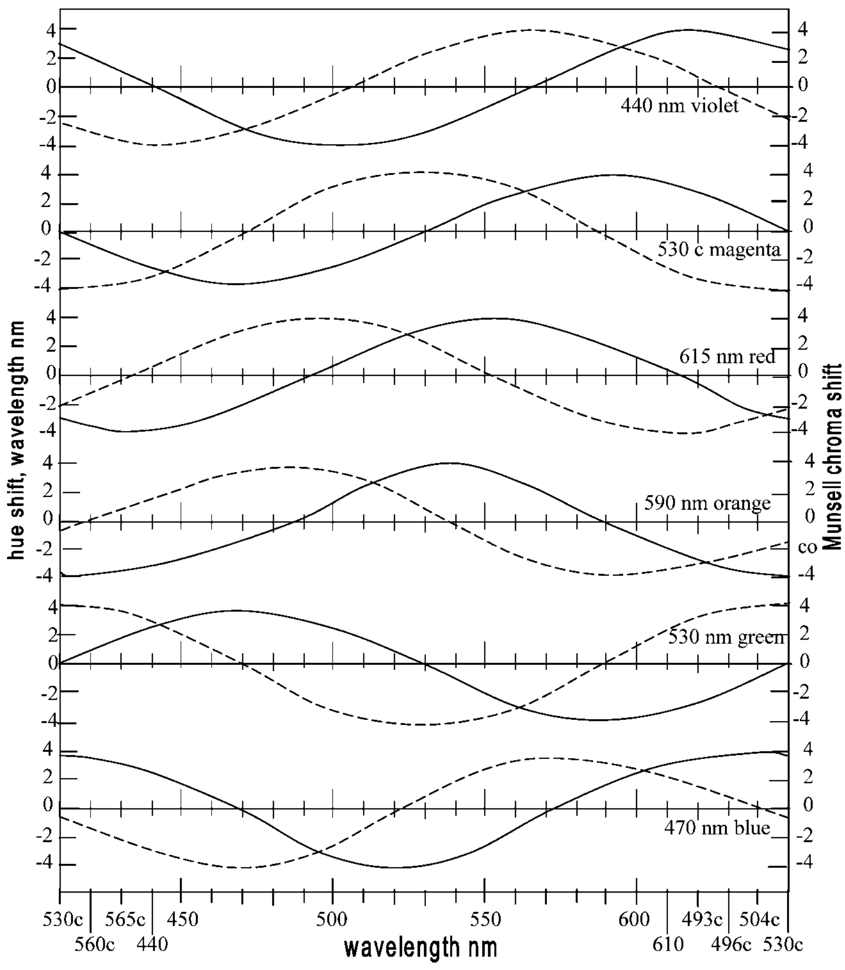

FIG. 9. Wh_C and Wc_C effects of wavelength on hue and chroma, for the contrast mode. Wh_C is wavelength effect on hue. A sample card *A* of $4^\circ \times 4^\circ$ visual field, 30 cd/m^2, high chroma, of the labeled wavelength, on white surround 100 cd/m^2, is first observed singly for 5 s and then observed for up to10 s simultaneously with an adjacent similar card *B* of same chroma and luminance but of the wavelength indicated on *x*-axis. The subject was instructed to report if, and how, the appearance of card *A* changed in hue or chroma. Six samples *A* are shown (displaced vertically). Hue shift (solid line) of each sample *A* is shown at left ordinate. Wc_C is wavelength effect on chroma. For the same stimuli, chroma shift (dashed line) is shown at right ordinate. Mean of observers RP & IC, over two sessions each, for illuminant D65. Amounts are intended to be relative only, and depend on luminance and temporal period. Note (approximately) sinusoidal curves for chroma are [1/4] cycle shorter wavelength than the hue shift curve.

effect on the reference sample will not change its hue (since both are the same blue), but the overlapping of the blue after-image on the blue reference sample will in theory induce an increased chroma. This case gives the maximum *positive* (=increased) chroma shift, and its approximate wavelength. If however the adjacent sample is the same hue (see Eq. 1) its complementary after-image will tend to neutralise or desaturate the reference sample (hence, maximum negative chroma shift) but not change its hue. This case gives the maximum *negative* chroma shift, and its approximate wavelength.

