Partial colour matching: a new method to evaluate colour appearance and derive unique hues

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Abstract

We introduce a new technique to describe hue content in colour appearance. In contrast with classical colour matching, which implies visual equivalence of colour stimuli, partial colour matching means that two coloured stimuli may be different (do not match each other) but may have some hue in common. When comparing a pink and an orange stimulus a trichromatic observer can see some red hue in both. Alternatively, red and green, being complementary, do not even partially match as they have no common hue. Using a sample of twenty Munsell chips, we carried out an experiment asking observers to decide if a partial colour match exists for every pair of chips. A partial colour matching matrix was used to derive the set of component hues which the observer used in their decision making process. The results reinforce the classical notion of four unique hues. It must be said, however, that the results were obtained without resorting to verbal categorisation or knowledge of unique hues. This maybe crucial for making use of the technique in the examination of children and subjects with colour vision abnormalities.

Introduction

An important dimension of colour appearance is hue. Leonardo Da Vinci was probably the first to notice that there are six hues - black (Blk), white (W), red (R), green (G), yellow (Y), and blue (B) - which are experienced as unique, the rest of hues being a combination of them (e.g., orange is a combination of red and yellow, purple is a combination of red and blue). Furthermore, each colour can be specified by the proportions of unique hues it contains. Two methods are usually used to describe colour in terms of the relative amount of unique hues - hue scaling and hue cancellation techniques [1].

The problem, however, is that there is no objective definition of hue in general, and of unique hues in particular. For instance, Wyszecki & Stiles ([1], p. 487) define hue as "the attribute of a colour perception denoted by blue, green, yellow, red, purple and so on", reducing it to corresponding verbal categories, for which there are no operational definitions. A definition of, say, unique blue as a hue containing neither red nor green, implies the definition of unique red and green. But unique red, in turn, is defined as a hue containing neither blue, nor yellow. As a result, it is left to an observer to decide which of the numerous shades of, say, green is "unique". As Mollon & Jordan ([2], p. 382) pointed out, a classical hue cancellation (not to mention hue scaling) technique, which is also based on such a "definition" of unique hue, is "in effect only an extension of the basic determination of the unique hues". If by chance a person with an extraordinary set of unique hues (e.g., Blk, W, R, G, Y, B, and one additional unique hue X which is not present in the human trichromatic vision) visited a colour vision laboratory, we would probably fail to establish the presence of X by existing methods.

We put forward a new method - partial colour matching - which enables us to establish the nomenclature of unique hues objectively, not presupposing their number, and without resorting to verbal categories.

Method

The method rests upon the following assumptions. First, each hue can be characterised by (decomposed into) a number (one, two, three, or more) of component (unique) hues. Second, observers are able to judge whether the hues of the two objects share any component hues.

As a matter of fact, any two colours may either match each other in hue, or be different. In the latter case, they may share some common component hues (as yellow and orange), or they may have no component hues in common (as red and green). We shall say that, being well above colour discrimination threshold, two colours *partially match* if they have at least one common component hue. Note that we assume here neither verbal definitions of unique hues, nor their number.

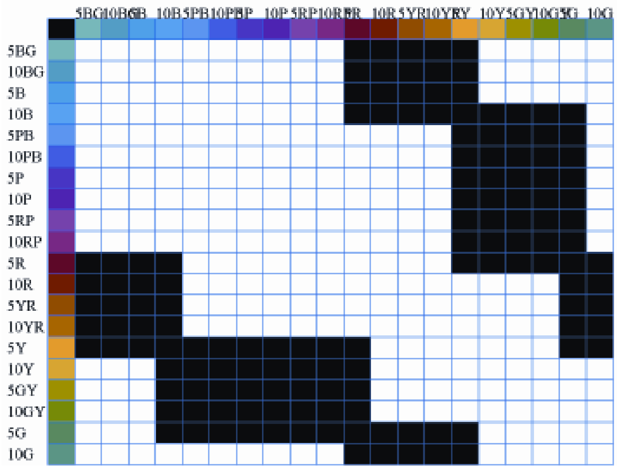

Figure 1. *Averaged and rounded matrix of observer KM responses. White checks denote those pairs of Munsell colour chips which were judged as having common hue components.*

