It is widely believed that color can be decomposed into a small number of component colors. Particularly, each hue can be described as a combination of a restricted set of component hues. Methods, such as color naming and hue scaling, aim at describing color in terms of the relative amount of the component hues. However, there is no consensus on the nomenclature of component hues. Moreover, the very notion of hue (not to mention component hue) is usually defined verbally rather than perceptually. In this paper, we make an attempt to operationalize such a fundamental attribute of color as hue without the use of verbal terms. Specifically, we put forth a new method—partial hue-matching—that is based on judgments of whether two colors have some hue in common. It allows a set of component hues to be established objectively, without resorting to verbal definitions. Specifically, the largest sets of color stimuli, all of which partially match each other (referred to as chromaticity classes), can be derived from the observer’s partial hue-matches. A chromaticity class proves to consist of all color stimuli that contain a particular component hue. Thus, the chromaticity classes fully define the set of component hues. Using samples of Munsell papers, a few experiments on partial hue-matching were carried out with twelve inexperienced normal trichromatic observers. The results reinforce the classical notion of four component hues (yellow, blue, red, and green). Black and white (but not gray) were also found to be component colors.

Keywords: color vision, color matching, elemental color, hue, component hue, unique hue, hue scaling, Munsell papers


**Introduction**

It is an old idea that colors can be decomposed into a small number of color qualia (such as “yellowness,” “redness,” “whiteness,” and the like) similar to chemical compounds being decomposed into a limited set of chemical elements (Kuehni & Schwarz, 2008; Valberg, 2001). For instance, Ewald Hering argued that there were six (four chromatic and two achromatic) “primary colors” (Urfärben) from which all other color sensations were composed (Hering, 1920/1964). We will refer to these hypothetical color qualia as *component colors*. The chromatic component colors will also be referred to as *component hues*. As known, most chemical elements exist on their own (i.e., in pure form, for example, gold), whereas a few exist only in mixture with other chemical elements (e.g., iron cannot be observed in pure form under natural conditions). Hering believed that the component colors could be observed “in pure form” as “unique colors” that are usually defined as non-reducible to any other color (Indow, 1987; Miller, 1997).

Hering’s idea of component colors was revived in the 1950s in order to assess hue in terms of component hues. It must be said that, curiously enough, there is no formal definition for such a fundamental attribute of color as hue. Indeed, Wyszecki and Stiles (1982, p. 487) define hue as “the attribute of a colour perception denoted by blue, green, yellow, red, purple and so on.” They simply reduce the definition of hue to verbal categories. Still, the lack of definition has not prevented color scientists from specifying hue operationally by the amount of the component hues it contains (Kaiser & Boynton, 1996).

There are two major methods to measure the amount of component hue contained in a particular hue: the hue cancellation technique (Jameson & Hurvich, 1955) and hue scaling (Boynton, 1997; Gordon & Abramov, 1988; Gordon, Abramov, & Chan, 1994). These procedures require an observer to have an understanding of what component hues actually are. Moreover, they rest upon the observer’s ability to establish the presence of a component hue in a particular hue. Specifically, hue scaling implies that observers are capable of evaluating in percentage the proportions between the component hues in the hue being measured. Therefore, a situation is created whereby observers are asked to judge hue in terms of something for which we offer no exact definition. The claim that component hues are to be unique (i.e., non-reducible) is not of much help, because there is no operational criteria for non-reducibility. Moreover, the hue cancellation procedure can, in principle, be readily applied with any (not necessarily unique) hue. As pointed out by Indow (1987), canceling, say, an orange hue is no more difficult than canceling yellow or red. Therefore, there is no guarantee that in a hue cancellation experiment observers cancel unique hues rather than some other hues. Besides, the hue cancellation technique is hard to apply to object colors.

The lack of an objective method to determine component hues before commencing hue scaling makes it quite
controversial to employ hue scaling for studying dichromatic color vision. It is not clear if dichromats experience the same set of component hues as normal trichromats, or they have a different nomenclature of component hues (Wachtler, Dohrmann, & Hertel, 2004). Although dichromats operate with the same verbal categories, there is no way to establish what they actually see when they assert that they see blue, or yellow, or any other hue (Jameson & Hurvich, 1978).

The situation becomes even more problematic when we do not restrict our consideration to the spectral light colors and deal with object colors. While black, white, and gray are included in the basic color terms (Berlin & Kay, 1969), it is not yet clear if they are component colors. For instance, Hering included black and white in his list of primary colors. However, do black and white have the same status as chromatic component colors? Is gray a unique color, or does it contain black and white in some proportion? In addition, there is a continuing debate concerning whether brown is a component color (Quinn, Rosano, & Wooten, 1988). Without an operational criterion, the notion of component color (as well as unique color) remains as vague as many other color categories (Mollon & Jordan, 1997).

