Material and lighting dimensions of object colour

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ABSTRACT
The dimensionality of the object colour manifold was studied using a multidimensional scaling technique, which allows for the representation of a set of coloured papers as a configuration in a Euclidean space where the distance between papers corresponds to the perceptual dissimilarities between them. When the papers are evenly illuminated they can be arranged as a three-dimensional configuration. This is in line with the generally accepted view that the object colour space is three-dimensional. Yet, we show that under variegated illumination another three dimensions emerge. We call them lighting dimensions of object colour in order to distinguish from the traditional three referred to as material dimensions of object colour.

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1. Introduction

In spite of the recent advances in colour science, some fundamental questions still remain unanswered. One is related to the colour perception of objects under variegated illumination. When an object is evenly illuminated by a single light source its colour can be quantified with tristimulus coefficients of the light coming from the object (Foster, 2008; Schanda, 2007; Wyszecki & Stiles, 1982). Specifically, all the papers reflecting lights with the same tristimulus coefficients (i.e., metameric lights) will be seen as having the same colour. Papers reflecting lights with different triplets of tristimulus coefficients will be perceived as being of different colour.

The situation becomes more complex for scenes with multiple illuminants. Even when tristimulus coefficients of the reflected lights are the same, this does not guarantee that the perceived colours will be the same also. In other words, metamerism of reflected lights does not guarantee object colour equality (Land, 1959; Whittle, 2003). Consider, for example, a grey paper under day light, a yellow paper lit by a blue light, and a blue paper lit by a yellow light. One can adjust the incident lights so that the three reflected lights will be metamic. Yet, the papers will not be perceived to be of the same colour. Furthermore, the yellow paper under the blue light will still look yellowish, and the blue paper under the yellow light bluish. This is a well known phenomenon of colour constancy with respect to illumination (Brainard, 2009; Hurlbert, 1998; Katz, 1935; Pokorny, Shevell, & Smith, 1991; Smithson, 2005).

Colour constancy does not mean, however, that the yellow paper lit by the blue light will look identical to the yellow paper lit by day light. There is an obvious perceptual difference in their colour’s appearance – this difference derives from lighting. We see that although these are the same papers, their appearance differs because they are differently illuminated. This difference that stems from lighting impedes an asymmetric colour match, that is, an exact colour match of papers lit by chromatically different lights. While asymmetric colour matching is widely used to measure colour constancy, the results obtained with this technique vary from study to study, so that still there is no consensus as to what extent colour perception is constant with respect to illumination (Foster, 2003).

From the ecological point of view (Gibson, 1979), our ability to perceive lighting is as important as perceiving materials. Yet, as pointed out by Kardos (1934), observers usually ignore shadows (i.e., differences in lighting). Unfortunately, lighting differences are neglected not only by observers, but generally by colour scientists too. Although lighting and material borders are known to be processed differently by the visual system (Kingdom, 2008), the colour dimensions of lighting have never been quantified. We address this issue from the experimental point of view by using multidimensional scaling (Cox & Cox, 2001). This method allows us to reveal the underlying dimensionality of the colour manifold, and quantify it; furthermore, we can derive the dimensionality without needing to qualify beforehand what the dimensions are.

Although multidimensional scaling has been used before to analyse the pattern of perceived similarities amongst Munsell papers (Munsell, 1929), the illumination was neutral and homogeneous (for a comprehensive review see Indow, 1988). The dimensions which emerged from the multidimensional scaling
analysis of evenly illuminated Munsell papers were shown to correlate well with the three classical colour dimensions: hue, chroma, and lightness (Indow, 1988). However, when the illumination varies in intensity, one more dimension (referred to as surface-brightness) springs up from the multidimensional scaling of achromatic (Logvinenko & Maloney, 2006) – as well as chromatic – Munsell papers (Tokunaga, Logvinenko, & Maloney, 2008a). Here we report on a follow-up experiment in which the illumination of Munsell papers varied in chromaticity. The rationale is to ascertain whether chromatic dimensions of the lighting aspect of object colour appearance can be captured by multidimensional scaling along with the classic three colour dimensions.

2. Methods

The experimental set-up was similar to that used by Tokunaga et al. (2008a), except that the illumination’s chromaticity varied (Fig. 1). Four normal trichromatic observers took part in the experiment. They were experienced in psychophysical observations but naïve as to the purpose of the experiment (except one – the co-author RT). Observers were presented with a stimulus display consisting of two identical arrays of seven Munsell papers – 10B5/12; 10B5/8; 10B6/4; N6.5/; 2.5Y7/6; 2.5Y8/10, and 2.5Y8/16 – illuminated independently by one of three light sources: yellow (Y), blue (B), and neutral (N) (Fig. 2). The intensity of the lights was approximately equal: 66.2 lux (Y), 62.2 lux (N), and 58.7 lux (B). The lights were adjusted so that the CIE 1931 chromaticity coordinates (Wyszecki & Stiles, 1982) of the light reflected from the yellow paper 2.5Y8/16 under the blue light, from the blue paper 10B5/12 under the yellow light, and from the grey paper N6.5/ under the neutral light were as close as possible: (0.267, 0.316), (0.267, 0.351), and (0.288, 0.345), respectively (Fig. 3b).