The wavelengths of peak and trough hue shifts are, of course, intermediate to the nulls and have been plotted at the exact middle though that may be an approximation. Here, the effect on hue is immediately perceptible over the entire sample, relative to its original appearance observed singly, and increases with stimulus interval up to about 30 s when (indeed after 5 s) it produces patches of different hue and lightness (see effect Wl mentioned earlier) in the sample rather than over the entire sample. A peak or trough wavelength of hue shift is intermediate to a peak and trough of chroma shift and therefore must be (at least approximately) a null of chroma shift, as plotted in Fig. 9, though the perception of changed hue and lightness makes this difficult to confirm. If the chroma nulls are not exactly the mean wavelength of the hue shift peak and trough wavelengths for all test samples, they are presumably so for the average of all hues or wavelengths. These relations are shown in Eqs. (1)–(5), where $\approx$ denotes "corresponds to"; *p, t,* and 0, denote peak, trough, and null, respectively, of hue or chroma shift; and subscripts $_{\mathrm{H}}$ and $_{\mathrm{C}}$ denote hue and chroma. "Sample λ" denotes the test sample is the same λ as the reference sample, and "sample λc" denotes the test sample is the complementary wavelength to the reference sample.

$$\text{sample } \lambda = \mathrm{O_H} = p_\mathrm{C} \text{ or } t_\mathrm{C} \tag{1}$$

$$\text{sample } \lambda\mathrm{c} = \mathrm{O_H} = p_\mathrm{C} \text{ or } t_\mathrm{C} \tag{2}$$

$$(p_\mathrm{H} + t_\mathrm{H})/2 \approx \mathrm{O_H} \tag{3}$$

$$(p_\mathrm{C} + t_\mathrm{C})/2 \approx \mathrm{O_C} \tag{4}$$

$$\mathrm{O_C} \approx p_\mathrm{H} \text{ or } t_\mathrm{H} \tag{5}$$

Note the hue shift and chroma shift curves are sinusoidal and are equal curve functions (if shift amounts in hue and chroma are normalized as in Fig. 4), with the chroma curve for a given sample lagging a quarter cycle, i.e. 50–70 nm, behind (shorter wavelength) the hue shift curve.

Effects Wh_C and Wc_C are interesting due to their evidently direct relationship, as expressed in Eqs. (1)–(5). This relationship has not previously been reported. Given either effect the other can be calculated. Similarly, effects Wl and Wc (Fig. 6) have been noted, above, to be closely related as generally inverse functions.

PURITY EFFECTS

Effect of Purity on Lightness/Brightness

Effect Pl is a component (like Wl) of the Helmholtz-Kohlrausch effect, and is usually judged by simultaneous comparison of chromatic lights or object colors with a reference white or grey and is thus a contrast effect (Pl_C). It is graphed in Fig. 10, adapted freely from data in Ref. 28 for CIE 10° observer and aperture colors, and in Ref. 20 for CIE 2° observer and object colors. The adaptation of data from different visual fields is excusable here since the lightness-(or brightness)-to-luminance ratios are very similar in both references. Simple tests of subject RP (by observing adjacent samples of different lightnesses in the contrast and then the no-contrast modes) indicated that the contrast effect Pl_C was not significantly different from the no-contrast effect Pl_N.

Effect of Purity on Chroma

Figure 10 also shows Pc, the effect of purity on chroma, from Munsell data for illuminant C, Value 5, and the CIE 2° observer. A CIE 1931 diagram with loci of Munsell Chroma for various Values (as in Ref. 3) was used to plot Figs. 7 and 10; the required purity was plotted on the diagram and the Munsell Chroma values were read off; presumably the values reflect experiments with separately viewed samples, so the mode is contrast (Pc_C effect). The similarity with the Pl_C (lightness-to-luminance ratio) curves in the same graph is to be expected, since higher chroma generally associates with higher lightness. Figure 7, already described above, is of interest here as indirectly indicating effect Pc_C for Munsell chroma, Value 5, for two forms of purity: excitation purity and the older and less commonly used colorimetric