A new method—partial hue-matching—has recently been developed to measure objectively the nomenclature of component colors in general, and component hues in particular, without assuming them to be unique and without resorting to verbal categories (Logvinenko, 2011). This method can be applied equally well to object colors as well as light colors. Here, we present some experimental results obtained for normal trichromats so as to illustrate how the method works and how it can be used to shed light on the questions raised above. We believe that the method is also applicable to dichromatic human observers. As the issue of component and unique hues is particularly problematic for object colors, we decided to test the new method on object rather than light colors.

### Partial hue-matching

The idea of partial hue-matching emerges from a simple fact that, even being different, two colors may contain some common component hue. If this is the case, a partial hue-match is said to take place. In an experiment on partial hue-matching, observers are asked to decide whether two colors share some common component hues (as, for example, yellow and orange), or they have no component hues in common (such as red and green). Admittedly, we assume observers to be capable of judging whether the colors of the two objects share some component hues.

Given a particular color, we call all the colors that partially match this color its partial hue-match. A set of colors that have identical partial hue-matches is termed a partial hue-matching class. The largest set of colors, all of which partially match each other, is called a chromaticity class. Intuitively, it is clear that a chromaticity class consists of all colors that contain a particular component hue. The formal proof of this statement can be found elsewhere (Logvinenko, 2011). Therefore, the number of chromaticity classes shows how many component hues observers employ. A partial hue-matching class contains all the colors with identical component hues (Logvinenko, 2011). Hence, the number of partial hue-matching classes indicates how many different combinations of component hues observers can see.

### Experiment 1: Chromatic component colors

The purpose of this experiment was to make use of the new method and to compare the results with the classical view on component hues of normal trichromatic observers.

#### Methods

##### Stimuli

A sample of 23 Munsell glossy papers was used as a stimulus set. The papers, taken from alternate pages of the Munsell book, were chosen to have the maximum Munsell chroma available for each page (5B6/10, 10BG5/10, 5B5/10, 10B5/12, 5PB5/12, 10PB4/12, 5P4/12, 10P4/12, 5R5/12, 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 set was completed with three achromatic papers: N9.5/ (white), N5.75/ (gray), and N0.5/ (black). For the sake of brevity, we will use the abbreviated notation for these papers as in Figure 1, denoting, in particular, the white, gray, and black papers as W, N, and BL, respectively.

The experiment was carried out in a neutrally painted cubicle, illuminated by fluorescent ceiling lights with spectral power distribution close to the CIE illuminant F11. The CIE 1931 chromaticity coordinates of the light reflected from the sample papers under this illumination, as measured with the PR-715 spectroradiometer, are presented in Figure 1.

The sample papers were displayed randomly and well separated on a large table covered by a white cloth (Figure 2). Each paper has a 2-cm width and 4-cm length giving, from an approximate viewing distance of 60 cm, an angular size of $2^\circ \times 4^\circ$.

##### Observers

Twelve normal trichromatic observers participated in the experiment. Their color vision was tested with Ishihara pseudo-isochromatic plates and Nagel Anomaloscope. They
had normal or corrected-to-normal visual acuity. All but one observer (the co-author LB) were naive to the purpose of the experiment.

**Experimental procedure**

As all the observers (except for LB) had no prior experience in color experiments, an introductory session was arranged for each observer individually, to make them familiar with the concept of hue before commencing the experiment. Specifically, the observers were shown the stimulus sample of Munsell papers (Figure 1) with instruction to select out the papers that had only one hue in the color. Nine observers chose the papers 5R, 5G, 10B, and 5Y. Observer LMC’s choice was nearly the same (5R, 5G, 5PB, and 5Y). Observer GP made six groups from the papers: (5R, 5RP), (10G, 5G), (5PB, 10B, 5B), (10Y, 5Y), (5YR), and (5P, 10P, 10PB). She believed that the papers in each group contained just one (same for the group) hue. Observer CM produced an unusually long list of papers having only one hue: 5RP, 10RP, 5R, 10R, 5YR, 10YR, 5Y, 10Y, 5GY, 10GY, 5G.

Next, a sample of Munsell papers of equal hue but varying chroma was presented, and the observers were asked if they all appeared to be of equal color. The answer was “no” for all the observers. They were then asked whether they were of the same hue. All the observers gave an affirmative response. Next, the experimenter asked what made the colors appear different if not a variation in hue. The observers described the difference using various names. Then, the experimenter told observers to ignore this difference in carrying out their task—to judge whether two colors contain a common hue. In addition, the observers were told to ignore all other differences in appearance (e.g., such as warm vs. cold colors).