Although the yellow paper lit by the blue light reflected a light of almost the same chromaticity as that reflected by the blue paper lit by the yellow light, these papers looked rather different. More-over, both looked different from the grey paper illuminated by the neutral light, which also reflected a light of similar chromaticity – and neither did they appear grey, as might have been expected if that was the colour observed under neutral illumination for those chromaticity coordinates.

The observers were instructed to evaluate dissimilarities between papers in the fields #1 and #2 (Fig. 1). A pair of papers, consisting of the yellow paper (2.5Y8/16) under the yellow illumination, and the blue paper (10B5/12) under the blue illumination, was set up as a standard of dissimilarity. It was permanently present in the observer’s view (fields #3 and #4 in Fig. 1). In the beginning, a pair of identical papers under different lights was pointed out, and observers were asked whether they looked the same or different. All the observers found the papers to appear different. Then observers were asked “to estimate the dissimilarity between the papers as compared to the standard with a number, taking the standard dissimilarity as 100”. All the observers had no problem with accomplishing this task.

The dissimilarity rating technique used in the present experiment was compared with the quadruple comparison method when the observers were asked to judge in which of two pairs the dissimilarity between Munsell papers was larger (Tokunaga, Logvinenko, & Maloney, 2008b). It was found that the output configuration for seven Munsell papers of maximal chroma derived from the dissimilarities obtained with the quadruple comparison method did not considerably differ from the output configuration derived from the dissimilarity rating technique. Notably, three of the four observers participated in the present experiment were subjects in this control study (Tokunaga et al., 2008b).

It should be emphasised that we did not specify explicitly the colour dimensions between which the dissimilarity was supposed to be measured. The intention was to ascertain the dimensions which will emerge from the multidimensional analysis of dissimilarities rather than to impose some dimensions on observers. Besides, it is always a problem whether inexperienced observers are capable of assessing some theoretically defined entities (such as hue, chroma, lightness) if they have not been familiar with these notions before. As to the task of evaluating dissimilarity, all our observers found it clear and easy to perform.

Two more fields, without Munsell papers (fields #5 and #6 in Fig. 1), were used to balance the overall illumination in the experimental display, and brought the total number of displays being used to six. The blank displays were illuminated variably, so that in any instance there were always two fields illuminated by each of the three lights (Fig. 2). This measure was taken to reduce chromatic adaptation and to keep the adaptation state of observers constant throughout the experiment. Observers sat at a distance of 2 m from the experimental set-up (Fig. 1). From this distance the angular size of the whole display was 25° × 27°. Vision was binocular.

The experiment was divided in six sessions. In separate session of the experiment, the fields #1 and #2 (Fig. 1) could each be illuminated by one of the three illuminants, giving a total of six possible illumination conditions (i.e., B–B, N–N, Y–Y, B–N, Y–N, and B–Y). In single trial, dissimilarity judgments were made between papers in the two fields. A session consisted of 49 trials in which all possible 7 × 7 pairs of papers were evaluated. In each trial a pair of papers (one in each field) was indicated randomly by small red light-emitting diodes next to the papers. Each response given to the pair by each observer was entered into a computer. No time restriction was imposed. A session lasted approximately 30 min. Each session
was repeated twelve times for each observer. The final ten repetitions were used for analysis.

3. Results

The dissimilarities were averaged across sessions and observers (Fig. 4). The Friedman test (a non-parametric analogue of two-way ANOVA) showed a highly significant effect of illumination condition on dissimilarity ($\chi^2 = 1162; p < 0.001$). The relationship between the dissimilarity judgments and the corresponding distances in the CIE 1976 uniform chromaticity diagram (Wyszecki & Stiles, 1982) (Fig. 5a) are shown in Fig. 5. As follows from Fig. 5a, when the illumination of two papers is the same, the dissimilarity between them is rather well correlated with the corresponding chromaticity (i.e., the distance in the CIE 1976 uniform chromaticity diagram). However, when the illumination is different there is almost no correlation at all (Fig. 5b). Even the dissimilarities between the same papers illuminated by different lights do not seem to relate to the CIE 1976 chromaticity differences (Fig. 5c). Such disassociation between the dissimilarities and the CIE 1976 chromaticity differences clearly indicates that the observers’ judgments of dissimilarity were not determined solely by the chromaticity of the reflected light. For example, in spite of very close chromaticity coordinates, the yellow paper 2.5Y8/16 under the blue light and the blue paper 10B5/12 under the yellow light were judged only slightly less dissimilar (by a factor of 0.8) than the dissimilarity in these papers under neutral light (97.3), whose difference in chromaticity coordinates was very large (Fig. 3). Fig. 6 shows that, generally, the dissimilarity judgments are poorly correlated with the luminance differences too. Interestingly, the correlation coefficients for the illumination conditions B–N and B–Y were found to be negative. Thus, neither chromaticity nor luminance of the reflected light can account for the apparent dissimilarities between the papers.

