Effects of psychophysical variables on colour attributes: a classification system

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ABSTRACT

A basic role of colour science is to specify the effects of the psychophysical dimensions on the colour attributes. Currently, the effects are not rigorously identified but loosely named after a few discoverers. We identify the many possible effects, propose a suitable classification system, and show that inadequacies in current data on effects may be partly due to lax definition of the effects and their experimental parameters.

1. INTRODUCTION

Colour science needs a data bank on the effects of the psychophysical dimensions on the colour attributes, particularly for colour appearance modelling, but current data are conflicting, scarce, and inadequately classified. Required is a rigorous system of classifying and naming the many possible effects. Classification promotes standard practice and potentially defines: (1) the gamut of effects including differentiation of similar effects, (2) relevant experimental parameters (eg, parametric factors in CIELAB-based colour difference formulas),[1] (3) areas requiring further research, and (4) roles and interrelationships of psychophysical variables in stimulating colour. The present study does not extend to the effects of a colour attribute (eg, lightness) on another attribute (eg, hue), which is a rather different set of effects.[2] Both sets are required for an advanced colorimetry of colour measurement and prediction.

2. CLASSIFICATION SYSTEM

For a given light source, the psychophysical variables are luminance, dominant wavelength, and purity, and the colour attributes are perceived lightness/brightness, hue, and chromaticness.[3] Chromaticness represents such perceptions as chroma, colourfulness, and saturation. The term "perceived" distinguishes the attributes from standard metrics, eg, CIELAB lightness or NCS chroma. The 3x3 matrix of single variables and single colour attributes gives nine combinations or possible effects, shown in Figure 1.

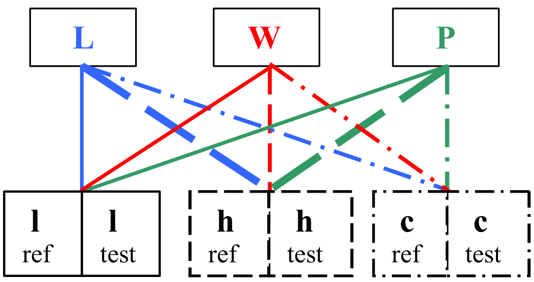

Figure 1: The nine lines (solid, dashed, etc) show the combinations of single psychophysical variables (L, W, P) with single attributes (lightness, hue, chromaticness, as l, h, c). Attributes are shown as adjacent reference and test samples, observed either singly or simultaneously, with different results. Heavy dashed lines L-h and P-h indicate the notably important Bezold-Brucke and Abney effects on hue.

Many effects on colour occur from combinations of psychophysical variables, such as wavelength and purity in the Helmholtz-Kohlrausch effect on lightness.[3] Table 1 gives the possible combinations of psychophysical variables and colour attributes for a given light source. An immediate deduction is that not all colour order systems can account for the nine effects in Class I (the basic class). In DIN, hue is constant with varying purity, and in NCS, maximum chroma is constant with varying wavelength. Hence DIN cannot represent the effect of purity on hue, and NCS cannot represent the effect of wavelength on chromaticness.

Table 1: Classification of effects of 3 psychophysical variables (luminance, wavelength, purity) on 3 colour attributes (lightness, hue, chromaticness) by singles, pairs, and triplets, for a given light source. Parentheses show number of combinations or effects per class. The 9 classes give a total 49 effects.

		Psychophysical Variables (3)		
		singles	**pairs**	**triplets**
	singles	Class I (9)	Class II (9)	Class III (3)
Colour Appearance Attributes (3)	**pairs**	Class IV (9)	Class V (9)	Class VI (3)
	triplets	Class VII (3)	Class VIII (3)	Class IX (1)

Table 2 below lists the Class I and Class II effects, named by readily understood terms for each type of effect, based on the initial letters of each psychophysical variable (L, W, P, in upper case) and colour attribute (l, w, c, in lower case). Here, "P" denotes colorimetric purity unless otherwise specified, lower case "l" denotes lightness, or brightness if specified, and "c" denotes chroma, or colourfulness if specified.

Table 2: Class I and Class II effects listed by type. Psychophysical variables by columns and colour attributes by rows. Class II contains the nine possible effects of paired dimensions on single attributes, including the Helmholtz-Kohlrausch effect (of wavelength and purity on lightness, ie, WPl).