The main experiment was divided into sessions. In a session, a test paper was randomly chosen by the experimenter from the stimulus set and positioned slightly to the side of the remaining papers (Figure 2). During one session, each paper served as a test once. The observer was asked to partition the remaining sample of papers into two groups—those that had a hue in common with the test paper and those that did not. All observers found this an easy and natural task. It was reinforced to the observer that they should ignore all differences between the papers.
Results and analysis

After numbering the stimulus papers, the observer’s results have been summarized as a response matrix \( r(i, j) \) \((i, j = 1, \ldots, 23)\), where \( r(i, j) \) stands for the number (between 0 and 5) of the affirmative observer responses to the \( i \)th and \( j \)th papers. For example, \( r(i, j) = 5 \) means that the observer judged the \( i \)th and \( j \)th papers as partially matching each other in all five sessions. Figure 3 (top) presents observer KM’s response matrix by a grayscale (from white representing \( r = 5 \) to black representing \( r = 0 \)).

Although partial hue-matching judgments are symmetrical by definition, a few asymmetries (i.e., entries for which \( r(i, j) \neq r(j, i) \)) are present in the response matrix. These are highlighted with red entries in Figure 3 (middle). We believe that the obtained asymmetry might have been caused by random fluctuations in observer’s criterion (see Discussion section below). So, each response matrix \( r(i, j) \) was symmetrized, that is, replaced by a matrix \( \tilde{r}(i, j) = (r(i, j) + r(j, i)) / 2 \). Finally, the response matrices underwent “thresholding,” that is, each matrix \( \tilde{r}(i, j) \) was replaced with a matrix

\[
\tilde{r}(i, j) = \begin{cases} 
1, & \text{if } \tilde{r}(i, j) \geq 2.5; \\
0, & \text{if } \tilde{r}(i, j) < 2.5.
\end{cases}
\]

The resultant response matrix for observer KM is shown in Figure 3 (bottom).

The white entries in a row of the response matrix make the partial hue-match for the paper corresponding to this row. For example, the partial hue-match for paper 5R consists of all the papers between 5PB and 10YR. The partial hue-matches for the three achromatic papers are singletons (i.e., includes only these papers themselves). A group of identical rows constitutes a partial hue-matching class. For example, papers 10G, 5BG, 10BG, and 5B form a partial hue-matching class. Paper 10B makes a partial hue-matching class on its own. So do papers 5R, 5Y, and 5G.

Chromaticity classes (i.e., the largest sets of papers all of which partially match each other) are harder than partial hue-matching classes to spot directly in a response matrix. A computer program was specifically designed to derive chromaticity and partial hue-matching classes from a response matrix. For observer KM, seven chromaticity classes were derived (Table 1). Three chromaticity classes were found to be singletons. They consist of one achromatic paper each. They will be referred to as the white, gray, and black chromaticity classes. In each of the rest of four chromaticity classes, there is exactly one paper that belongs only to this chromaticity class. If the main assumption that all the papers in a chromaticity class have some hue in common holds true, then these papers contain just one hue, which constitutes the corresponding chromaticity class. In other words, these papers are of unitary hue. Therefore, each of these unitary hue papers gives an idea of what hue constitutes the corresponding chromaticity class. For observer KM, the four papers of unitary hue are 10B, 5R, 5Y, and 5G. Note that these are the papers that observer KM picked up when asked to find the papers with unitary hue before the experiment. We will refer to these chromaticity classes as blue, red, yellow, and green, respectively.

The chromaticity classes for observer KM, as well as for another five observers whose results are very much alike, are presented in Figure 4, where the stimulus papers, except for the achromatic ones, are displayed in a “hue circle.” The order in which the papers are displayed is the same order in which they appear in the Munsell atlas. The chromaticity classes are marked with colored arcs on the circumference of the circle, each of which envelopes all the papers belonging to one chromaticity class. The color of an arc is the same as that used to mark the paper with unitary hue in the corresponding chromaticity class. Such a hue circle clearly indicates to which chromaticity classes each Munsell paper belongs. A paper enveloped by just one arc has a unitary hue. That covered by exactly two arcs has a binary hue.

As well as the chromaticity classes, the hue circle allows the partial hue-matching classes to be seen. From the above definitions, it follows that papers that belong to only one chromaticity class (thus, enveloped by one arc) form a partial hue-matching class of unitary hue. Papers that belong to exactly two chromaticity classes (thus, enveloped by two arcs) constitute a partial hue-matching class of a binary hue. As one can see in Figure 4, apart from four chromatic unitary partial hue-matching classes, observer KM has four binary partial hue-matching classes: yellow–red, green–yellow, blue–green, and red–blue.

The six observers whose hue circles are depicted in Figure 4 brought about very similar results: three achromatic singleton chromaticity classes, four chromatic chromaticity classes, four chromatic unitary partial hue-matching classes, and four chromatic binary partial hue-matching classes. The results of observers LM and KM are completely identical. Those of observers GS, KMC, LB, and WL differ only in that not all their chromatic unitary partial hue-matching classes consist of one Munsell paper. For instance, the red unitary partial hue-matching class comprises two or three Munsell papers for these observers.