An experiment on partial colour matching was conducted with five trichromatic human observers who were presented with a series of twenty Munsell chips (5BG6/10, 10BG5/10, 5B5/10, 10B5/12, 5PB5/12, 10PB4/12, 5P4/12, 10P4/12, 5RP5/12, 10RP5/14, 5R4/14, 10R5/16, 5YR6/14, 10YR7/14, 5Y8.5/14, 10Y8.5/12, 5GY7/12, 10GY6/12, 5G5/10, 10G5/10). The chips were randomly arranged on a table covered with a white cloth in a room with standard incandescent illumination. One chip was randomly singled out as a test chip. Observers were asked to pick out those chips whose colour has at least one common component hue with the test chip. They were instructed to ignore any difference in the strength of common component hue present. For instance, a red chip was to be judged as partially matching an orange irrespective of how small a tinge of red it had. Each of the twenty chips was used as a test 5 times. After averaging and rounding up, the results were presented in a matrix format (Fig. 1). White entries denote pairs of chips partially matching each other (e.g., 5B and 10P). Given a particular chip, we call any chip which partially matches this chip, a *partial colour match*. For example, the partial colour matches for 10G in Fig. 1 comprises 5BG, 10BG, 5B, 10Y, 5GY, 10GY, 5G, and 10G. Any set of chips that have identical partial colour matches are termed a *matching class*. The largest set of chips all of which partially match each other is called a *chromaticity class*.

We have proved [3] that, if observers make their decision on the availability of common component hues, then two results follow. Firstly, a chromaticity class comprises exactly all the chips which contain some particular unique hue (as a component hue). Thus, the number of chromaticity classes shows how many unique hues observers employed. Secondly, a matching class contains all the chips with identical component hues. Hence, the number of matching classes indicates how many different hues observers experienced (when presented with this particular set of Munsell chips).

Results

We found four chromaticity classes, thus four unique (component) hues; and eight matching classes for all observers (Figures 2-6).

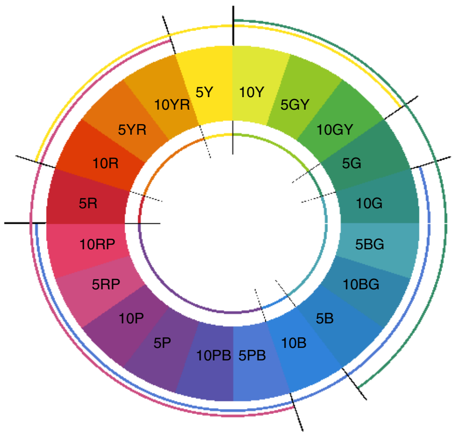

Figure 2. *Chromaticity (marked with outside arcs) and matching (marked with inside arcs) classes as derived from the response matrix in Fig. 1.*

Chromaticity classes for observers KM and LMF (Figures 2-3) consist of all the chip having (i) a yellow tinge (10R to 10GY), (ii) a blue one (10G to 10RP), (iii) a red one (10YR to 5PB), and (iv) a green one (10Y to 5B). Therefore, for these observers the unique (component) hues as revealed by the partial colour matching method are the classical Y, B, R, and G. Since we employed only chips with maximal Munsell chroma, we did not find (as expected) a "black" or a "white" chromaticity class.

Four of the eight matching classes contain only one component hue (i.e., belong to only one chromaticity class). We call the colours of the chips in a one-component matching class *unitary* colours. The other four contain two component hues. We call the colours of the chips in a two-component matching class *binary* colours (cf the conventional term "binary hue" in [1] p. 487).