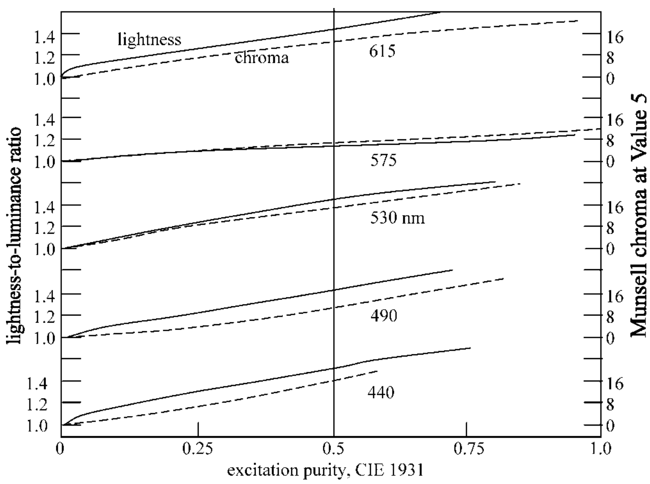

FIG. 10. Effects Pl and Pc, of purity on lightness and on chroma, for CIE 2° field and illuminant D65. Left ordinate: Pl_C as lightness-to-luminance ratio for object colors of indicated excitation purity and labeled wavelengths, from Refs. 20, 28 (see also Fig. 12 below). Right ordinate: Pc_C as Munsell chroma, Value 5, as a function of excitation purity for CIE 2° field and the same labeled wavelengths.

purity (see Appendix A); the curves are quite different, indicating care should be exercised when selecting which form of purity to employ. Contrast and no-contrast effects for Pc were tested by observer RP viewing adjacent Munsell samples of different chromas in the contrast and then the no-contrast modes. There was little or no difference between effects Pc_C and Pc_N.

Effect of Purity on Hue

The effect of purity on hue (in the contrast mode) is the well-known and commonly observed Abney effect,[29] Ph_C, which predicts that varying purity usually causes hue shift. Most data are for the contrast mode, the most common condition for the Ph effect. The roles of this and the equally-common Bezolde-Brucke effect are evidently to (1) sharpen the perception of borders between objects, and (2) improve the perception of three-dimensional objects, by adding hue-shift differences to chroma and lightness differences in the highlight and shadow areas.

As noted in Ref. 16, data sets on the Ph_C effect differ widely, often with opposing directions of hue shift. The number of hue shift nulls vary from two (in Munsell data, NCS data, and in Robertson's data[30]) to three or four (three implies four as nulls occur in pairs, e.g. either side of a peak) in Refs. 11, 23, 31, 32, 33, or even six nulls.[34] Abney's own limited data[29] specify only two nulls but imply two peaks and thus four nulls, but differ from other data since he used a yellowish light and he diluted samples by adding white light without readjusting to equal luminance. OSA-UCS data (for 10° visual field) do not agree with Munsell or NCS but indicate four nulls: two about 490 and 700 nm, and weak nulls about 530 and 550 nm between loci of very little curvature. These disparities in data sets are of major concern to color appearance modeling, but the majority of data sets indicate four nulls in the Ph effect.

Figure 11 shows four data sets for effect Ph_C with both samples (saturated and desaturated) of a pair at equal luminance. All sets agree on the yellow null and the peak in red. My recent data[33] (for 31 observers) and Kurtenbach's data[32] both indicate a second peak in cyan, while Munsell data and NCS data come very close to such a peak. I tested the Ph effect for both the contrast and no-contrast modes,[33] and found no significant difference. The Inset shows my Ph_C data as constant hue loci in CIE 1931 space; two of the nulls are similar to Munsell loci. My data suggested, from an informal test, that Ph_C for large visual fields remains a similarly bimodal curve.

SIX OTHER COMMON EFFECTS

The effects described above are the basic nine effects (comprising Class I, see Tables I and II) of the 3 × 3 matrix of psychophysical dimensions and color attributes. Six rather more complex, yet common, effects are described below. Each combines two or more psychophysical dimensions or color attributes.

Effect WPl_C (or Helmholtz-Kohlrausch effect), of wavelength and purity on lightness, is illustrated in Fig.