Figure 5 presents the results produced by another four observers. The chromaticity classes and partial hue-matching classes yielded by observers AP and DB are...
Figure 3. Partial hue-matching responses obtained in Experiment 1 for observer KM: (top) the raw response matrix; (middle) the symmetrized response matrix; (bottom) the thresholded symmetrized matrix. See text.
similar to those in Figure 4 except that they produced a discontinuous chromaticity class each. Indeed, there is a gap in the blue arc for observer AP and in the yellow arc for observer DB. Yet, permutation of papers 5BG and 10G eliminates the discontinuity of the chromaticity classes for observer AP. So does the permutation of paper 5R with papers 5RP and 10RP for observer DB.

The data from the other two observers are different again. Observers LMC and CB brought about five and six chromaticity classes, respectively (Figure 5). Not all of them have a corresponding unitary partial hue-matching class. Specifically, observer LMC has the yellow (5Y), blue (10B and 5PB), and red (or purple) unitary partial hue-matching classes. Observer CB has also three unitary partial hue-matching classes—yellow (5Y), red (5R), and green (5G and 10G). A tertiary partial hue-matching class has come up for observer LMC. The hue circle of observer CB contains three tertiary and one quadruple partial hue-matching classes.

The last two observers yielded response matrices that are rather different from the other ten and from each other (Figures 6 and 7). It is argued below (see Discussion section) that such patterns of responses testify against the observer judgments being based on component hues.

**Discussion**

It has been proven that chromaticity classes can be uniquely recovered from a response matrix only if there is a unitary partial hue-matching class in each chromaticity class (Logvinenko, 2011). This is the case for eight (of twelve) observers (all six in Figure 4 and two—AP and DB—in Figure 5). As all these observers produced four chromatic and three achromatic chromaticity classes, one can conclude that these observers have the six component colors as anticipated by DaVinci and Hering, and a gray component. We will refer to these eight as “classical” observers.

Note that for some of these observers the unitary partial hue-matching classes were found to be rather broad (up to three Munsell papers). We believe that such inter-individual differences might have been due to variability in observer’s criterion. Consider, for example, paper 10Y. For most observers, it belongs to the binary green–yellow partial hue-matching class. However, it is included in the unitary yellow partial hue-matching class for observers LB and AP. It means that these two observers judged this paper as having no hue in common with the other papers in the green chromaticity class. In plain words, they decided that this paper is not tinged with green. The reason for this might have been that they needed a stronger tinge of green than the rest of the observers to make a positive decision. In other words,

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<th>Blue</th>
<th>10G</th>
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<td>5Y</td>
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<td>5GY</td>
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<td>10YR</td>
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<tr>
<td>Red</td>
<td>5PB</td>
<td>10PB</td>
<td>5P</td>
<td>10P</td>
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<td>5R</td>
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<tr>
<td>Green</td>
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<td>5B</td>
<td>10B</td>
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<td>White</td>
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Table 1. Chromaticity classes obtained for observer KM.

Figure 4. The results of Experiment 1 for observers KM, LM, GS, KMC, LB, and WL, presented in the form of hue circles.
these observers had a higher threshold criterion for detecting green. Moreover, it looks as if observer LB employed a high (whereas observers KM and LM employed low) criterion for all component hues.

It must be said that finding a point in the hue circle and dividing it into two segments—tinged with green and not tinged with green—is a typical threshold situation.

Indeed, any row in the response matrix in Figure 3 (top) can be considered as a kind of psychometric function. If one needs to estimate accurately enough this dividing point, one has, first, to increase the number of repeats (e.g., from 5 to at least 20) and, second, to employ more sample papers. However, this would considerably increase the total number of repeats, making the experiment impractically long.

One cannot exclude that the gaps in the blue chromaticity class for observer AP and in the yellow chromaticity class for observer DB are also due to the low repeat number. At any rate, an experiment with a larger number of repetitions is needed before coming to a conclusion concerning these chromaticity classes for these two observers.

For the rest of the observers—LMC (Figure 5), CB (Figure 5), GP (Figure 6), and CM (Figure 7)—not every chromaticity class contains a unitary partial hue-matching class. In this case, the chromaticity classes derived from the response matrices as described above should, strictly speaking, be interpreted as color categories (Logvinenko, 2011). More specifically, if one assumes that there is a set of color categories, and an observer responds affirmatively when two papers belong to the same category, then the papers in each chromaticity class belong to the same color category. A particular case of color category is that made by all the colors having the same component color. We will refer to this as a component-color category.

The most likely interpretation for observers LMC and CB is that along with component-color categories they used other color categories to make their judgment. For example, for observer LMC, of the two chromaticity classes that do not include a unitary partial hue-matching class one can be interpreted as an “orange” color category,
the other one as either the classical green component-color category, or as a more general “green” color category. Only two of the six chromaticity classes produced by observer CB contained a unitary partial hue-matching class. Therefore, the other four should be interpreted as some other color categories.