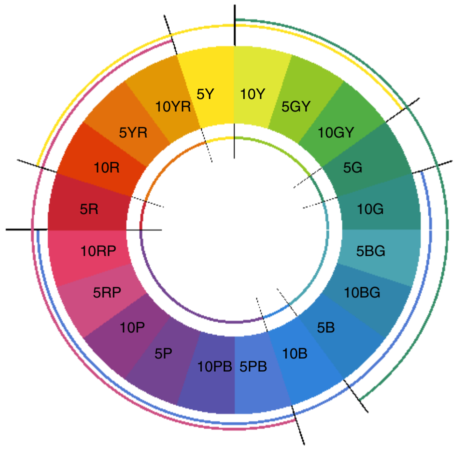

Figure 3. *Chromaticity and matching classes for Obs. LMF.*

Each of the one-component matching classes happened to consist of just one chip for KM and LMF. All these chips have a single hue letter notation in the Munsell system (5Y, 10B, 5R, 5G). These colours are often chosen when observers are asked to find unique colours in the Munsell atlas [4]. They are also in line with the unique hues as established by the traditional hue scaling technique [5].

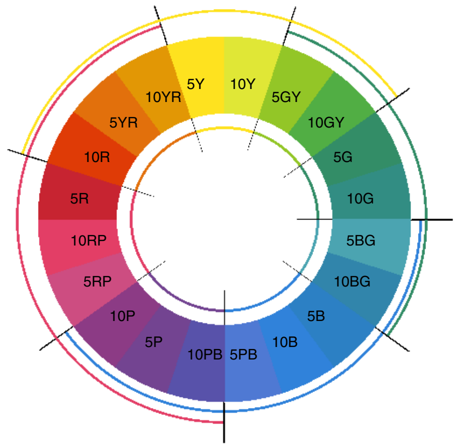

Figure 4. *Chromaticity and matching classes for Obs. LB.*

The results for Obs. LB are similar to KM and LMF except for her one-component matching classes are broader (Fig. 4). The Y, B, and G matching classes comprise two chips, and the R class three (5R, 10RP, and 5RP). The other side of this is that the chromaticity classes for LB contain fewer chips than for other observers. This happened because LB adopted a higher criterion when deciding whether a particular component hue is present in a particular chip. It is a typical threshold task. When one moves from, say, the yellow chip around the colour wheel, the amount of yellow in neighboring chips progressively decreases, becoming barely noticeable. The observers were advised to fix some criterion (of component-hue availability) and to keep up with it during the experiment. As they were not given any instructions on the criterion magnitude, it might have been different for different observers. Note, however, that a difference in criterion should not alter the number of chromaticity classes found in the data or their locations on the color circle: only their widths would change. In fact, LB exhibited the same four chromaticity classes as KM and LMF, only slightly truncated.

The chromaticity classes, particularly Y, for observers ET and DB differ in a more radical way. Specifically, for ET, the unitary green is 10G rather than 5G (as for KM and LMF), and, even more importantly, 5BG belongs to the Y (rather than B) chromaticity class. Note that chip 5BG follows 10G in the Munsell atlas (when one moves from yellow to blue hues). Hence, if 10G does not contain yellow hue then neither should 5BG. Yet, observer ET saw a tinge of "yellow" in 5BG but not in 10G.

A similar phenomenon takes place for Obs DB at the border between the Y and B chromaticity classes, only in the opposite part of the colour wheel (Fig. 6). While DB perceives 5R as unitary red (as all other observers), he sees a "yellow" tinge in chips 10RP and 5RP that belong to the B chromaticity class for other observers. According to Munsell notation these chips are purple (i.e., they contain a shade of blue). Therefore, if 5R does not contain yellow, then 5RP and 10RP would not be expected to.

Thus, both observers ET and DB have a Y chromaticity class which is essentially different from that of the other three observers. Indeed, their Y chromaticity classes contain chips with a blue shade according to Munsell notation, and which belong to the B chromaticity class for the other observers (5BG for ET and 10 RP and 5 RP for DB). Therefore, unique yellow hue for ET and DB must be qualitatively different from that of the other observers. Yet, their unique yellow is perceptually opponent to unique blue, as for the others, in the sense that the Y and blue chromaticity classes do not overlap.