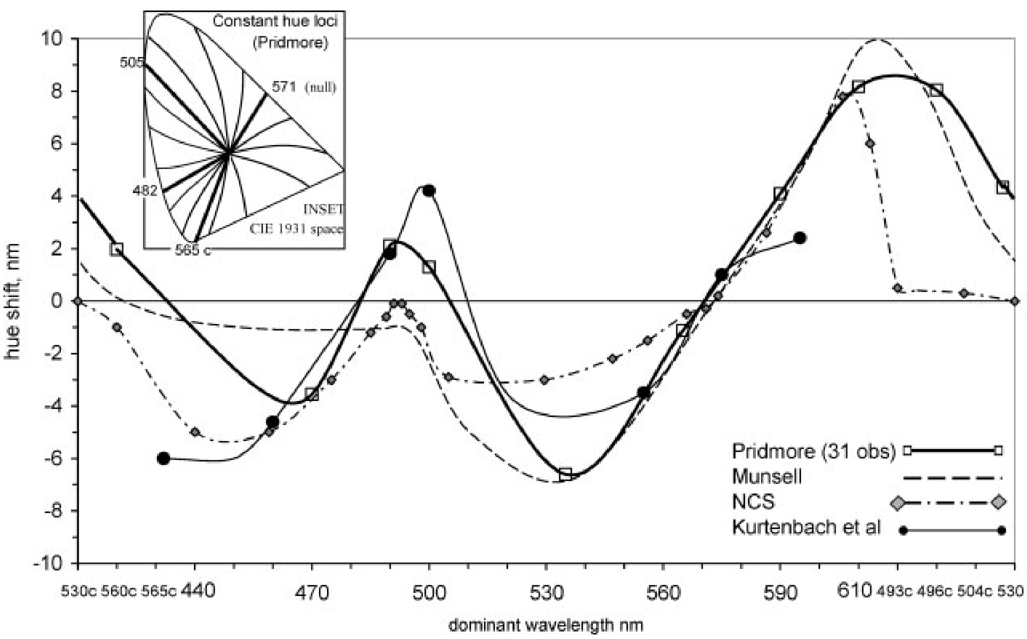

FIG. 11. Four data sets on Ph_C (effect of purity on hue, Abney effect), as a function of equal luminance: Pridmore (31 observers),[33] Munsell, NCS, and Kurtenbach *et al*.[32] (for 3 observers; data point at 595 nm omits 3rd observer as wildly discrepant from the other two [opposite hue shift]; note the curve from 500–555 nm is an estimate). The NCS curve represents equal luminance for both samples (high and mid purity) of a given wavelength,[33] but NCS luminance varies between wavelengths. Inset: Pridmore data[33] on constant hue loci in CIE 1931 diagram; curvatures exaggerated for clarity; note the nulls at 571 nm and 565 c are similar to Munsell data.

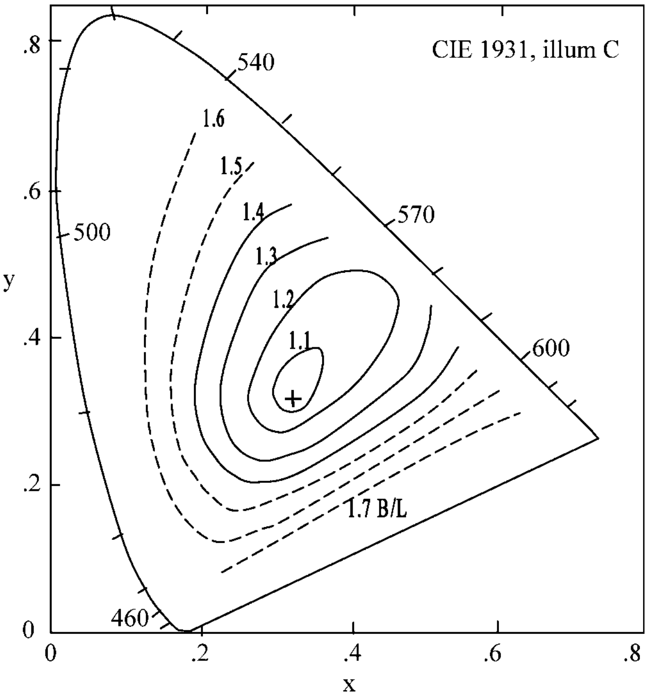

FIG. 12. Effect WPl, of wavelength and purity on lightness (in contrast mode.) This is the Helmholtz-Kohlrausch effect, whose component effects are Wl (effect of wavelength on lightness) and Pl (effect of purity on lightness). The contours represent Brightness-to-Luminance ratio, and are freehand adapted or extrapolated from Refs. 20, 28.