As to observer GP, it seems as if she did not follow the instruction to base her judgments upon component hues. Indeed, assume that an observer in a partial hue-matching experiment produces an affirmative answer when two papers are just similar to each other. For example, only adjacent (in the hue circle) papers result in a positive response. In this case, the white entries in the response matrix will take the form of a narrow (two checker wide) strip around the main diagonal. If the threshold of similarity is higher (say, two neighboring papers), the white strip will be wider (four checkers wide, respectively). The response matrix in Figure 6 looks as if the decision on “cold” colors was made on the basis of component hues, whereas “warm” colors were evaluated in terms of their similarity, the similarity threshold being 2–3 neighboring papers. Note that the unitary colors as produced by observer GP before the experiment are not in line with the unitary chromaticity classes as derived from the response matrix. It corroborates the conjecture that this observer might have replaced the task given with the similarity judgment.

A similar inconsistency was found for observer CM. At the preliminary stage, she named twelve chromatic Munsell papers as having unitary color. If this were the case, her response matrix would contain a number of lines with just one white entry. To the contrary, the response matrix in Figure 7 contains only three such lines, all of them corresponding to the three achromatic papers. Therefore, if this observer followed the instruction (to rest a decision on the availability of common hues), it would follow that she saw a common hue in almost any pair in the sample of Munsell papers.

## Experiment 2: Achromatic component colors

The black, white, and neutral papers were found to make a singleton chromaticity class each. It means that no other paper used in Experiment 1 contains black, white, and gray component colors. This is hardly surprising since the chromatic part of the stimulus sample comprised Munsell papers of maximal chroma. In this experiment, we ascertain whether including “whitish” and “blackish” Munsell papers will result in broadening of achromatic chromaticity classes.

## Methods

The sample of 25 Munsell glossy papers used in this experiment (including the same three achromatic papers as in Experiment 1) is displayed in Figure 8. The CIE 1931 chromaticity coordinates of the reflected light for these papers are shown in Figure 9. If one likens the Munsell tree to a globe, then the stimulus papers in Experiment 1 make a closed curve that can be likened to the equator, whereas the present sample could be thought as being arranged along two opposite meridians.

Six of the observers who participated in Experiment 1 took part in this experiment. Experimental setup and procedure were the same as for Experiment 1.
Results

As in Experiment 1, the gray paper makes a singleton chromaticity class for all the observers. All the other chromaticity classes are shown on a hue circle for each observer in Figure 10. As one can see, the white chromaticity class is a singleton only for observer GS. The black chromaticity class has been found to be a singleton for two observers, GS and CB. For the other observers, the black and white chromaticity classes comprise more than one paper. The black paper makes a unitary partial hue-matching class for all observers. So does the white paper, with an exception for observer LM.

Three observers (CB, LM, and LB) produced four chromatic chromaticity classes that are in line with the results of Experiment 1. The other three produced only three. For these observers, the green and blue chromaticity classes revealed in Experiment 1 merge into one chromaticity class that can be named as blue–green. The blue–green chromaticity class for observer GS and the blue chromaticity class for observer LB were found to overlap with the yellow chromaticity class.

It must be said that the computer program produced one more chromaticity class each for observers GS and LB (Figure 11). However, these classes have been removed because they were superfluous (Logvinenko, 2011), in that by removing these classes the response matrix is not affected. More specifically, given a set of chromaticity classes, consider an ideal response matrix produced as described above: a pair of papers is assigned 1 if there is a chromaticity class to which both the papers belong. This matrix, of course, amounts to the response matrix obtained in the experiment. It was found that, except for these two chromaticity classes, all the other chromaticity classes (derived in this and the previous experiment) are such that removing any of them changes the response matrix. These two classes can be removed without changing the ideal response matrix. Such chromaticity classes will be referred to as parasitic. They can be taken out of consideration.

Discussion

The black and white chromaticity classes have been found to be on a par with the other (chromatic) chromaticity classes. In contrast, the gray paper makes
a singleton chromaticity class for all observers, as in the previous experiment. These results shed light on the nature of the achromatic component of object colors (for a review, see, e.g., Heggelund, 1974). Although the old concept of a homogeneous achromatic dimension according to which blackness is simply due to the lack of light (e.g., von Helmholtz, 1867) has been abandoned (Volbrecht & Kliegl, 1998), the lightness dimension, varying from black to white, is a pivotal feature of the current theories of color (Wyszecki & Stiles, 1982) and models of color appearance (Fairchild, 2005). If black, gray, and white belonged to the single lightness dimension, then they would make a common chromaticity class. On the contrary, we found that for all our observers the black, white, and gray chromaticity classes do not overlap. Moreover, many Munsell papers were found not to belong to the black, white, and gray chromaticity classes. Hence, these papers do not contain any of the three achromatic components. This contradicts the existence of an achromatic dimension as such. Indeed, the notion of dimension implies that all the colors share this dimension. For example, if width and height are the dimensions of rectangles, then any rectangle has width and height. There is no rectangle without, say, width. However, as follows from our experiments, not all Munsell papers have an achromatic component.