Discussion

Our observers found the instruction to decide whether two Munsell chips contain some common hue(s) quite natural and easy. At any rate this task seemed to be easier to conduct compared to evaluating the amount of unique hues in percentage as the classical hue scaling technique requires.

Still, the validity of the method essentially depends on the observers' ability to make a judgment on the basis of hue content. Surprisingly, we found that not all observers could base their judgments on component hue content alone. For example, an important part of instruction was that the strength of the component hue should not matter. Based on hue content, slightly yellowish red and slightly reddish blue should partially match each other although the dissimilarity between these two colours is quite large. We found that some observers (not reported here) had a strong tendency to judge such pairs (i.e., with a large dissimilarity) as "not partially matched". In other words, we found that some observers are prone to replacing the task of hue judgment with one of colour similarity.

We believe this happens when observers are not experienced enough in evaluating the chromatic content of their colour sensations. Indeed, at the first glance, it is hard to spot that, for instance, chips 5PB and 10YR have a common component hue (so small is the common shade of red in these chips). After some training, however, most trichromatic observers are rather confident in judging these chips as a partial match. All our observers did 3 training sessions, the results of which were not included. They did not have any feedback during training since the rationale was to give them an opportunity to practice partial colour matching rather than to teach them how to make their judgments.

An important feature of our chromaticity classes is that the chips within each of them could be ordered with respect to the strength of the component hue constituting the class (referred to as *chromatic order*).

By and large, the chromatic ordering was found to be in line with the Munsell notation. We present here the ordering results only for observers LMF and DB.

	<u>The R chromaticity class</u>:
<u>LMF</u>	5R>10R>10RP>5YR=5RP>10P>10PB>5PB;
<u>DB</u>	5R>10R>5RP>10RP>5YR>10P>10PB;
	<u>The G chromaticity class</u>:
<u>LMF</u>	5G>10G>10GY=10BG>5GY>5BG>10Y=5B;
<u>DB</u>	5G>10GY>5GY>10G>5BG>10BG>10Y>5B;
	<u>The B chromaticity class</u>:
<u>LMF</u>	10B>5B>5PB>10BG>5BG=10PB>10P=5P>10RP>5PR;
<u>DB</u>	10B>5B=5PB>10PB=10BG>5P=5BG>10P=10G;
	<u>The Y chromaticity class</u>:
<u>LMF</u>	5Y>10Y>10YR>5YR=5GY>10R=10GY;
<u>DB</u>	5Y>10YR>10Y>5YR>5GY>10GY>10R>10RP>5RP.

Here > stands for "the strength of the component hue constituting the chromaticity class is not less than". For example 5R>10R means that the shade of "red" in chip 5R is not weaker than in 10R. The equality sign means that two chips contains the same amount of the hue in question (i.e., they cannot be preferred to each other in this respect).

Note that chromatic orders from Obs DB are, generally, finer than those from LMF (4 vs. 7 equality signs). For instance, Obs LMF distinguishes five different shades of yellow whereas DB nine (i.e., nearly twice as much). Therefore, the peculiarity of his Y chromaticity class cannot be accounted for by his poor chromatic discrimination in general.

The chromatic orders are found to have the properties of a weak order – they are complete and transitive. Specifically, any two chips x and y are chromatically comparable (i.e., either x has the component-hue strength not less than y, or y not less than x). And for any chips x, y, and z, if x has the component-hue strength not less than y, and y not less than z, then x not less than z.

It follows that the features which observers used in forming their decisions (concerning partial colour matching) are one dimensional variables (continua). Hence, a chromaticity class cannot be based on a binary hue (e.g., orange or violet), because, having two dimensions, such a hue cannot be linearly ordered. For example, a component-hue constituting the Y chromaticity class for Obs DB is definitely not the yellow as experienced by the other three observers. However, it is not a shade of, say, violet, or lilac, or other compound hue. It must be a unique (unitary) hue.