Class I	**Luminance (L)**	**Wavelength(W)**	**Purity(P)**
lightness	Ll	Wl	Pl
hue	Lh	Wh	Ph
chroma	Lc	Wc	Pc
Class II	**L & W**	**L & P**	**W & P**
lightness	LWl	LPl	WPl
hue	LWh	LPh	WPh
chroma	LWc	LPc	WPc

Types of effect may be classified by temporal mode of observation. Mode N denotes no-contrast effects[4] (stimuli observed singly, at a minimum 35 s interstimulus interval) and mode C denotes contrast effects (simultaneous or immediately successive stimuli). The mode is shown by subscript $_N$ or $_C$, eg, Lh_C.

The remaining classes are similarly named. Eg, $WPlc_C$ denotes the contrast effect of wavelength and purity (WP, eg, chromaticity), on lightness and chroma (lc). The type's name may also specify experimental parameters such as illuminant, illuminance level, or viewing mode, in parentheses; eg, an effect's name may be "$WPlc_C$ (D65, 50 lx, surface colour)." If using reference 1 experimental conditions (known as CIE94 or CIEDE2000 reference conditions), the parentheses may specify those conditions, which include illuminant, illuminance, background, viewing mode, sample size and separation, etc, all of which substantially affect the perception of colour.

The remaining effect on colour is that of chromatic adaptation, ie, of variable light source, which cannot be treated by variables L, W, P, alone. At least another psychophysical variable is necessary. Currently, chromatic adaptation transforms use several colorimetric variables including CIE tristimuli and von Kries functions. However, given the present focus on fundamental psychophysical dimensions, it is interesting to find the further dimension required. This is illuminant correlated colour temperature (K), since it represents the relevant variable in light sources. If the source chromaticity differs significantly from the CIE illuminant locus it can be specified by W, P, K, where K is a correlated colour temperature of specific CIE chromaticity,[3] and W, P, (eg, W=490 nm, P=0.3 pc) relate to that CIE chromaticity as the "ideal" neutral. In this way, four variables (L, W, P, K) are the minimum necessary for the gamut of effects on colour attributes. For theoretical interest, Table 3 shows the possible combinations, giving 12 classes and 105 possible effects. This is a classification system for total colour space, and incorporates but extends the types of effects in Classes I-IX.

Table 3: Classification of effects for 4 psychophysical variables (luminance, wavelength, purity, and colour temperature) on 3 colour attributes (lightness, hue, chromaticness) by combination of singles, pairs, triplets, and quads.

		Psychophysical Variables (4)			
		singles (4)	**pairs (6)**	**triplets (4)**	**quads (1)**
Colour Appearance Attributes (3)	**singles (3)**	Class I (12)	Class II (18)	Class III (12)	Class X (3)
	pairs (3)	Class IV (12)	Class V (18)	Class VI (12)	Class XI (3)
	triplets (1)	Class VII (4)	Class VIII (6)	Class IX (4)	Class XII (1)

3. LIMITATIONS OF CURRENT DATA

Data on many effects are scarce or conflicting. The best known Class I effects are probably the Ll (or Stevens), Lh (or Bezold-Brucke), Ph (or Abney), and Lc (or Hunt) effects.[3-5] The proposed classification differentiates similar effects and gives a clearer indication of effect than the discoverer's name. For example, "Abney effect" may refer to the original parameter (a stimulus diluted by addition of white, and thus increased luminance) or the correct parameter (both stimuli at constant luminance). Data on the temporal modes' difference in effect are particularly scarce since the modes are rarely differentiated.

Three examples suffice. Most data on the Lh (or Bezold-Brucke) effect refer to the contrast mode.[3-5] The two modes (N and C) of Lh are widely presumed to represent the same effect, and have been compared experimentally and differentiated only once.[4] Reference 4 shows that the two effects, each for two observers, give similar curves but the Lh_N no-contrast curve is shifted to shorter wavelength by 10-25 nm. This shifts the peaks to nulls and vice versa, thus drastically changing the effect.

A second example is the Ll (or Stevens) effect,[3,5] where an image of various luminances is observed altogether, demonstrating that higher luminance gives exponentially greater lightness contrast. In the no-contrast condition, however, where one of the various lightnesses (say, a white patch) is observed singly in one level of illuminance and later in a higher level, the effect of luminance on lightness is minimal (the patch still appears white).[5] A third example is the Wh effect. If samples of different wavelength are observed singly, they appear quite different hues than if observed simultaneously in pairs.[5]

Munsell and NCS data on the Lh_N effect (of no-contrast luminance on hue) exemplify conflicting or confusing data. Figure 2 is adapted from Hunt,[6] who shows the two data sets give largely opposed curves. A third data set, for two subjects,[4] is also very different. Plainly, the Lh_N effect needs clarification; its lack of even an approximate agreement between data sets delivers low credibility, and any model based on such data must lack reliability. A mean of the three sets resembles the Pridmore curve,[4] suggesting it may represent a suitable function until Lh_N is clarified.