Following Hering (1920/1964), achromatic colors have been thought of as a mixture of black and white in different proportions (Heggelund, 1974). The lack of overlap between the black, white, and gray chromaticity classes undermines this view. To be precise, the color of the gray paper used in the experiment certainly contains neither black nor white.

Note that there are binary partial hue-matching classes intersecting with the black and white chromaticity classes. It follows that there is no essential difference between the achromatic component colors (i.e., black and white) and the chromatic ones (i.e., component hues). As the black and white chromaticity classes do not overlap, black and white can be called opponent using Hering’s terminology.3

As to the two other opponent hue pairs of Hering, we found no overlapping for the red and green chromaticity classes despite some researchers claiming that it was possible to experience simultaneously Hering’s opponent hues (Crane & Piantanida, 1983). However, for observer LB, the yellow and blue chromaticity classes do overlap. It should be mentioned that there is an overlap between the “blue–green” and yellow chromaticity classes for observer GS as well. However, it is not a “pure” blue chromaticity class. The blue and green chromaticity classes revealed in Experiment 1 for this observer do not overlap. Note that observer GS saw yellow and blue together in paper 10Y9/2, which is of very low chroma and is at the border of both the blue–green and yellow chromaticity classes. Similar overlapping of the yellow and blue curves was observed in experiments on hue scaling (e.g., Gordon et al., 1994). Such overlapping is usually attributed to measurement errors. In contrast, observer LB saw yellow in paper 2.5B7/8, which has rather high chroma. However, she did not show any overlapping of the blue and yellow.

Figure 10. Hue circles derived from the Experiment 2 data.

Figure 11. Hue circles for observers with parasitic chromaticity classes.
chromaticity classes in Experiment 1. So, one needs more data to decide whether the yellow and blue chromaticity classes really do overlap. This may shed light on the old problem: whether green is a component hue or is composed of blue and yellow. The latter view was defended by Brentano (Nida-Rumelin & Suarez, 2009, p. 352), Holt (Boring, 1946, pp. 175–176), and some other authors (for a review, see Nida-Rumelin & Suarez, 2009).

The gray chromaticity class was found not to overlap not only with the black and white chromaticity classes but also with all the other chromaticity classes. It means that observers saw a shade of gray in none of the sample papers, bar the gray paper itself. This finding is rather surprising because the stimulus sample includes a few Munsell papers of the lowest chroma (e.g., 10Y9/2, 10G9/2, and 5BG9/2). This undermines the commonly accepted view that low saturated colors are perceived as a mixture of pure hues and gray. We decided to look into this issue in the next experiment.

**Experiment 3: Is gray a component color?**

The rationale for this experiment is to ascertain if the papers with low chroma, which look rather bleak (close to neutral gray), will complete the gray chromaticity class (recall that for all observers in the previous experiments gray made a singleton chromaticity class).

**Methods**

Two sets of glossy Munsell papers of the same hue as in Experiment 1 were used as stimuli. In the first set, all the papers had Munsell chroma /4 (i.e., 5BG6/4, 10BG5/4, 5B5/4, and so on); in the second set, all the papers had Munsell chroma /2 (i.e., 5BG6/2, 10BG5/2, 5B5/2, and so on). Both sets were also completed with the three achromatic papers employed in the previous experiments: N0.5/, N5.75/., and N9.5/.

The experiment was divided into two sessions. In each session, one stimulus set was used. Experimental setup and procedure were the same as in Experiment 1. Two observers took part in the session with chroma /4 and five with chroma /2. All observers in this experiment had participated in the first experiment and so were experienced with the procedure.

**Results**

In the first session (with chroma /4), the black and white chromaticity classes were found to be singletons for both observers. The gray chromaticity class was also found to be a singleton for observer LB. The gray chromaticity class for observer KM was found to consist of three papers (5RP5/4, 5PB5/4, and N5.75/). The other chromaticity classes obtained for these observers are presented in Figure 12.

In the second session (with chroma /2), all three achromatic chromaticity classes proved to be singletons for observer KMC. Figure 13 shows the chromatic chromaticity classes for this observer. The response matrices for the other observers are given in Figure 14.

**Discussion**

If gray were a component color, and allowing that any color of low chroma were a mixture of some component hue (or hues) and gray, then all the papers used in this experiment should have merged into one chromaticity class. However, this did not happen. Moreover, it was found that for four of the five observers, not more than two papers were included in the gray chromaticity class.
(seven papers for observer KM). All these papers have purplish, barely discernible colors. None of these papers were judged to have a common shade with gray in the first session (chroma /4) by observer LB and only two (of seven) by observer KM. Note that the response matrix of observer KM for chroma /2 resembles a narrowband diagonal matrix that is typical for the similarity judgments as discussed above. One could conjecture that the sample papers with chroma /2 were at threshold discernibility for observer KM; thus, proper hue judgment was hardly possible for her.