12. Its components are Wl_C (effect of wavelength on lightness, and on *B*/*L* ratio, Fig. 6) and Pl_C (effect of purity on lightness, Fig. 10). The solid contours are graphed from tabled data[20] and the dashed contours are freehand drawn from inter- and extra-polation from Refs. 20, 28.

Effect LPh_C, the contrast effect of luminance and purity on hue, is shown in Fig. 3 above (blue line, mean of two observers RP and IC) and represents the combined Bezold-Brucke and Abney effect. This combination of Lh and Ph effects is common in everyday scenes. The experiment employed CRT monitor stimuli of 2 deg visual field, 30 cd/m^2 on 100 cd/m^2 background simulating daylight D65, and maximum available purity (same samples as Ref. 33). These saturated and bright samples (say, *strong* color samples) were compared with (say, *weak* color) samples of the same wavelength (measured by Philips PM5639 color analyzer) but desaturated to 0.6 of the maximum colorimetric purity and reduced to 12 cd/m^2 luminance. The observers, for two sessions each, estimated hue shift from the *strong* to the *weak* sample by the same JND method as in Ref. 33 [i.e. by estimating the shift as a number of just-noticeable-differences, later converted to wavelength by reading from a nominal function of wavelength discrimination graphed to wavelength nm (*x*-axis) and wavelength nm per JND (*y*-axis)]. The method's accuracy is adequate for hue shifts of no more than about 3 JNDs. Because of the method and the large shifts involved, this experiment's results may be approximate. From these results, it is not clear whether the LPh_C effect is an arithmetical sum or some other combination of the Bezold-Brucke and Abney effects.

Effect Lhc, of luminance on chromaticity, is illustrated in Fig. 13 in the form of chromaticity ellipses. Each ellipse represents an area of chromaticity that appears uniform, of no discriminable difference in hue or chroma. Higher luminance gives humans better color discrimination therefore smaller discrimination ellipses (and smaller discrimination error). Shown are the RIT-DuPont color discrimination ellipses[35] for equal luminance 42 cd/m^2 and the much smaller ellipses for equal luminance 2120 cd/m^2, as predicted in Ref. 36 from analysis of four data sets. Note how higher luminance of samples improves chromaticity discrimination, reducing ellipse area and the *a*/*b* ratio of the ellipse axes *a* and *b*, thus improving the circularity of ellipses.

The Llhc effect, of luminance on color (all attributes, *l*, *h*, *c*) is also shown in Fig. 13. The lightness axis is perpendicular to the *x, y,* chromaticity plane. Where the Lhc effect acts on ellipses, Llhc acts on ellipsoids (3-dimensional color). The schema of color discrimination ellipsoids at top left illustrate that though sample higher luminance (e.g. 2120 cd/m^2, for the left ellipsoid) improves