Another example of confusing data is the Ph (or Abney) effect of purity on hue. Ph_N and Ph_C (no-contrast and contrast modes) remain undifferentiated and various data give various hue shifts and nulls (as illustrated in reference 7). Munsell and NCS data give opposing hue shift directions in the nonspectral hues, with nulls near 560 c and 493 c respectively. However, the differences may be because NCS uses equal blackness while Munsell uses equal luminance.

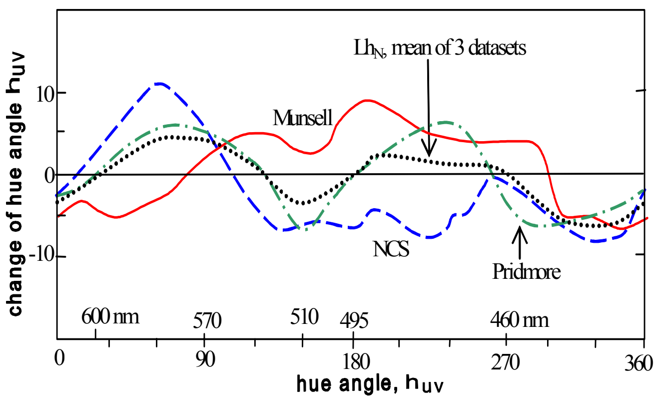

Figure 2: Three data sets for the Lh_N (or Bezold-Brucke) no-contrast effect. Solid line: Munsell data, from Hunt.[6] Dashed: NCS data, from Hunt.[6] Note the two curves are generally opposed, agreeing only in the nonspectral area. Dash-dot line: Pridmore data.[4] Dotted line: Mean of the three curves.

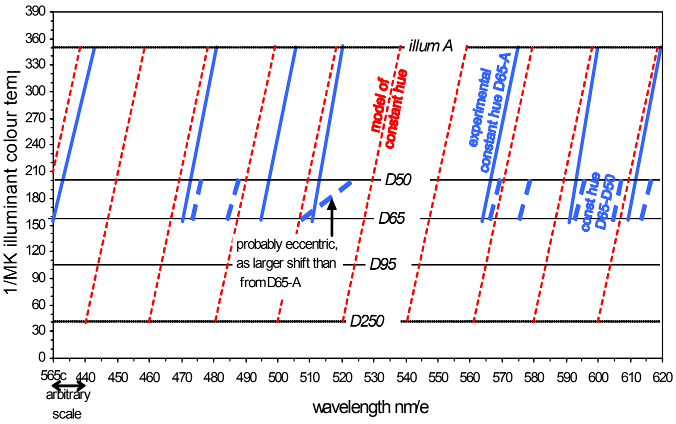

Figure 3: Effect Kh_N, of illuminant correlated colour temperature K on hue. Solid sloping lines connect the wavelengths of constant hue for illuminants D65 and A, derived from the mean of two data sets.[8,9] Dashed lines for D65 to D50 represent only one data set.[8] Dotted parallel lines show Equation (1) model of any constant hue for any illuminant from D250-A.

Clearly, all possible types of effects will not be reported for some decades, if ever. However, Class I is by far the most important: To understand the psychophysical variables' influences it is first necessary to define the effect of each variable on each attribute. Arguably, it is desirable to measure the psychological effect (eg, hue shift) in psychophysical terms (eg, wavelength shift) so that the psychophysical variables can be related, and so predicted, in cause and effect. Simple relations between stimulus and effect are more likely in a single domain (eg, psychophysics) than in mixed domains (psychophysics and psychology) which can lead to unnecessarily complex models. For example, the Kh_N effect (of colour temperature on hue) is usually modelled by complex chromatic adaptation transforms incorporating CIE tristimuli and von Kries-type functions, whereas data[8,9] plotted in psychophysical terms of wavelength versus 1/K (see Figure 3) indicate a very simple relationship.[10] Equation (1) predicts wavelength shift (s) of a constant hue from illuminant 1 to illuminant 2, whose colour temperatures in MK^{-1} are t_1 and t_2. Thus a constant hue wavelength in illuminant D65 is 2.6 nm longer in D50, or 11.2 nm longer in illuminant A.[10] This agrees well with mean wavelength data as shown in Figure 3.

$$s = (t_2 - t_1)/17.5 \tag{1}$$

4. CONCLUSION

For both basic and applied science purposes, more data on the effects are required, and in better agreement. We believe this will be assisted by a standard and detailed method of classifying and differentiating the many effects and their influential experimental parameters.

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