As the chroma threshold varies between hues, some Munsell papers of chroma /2 might have been in the threshold zone for some observers. This explains why few papers were found to belong to the gray chromaticity class. Therefore, it is safe to assume that when a color is above saturation threshold it is judged as having no common shade with gray. It follows that gray has a special status. It does not combine with any other component color, even with black and white, so as to form another color. This is in line with some results obtained by others (Quinn, Wooten, & Ludman, 1985). Dubbing its special status, one may say that gray is not a component color at all.

### General discussion

A new technique (partial hue-matching), designed to reveal the component colors into which each color can be decomposed (Logvinenko, 2011), was applied to a group of twelve trichromatic observers. Eight observers were found to have the classical set of four chromatic and two achromatic component colors (Hering, 1920/1964). However, the results of four other observers were not consistent with the classical theory of six component colors (Hering, 1920/1964; Hurvich & Jameson, 1957). How can one account for these individual differences? Do these four observers have color vision equipped with more component colors, or do their results undermine the very method, showing its limitations?
It should be borne in mind that the technique itself is not restricted exclusively to component color analysis. In a broader context, the technique can be interpreted as follows. An observer is presented with a stimulus pair and asked to judge if there is some “feature” in common for the pair. In other words, observers are assumed to produce an affirmative response when two stimuli have a common feature. Using the same analysis as that used to derive chromaticity classes, one can derive from the response matrix stimulus subsets having some “feature” in common. If the features are component colors, then these subsets are the chromaticity classes. Yet, even if an observer used some other set of features rather than component colors, one can ascertain what these features were by analyzing the stimulus subsets derived from the response matrix. Therefore, although the partial hue-matching technique implies the observer’s ability to discern component colors, the response matrices remain tractable even when this assumption is failed.

For instance, although observers were instructed to detect common hues, in Experiment 2 they responded affirmatively when comparing whitish colors with pure white. This unequivocally testifies that they treated whiteness as “hue.” Yet, in Experiment 3 they responded negative when comparing whitish colors (even with the lowest chroma) with gray. It follows that, first, they differentiated between whiteness and grayness; and second, they did not treat grayness as “hue.” In other words, contrary to the established color terminology, our observers counted white and black as hue. Note that this conclusion comes not from their introspective analysis but from their behavioral data. We believe that the color terminology should be revised so as to accommodate this fact.

So far, we have used component colors as a generic term to refer to the component hues as well as black and white. However, black and white are not hues according to the established terminology. Moreover, strictly speaking, there is a difference between the concepts of color and hue: indeed, there is a whole series of colors that have the same hue. Therefore, our terminology would be more coherent if, for example, we were to extend the list of hues including black and white into it (as achromatic hues). In this case, one can drop off the term component colors in favor of component hues.

As shown elsewhere (Logvinenko, 2011), if there is a unitary partial hue-matching class for every chromaticity class, then the set of component colors can be derived from the response matrix uniquely. In other words, the necessary condition of unique derivation of the component colors is that every component color exists as a unitary (unique) color. The results of eight observers meet this criterion. The results of the other four show that the observer’s ability to base their decision on component hues should not be taken for granted: if it were, then we would have to say that observer GP has at least nine component hues and observer CM even more.

If not component hues, what features could these four observers use? One may hypothesize that they interpreted the instruction to decide “whether the two stimuli have a common hue” as “whether the two stimuli have the same hue.” As in ordinary language hue has, generally, a broader meaning, being practically synonymous of color, such an interpretation would lead observers to decide “whether the two stimuli have the same color.” In this case, the chromaticity classes are, effectively, the stimulus subsets having the “same color.” Therefore, a posteriori, analyzing the chromaticity classes derived from the response matrix, one can find out what “same color” meant for a particular observer. At least two different interpretations of “same color” come out of our results.

First, it is a rather broad color category corresponding to some linguistic color category. Second, two colors are judged as the same if the subjective distance (dissimilarity) between them does not exceed some fixed criterion. The results of observers LMC and CB are of the first type, while that of observer GP is of the second type. Specifically, observer LMC used five color categories: four classic chromatic component hues and orange. Interestingly, the latter is included in the list of basic color terms (Berlin & Kay, 1969). Apart from four classical chromatic component hues, observer CB used color categories that could be tentatively named as lilac and purple. Once again, the latter is a basic color term.

As to the results of observer CM, the above mentioned inconsistency of her results proves that this observer certainly has problems with color categorization. A similar problem has recently been described, where a patient with color agnosia was unable to group similar colors (Nijboer, van Zandvoort, & de Haan, 2006; van Zandvoort, Nijboer, & de Haan, 2007).

Since the partial hue-matching technique itself does not guarantee that observers will rest their decision on component colors, one needs an objective criterion that will enable distinguishing chromaticity classes based on component colors from those based on other color categories or subjective distance. Such criterion depends on our understanding (definition) of component colors in general. For example, if irreducibility is taken as a major feature of a component color, then one has to examine whether the chromaticity classes, derived with the partial hue-matching technique, bring about the component colors that meet the criterion of irreducibility. Unfortunately, it is not quite clear how such examination could be done.