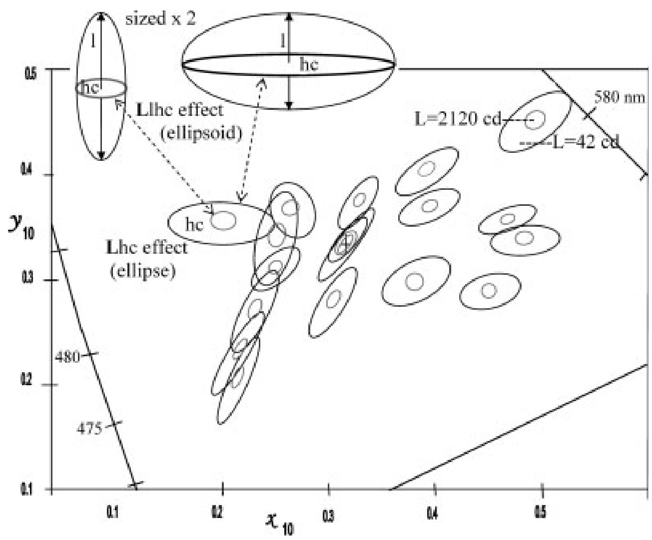

FIG. 13. Effect Lhc, of luminance on chromaticity (in the no-contrast mode, i.e. samples were observed singly, on a white surround). Luminance here refers to the sample. Shown are RIT-DuPont color discrimination ellipses (black) for equal luminance 42 cd/m^2 and the far smaller ellipses (grey) for equal luminance 2120 cd/m^2, in CIE 1964 (10 degree) diagram.[36] Also shown is the **L**lhc effect, of luminance on (3-dimensional) color, i.e. the effect on 3-dimensional color ellipsoids in the *x, y, Y,* space, on the two color discrimination ellipsoids at top left (note the times 2 scale). The double-ended arrow indicates the lightness (and luminous reflectance *Y*) axis. The greater the luminance of the sample, e.g. 2120 cd/m^2, the smaller the chromaticity ellipse (shown as "hc") but the larger the lightness discrimination axis "l" (and larger discrimination error) of the ellipsoid. See also Fig. 1, color solids.

discrimination of *chromaticity* (hence smaller chromaticity ellipses, labeled "hc") it worsens discrimination of *lightness* (hence larger lightness axes "*l*"). See also Fig. 1, for a schema of the Llhc effect: the right hand color solid represents increased lightness and chroma and some hue shift as the effects of higher sample luminance relative to the left hand color solid.

The Wh (shadows) effect, of wavelength of light source on hue, is shown in Fig. 14. The figure details the case of highly chromatic light source, such as stage lights, throwing shadows perceived as the complementary color to the light source, upon light achromatic or near-achromatic surfaces. Goethe[37] first reported the phenomenon as "colored shadows." It is a form of the Helson-Judd effect confirmed in the Munsell Color Science Laboratory and is clearest with near-monochromatic light sources.[4] The effect is observed immediately but grows stronger (shaded areas appear more chromatic) after adaptation of 20 seconds or more. The effect is also seen in the general hue-cast of all colors darker than the surround (or the average luminance of the scene).

Kodak Wratten filters numbers 15 (yellow), 23A (orange), 25 (red), 32 (magenta), 34 (violet), 46 and 98 (blue), 55 and 74 (green), and 65 (cyan), were tested with subject RP, by observing objects (luminance 40 cd/m^2) illuminated by Wratten-filtered lights; in all cases, the hue of an object's shadow is approximately complementary (as distinct from opponent-color) to the light source's dominant wavelength. For example, with filter 55 (green, 520 nm) placed over a daylight-white source approximating D50, shadow areas appeared purplish red (about 520 c); with filter 23A (red, 610 nm), shadow areas appeared cyan (about 493 nm); and with filter 98 (blue, 440 nm), shadow areas appeared yellowish grey (not brown), with the yellow (about 570 nm) most distinct around the shadow edges. Most clearly seen with monochromatic sources, e.g. stage lights in theaters, it is also seen in shadows thrown by highly chromatic light sources. For example, sunlight filtered by yellow-brown bushfire smoke causes tree shadows to appear distinctly blueish, as commonly noted by fire-fighters in Australia's annual bushfires.