One can argue that DB, as well as other observers, might have based their judgments on some one-dimensional variable having nothing to do with hues at all, for example, on "darkness". However, in this case we have to admit that there are four different types of "darkness" for our observers. Furthermore, "Y-darkness" was found to be incompatible with "B-darkness", and "R-darkness" with "G-darkness" (the corresponding chromaticity classes do not overlap). Having analysed all the properties of these "darknesses" as revealed in our experiment for observers KM, LMF, and BL, we come to the conclusion that for these observers they are just euphemisms for the classical unique hues.

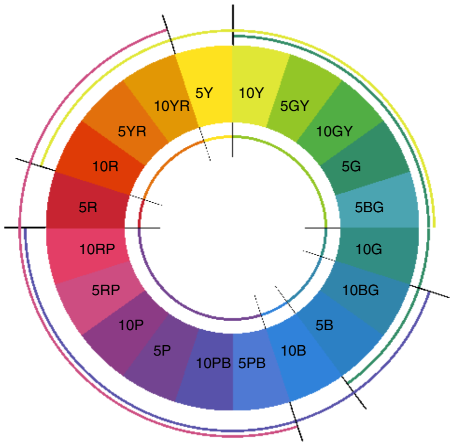

Figure 5. *Chromaticity and matching classes for Obs. ET*

It has been known for a long time that there is large inter-individual variation in unique hues among normal trichromatic observers [2, 4, 5]. The partial colour matching technique allowed us to reveal inter-individual differences between normal trichromats in the very chromatic dimensions. Particularly, the Y dimension (chromaticity class) is qualitatively different for observers DB and ET on the one hand, and the remaining subjects on the other. Partial colour matching can be especially pertinent when studying the colour vision of dichromats. So far there is no consensus on their chromatic dimensions. According to the classical Hurvich-Jameson theory of colour vision, protanopes and deteranopes should have only the yellow and blue chromatic dimension, missing the red and green ones [6]. However, there is strong opinion that protanopes and deteranopes do see shades of red and green [7]. Still, it is not clear whether it is skilful usage of verbal colour categories based on achromatic differences between colours, or these people really have four proper chromatic dimensions [8]. Partial colour matching can be used to ascertain the chromatic dimensions of protanopes and deteranopes separately from their colour category content.

Also, the partial colour matching may shed some light on a problem of a possible tetrachromatism of some human observers. Molecular genetic studies show that most people have more than two genes encoding both M-like and L-like photopigments [9]. Although phenotype-genotype interrelations are not straightforward, the existence of multiple photopigment genes has led authors to suggest that there exist individuals with more than three types of cone photopigment [10]. These people should have at least tetrachromatic colour vision. However, tetrachromacy in human subjects has not yet been found [11] except at mesopic light levels when both rods and cones operate, that was usually accounted for by rod-intrusion. It would be interesting to find out how many chromaticity classes people with more than three types of cone photopigments have, and how they are related to those discovered for normal trichromats.

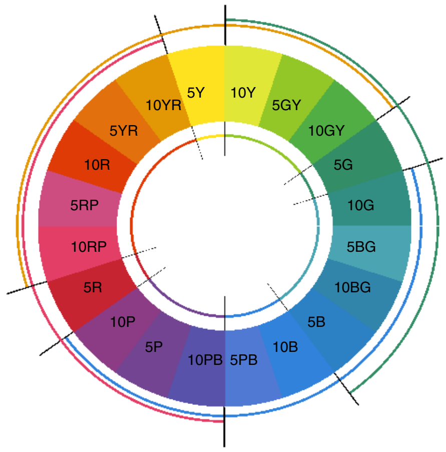

Figure 6. *Chromaticity and matching classes for Obs. DB.*

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Authors' Biographies

Alexander Logvinenko received his BS in psychology (1972) and in applied mathematics (1979), and his PhD in psychology (1974) from the Moscow State University, Russia. He had worked in the Psychology Department of the Moscow State University (1975-1992), and the Queen's University of Belfast (1993-2004). Now he is a professor of vision sciences at Glasgow Caledonian University. His research interests are in colour vision and psychophysics.

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