Alternatively, unidimensionality can be taken as a criterion for component color. This implies that a set of colors containing the same component color can be strictly ordered (i.e., lined up) with respect to strength of this component (referred to as chromatic order). In fact, the hue scaling procedures, which are based on estimating the amount of a unique hue in a particular color, implicitly assume such a unidimensionality of unique hues. Therefore, if a chromaticity class is based on a component color (i.e., all the colors in it contain some amount of the same
component color), then this class should allow strict ordering (with respect to the component color strength). When a chromaticity class is based on a binary hue color category (e.g., orange or purple), let alone an arbitrary color category, one can hardly expect that such a set of colors can be strictly ordered, because there is no clear grounds for such ordering.

It was found in our early study that observers were indeed capable of lining up the colors within a chromaticity class (Logvinenko & Beattie, 2006). It should be mentioned, however, that in this study all the observers yielded only classical chromaticity classes. Therefore, chromatic orders were established only for the chromaticity classes of this kind. Whether non-classical chromaticity classes lend themselves to strict ordering remains to be investigated.

While we did not examine chromatic order in the present experiment, it would be safe to conclude that, first, the eight observers based their judgments on component colors; and second, they have four classic chromatic component hues. This is in line with other studies addressing this issue from the experimental point of view (Boynton, 1997; Miller, 1997). Using a special rating technique, Sternheim and Boynton (1966) established that yellow, blue, green, and red make a minimal hue set necessary to rank any other spectral colors. These necessary hues were referred to as elemental (Wooten & Miller, 1997). Sternheim and Boynton also showed that orange was not an elemental hue. In other words, they showed that for spectral colors to be fully described orange was not necessary, that is, the percentage of, say, red assigned to a color did not depend on whether orange was included in the rating hue set. It was established in a similar study that purple is not an elemental hue (Fuld, Wooten, & Whalen, 1981) nor is brown (Quinn et al., 1988). The present study corroborates these results. Indeed, while the chromaticity classes that can be interpreted as orange and purple emerged from the response matrices of some observers, neither orange nor purple was found to be unitary hues. Interestingly, although the sample papers contained some that observers verbally named brown, no chromaticity class that could be interpreted as brown was found. Therefore, we conclude that in line with the previous studies orange, purple, and brown are unlikely to be component hues.

It should be kept in mind that the results of a partial hue-matching experiment can, in general, depend on stimulus sample—unless the sample is large enough to be representative, that is, to include all the component colors. If, for instance, whitish (or blackish) colors are not included, then the white (or black) chromaticity class is unlikely to arise. Theoretically, the whole Munsell set would be an ideal sample. However, the partial hue-matching technique is rather time-consuming. A reasonable compromise would be to evaluate chromaticity classes in two steps. First, the chromaticity classes are derived as described in the present paper using a reasonably large sample of colors. Second, those chromaticity classes that the observer is capable of strictly ordering (with respect to the strength of the component colors constituting these classes) will be used to indicate component colors in the next experiment with a larger sample. The rationale is to use the chromaticity classes derived at the first stage as perceptual (rather than verbal) labels to indicate component colors in the next experiment with the larger sample, so as to produce broader chromaticity classes.

An attempt to implement this plan was made by Beattie and Logvinenko (2006). After evaluating the chromaticity classes for 20 Munsell papers, and establishing chromatic orders for these chromaticity classes, observers were presented with a chart containing a sample of 325 Munsell papers (with maximum chroma). They were asked to pick up papers containing any amount of the component hue constituting the chromaticity class in question, thereby forming a complete chromaticity class for this component hue. Notably, all the papers eventually found their chromaticity class. Observers then ordered the complete chromaticity class, forming an ordinal scale for the given component hue. We would emphasize that no verbal naming was used in determining the chromaticity classes, or the component hues, in this study. Such a technique of hue scaling without hue naming can be especially useful when studying the color vision of dichromats.

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Footnotes

1 As the purpose was to conduct the experiment with inexperienced observers, we deliberately avoided using any scientific terminology. At the same time, the intention was to make sure that observers base their decision solely on the hue content. For example, a red paper was expected to be judged to partially match an orange paper irrespective of how small a tinge of red it has.
We believe that observers GS and LM have rather high threshold that might account for that the white and black chromaticity classes are quite narrow. We also believe that including more “blackish” and “whitish” Munsell papers would result in extending these chromaticity classes.

As noted by Heggelund (1974), Hering’s opinion on black and white was not consistent. On the one hand, he claimed that they were opponent; on the other hand, he claimed that achromatic colors were made of black and white.

In other words, no paper was left in the end of experiment. All the papers were picked up. This testified that the set of chromaticity classes revealed at the first stage was complete.

References