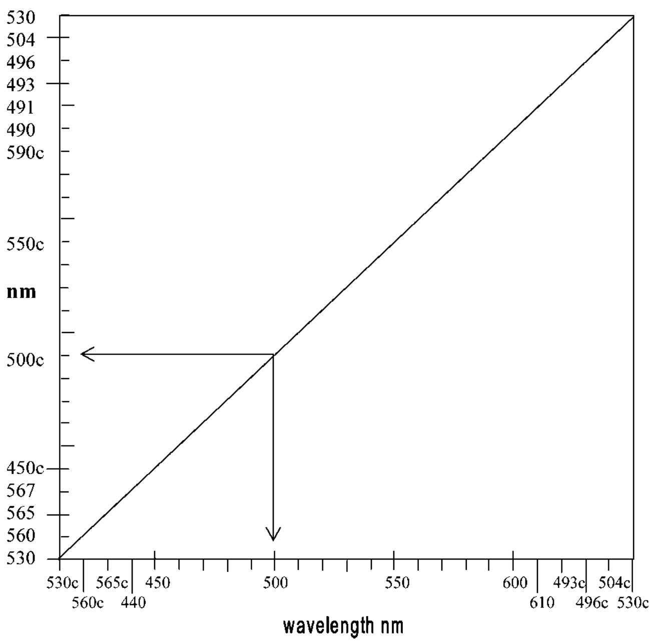

FIG. 14. Wh (shadows), the effect of wavelength of light source on hue (the phenomenon of colored shadows), in contrast mode; the effect cannot occur in no-contrast. The wavelength refers here to a highly chromatic light source, whose dominant wavelength is shown on the *x*-axis. The effect is a form of the Helson-Judd effect, where shadows thrown by a highly chromatic light source are complementary to the color of the light source. The *y*-axis shows the approximate wavelength of the shadow (as the complementary to the light source's dominant wavelength), found by drawing a vertical line from the light source's wavelength (*x*-axis) to its intersection with the diagonal (e.g. see arrowed lines at 500 nm and the complementary 500 c). For illuminant D65.

This effect is difficult to categorize since it concerns chromatic light sources. These are not anywhere near Planckian sources so the effect is not caused by variable Planckian light source, where the main variable is color temperature K.

Notably, if a scene is illuminated by both a white light source and a chromatic light source, each from different angles, an object throws two shadows: that thrown by the white light is the hue of the chromatic light source, and that thrown by the chromatic source is the complementary color.

Effect Kh, of illuminant correlated color temperature K on hue, is summarized in Fig. 15. This effect cannot be specified by L, W, or P, but only by illuminant correlated color temperature K. Hence this effect is an example of the effects of variable Planckian light source, i.e. chromatic adaptation. Black lines (solid, dashed, etc.) plot the wavelengths of constant hues across four illuminants, D95, D65, D50, and A, representing much of the practicable gamut of illuminant color temperature. Wavelength data is derived from six data sets on corresponding colors as described in Pridmore[38]; in the case of D65-A, the solid black lines represent the means of four data sets. Dotted parallel lines represent predictions, at 20 nm intervals, from an extremely simple model of constant hue in all illuminants.[38] The model is shown as Eq. (6), where s is wavelength shift nm of a constant hue from illuminant 1 to illuminant 2, and t_1 and t_2 are the two illuminants' reciprocal correlated color temperatures in MK^{-1}.

$$s = (t_2 - t_1)/17.7 \tag{6}$$

In the plane of wavelength and illuminant color temperature MK^{-1} (Fig. 15), the model's parallel gray lines approximate the mean angle of the sloping black lines of experimental constant hue from daylight D95 to tungsten light A. The model's lines are 87 degrees from horizontal in the full scale graph (Fig. 15 is compressed vertically to save space). The model exemplifies how the analysis of effects assists color appearance modeling.

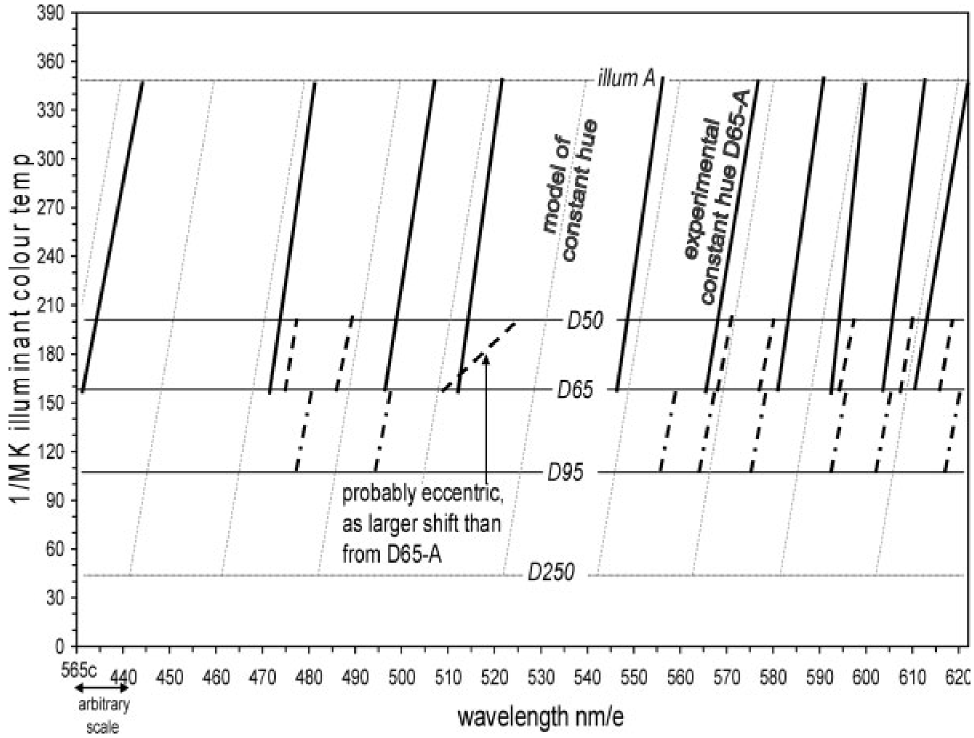

FIG. 15. Effect Kh, of (Planckian or Daylight illuminant) correlated color temperature K on hue (in no-contrast mode). Graph axes are wavelength versus reciprocal megaKelvin (1/MK). Solid sloping black lines connect the wavelengths of constant hue for illuminants D65 and A, as the means of four data sets on corresponding colors.[38] Dashed black lines show wavelengths of constant hues for D65-D50, and dash-dot black lines those for D65-D95.[38] Dotted parallel grey lines represent a model [Eq. (6)] of constant hue for any illuminant from D250 to A.

CONCLUSIONS

Fifteen of the commoner types of effects have been described. In six cases (Lc, Wh_N, Wh_C, Wc, Wh [shadows], Kh), new data were presented in support of effects. The study analyzed, to varying degrees of depth and novelty, relationships between psychophysical stimuli and perceived effects, and between effects. Such relations may appear complex but are consistent. For example, with increasing luminance the Ll_C effect (section Luminance Effects) unifies, and simultaneously represents, several phenomena including increased chroma (Fig. 1), increased brightness contrast (Fig. 2A), simultaneous contrast from adjacent stimulus or surround, and decreased lightness discrimination (Fig. 13). Improved understanding of relations between the effects will potentially allow the confirmation or adjustment of known effects and the prediction of the results of altering experimental parameters.

APPENDIX A: DEFINITIONS

Unrelated (or Aperture) Color: Color that appears to be a glowing light or a color seen in isolation from other colors. (Normally seen on a dark background.)

Related (or Object or Surface or Reflective) Color: Color perceived to belong to an object seen in relation to other colors; this includes a color sample observed singly but in a white surround.

Brightness (related and unrelated colors): Attribute of visual sensation in which an area appears to emit more or less light.

Lightness (related colors only): The apparent brightness of an area judged relative to that of a similarly illuminated area that appears to be white.

Colorfulness: Attribute of visual sensation in which the perceived color of an area appears to be more or less chromatic or colorful.

Chroma: Colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

Excitation Purity: A colorimetric term approximating chromaticness, calculated (for a given illuminant and chromaticity diagram) as A/B, where A is the distance from the illuminant point to a given chromaticity of given wavelength, and B is the distance from the illuminant point to the spectrum locus at the same dominant wavelength. (Formulae in Wyszecki & Stiles, 1982)

Colorimetric Purity: A colorimetric term approximating chromaticness, it represents the proportion of chromatic luminance in a color mixture (a mixture of a monochromatic component and an achromatic component), calculated as C/D, where C is luminance of the monochromatic component (known as chromatic luminance) and D is total luminance of the color mixture.

Value: Munsell Value correlates linearly to lightness (and nonlinearly to relative luminance), and is a 10-step gray scale from black (0) to white (10) in uniform steps.

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