To look into the internal structure of the dissimilarity judgments, the averaged dissimilarity matrix was analysed using a non-metric multidimensional scaling algorithm (Cox & Cox, 2001). Fig. 7 shows the configuration obtained for a 3D output space (see also Table 1). The distances between the points are, in general, in the same order as the corresponding dissimilarities. The stress of the configuration in Fig. 7 (i.e., an index showing the relative proportion of the mismatches between the distances and the dissimilarities) is 0.03. The stress of the configuration obtained for 1D, 2D, and 4D output space was 0.09, 0.04, and 0.02 respectively. The decrease in the rate of change of stress with dimension indicates that the output configuration is practically two-dimensional. Choosing a larger dimension, for instance, 3D as in Fig. 7, does not change essentially the configuration apart from that the curves become somewhat zigzagged. The small and equal difference between the stress values for two and three dimensions on the one hand, and three and four dimensions on the other, points out that this zigzagging might have been due to noise.
The yellow line connects the symbols standing for the seven Munsell papers (the colour of the symbol indicates the colour of the paper) illuminated by the yellow light. Likewise, the blue and black lines correspond to the blue and neutral illuminations. The distance between symbols represents the dissimilarity between the corresponding stimulus pairs (paper/light). Under any single illumination the papers fall along a slightly zigzagging curve, and the curves for the three lighting conditions are shifted along a direction transversal to the curves. Note that the curves representing the neutral and yellow illuminations are very close to each other. This can be thought of as a sort of colour constancy.

Fig. 8 shows how the stimulus papers are arranged in the CIE (L’/a’/b’)-space. The L’/a’/b’-coordinates of the stimulus papers have been evaluated for each illuminant independently, the tristimulus values of the illuminant having been taken as the white reference. Although the CIE (L’/a’/b’)-space is not supposed to be used for multi-light scenes, Fig. 8 helps illustrate whether it is possible to account for our results with this space widely used for representing the colour of reflecting objects. As one can see the configuration in Fig. 8 is qualitatively different from that in Fig. 7. Indeed, the three curves in Fig. 8 intersect at a point (which corresponds to the neutral Munsell paper), whereas the three curves in Fig. 7 are approximately parallel curves.

Each of the curves in Fig. 7 represents the yellow–blue continuum under a single illumination. Therefore, three yellow–blue continua – each for each illumination – have been revealed with multidimensional scaling. Moreover, they have been found to coexist, being dissociated in the dissimilarity space. As follows from Fig. 8 the dimension along which the three yellow–blue curves are displaced with respect to each other cannot be interpreted as lightness (i.e., L’). Nor can it be reduced to any other dimension of object colour (e.g., hue or chroma). Therefore, it must be a new colour dimension. While it obviously relates to the chromaticity of the illumination, it does not render the chromaticity of the reflected light. Indeed, if this were the case the yellow circle in the blue curve, the black cross, and the blue pentagram in the yellow curve would coincide because, as mentioned above, the chromaticity coordinates of the corresponding lights are nearly equal.

We believe that this new dimension is another yellow–blue continuum. To differentiate between these two kinds of yellow–blue continuum we use the terms material and lighting. The material
The yellow–blue continuum varies along the curves, the lighting yellow–blue continuum in a transverse direction.

The end points in each curve represent the yellow and blue papers so the distance between them along the curve represents the subjective difference between the yellow and blue hue. We will call it lighting hue difference to distinguish it from the material hue difference represented by the curve length. Hence, the distance between the yellow and blue crosses represents the lighting hue difference, whereas that between a circle and a pentagram in the same curve represents material hue difference. Thus, each paper has material hue and lighting hue which can be rather different. For example, the paper 2.5Y8/16 under the blue light has yellow material hue and blue lighting hue, whereas the paper 10B5/12 under the yellow light has blue material hue and yellow lighting hue.

The subjective strength (pronouncedness) of material and lighting hues is also different. Let us call them material and lighting chroma, respectively. Material chroma varies from zero to its maximum value when one moves in Fig. 7 from a cross along the corresponding curve towards its end. Lighting chroma varies transversely. Specifically, lighting chroma is zero for all the points on the black curve (neutral illuminant). When moving from the black curve towards the blue (respectively, yellow) one, lighting chroma increases.

A phenomenon similar to the discounting of the achromatic lighting dimension, i.e., surface-brightness (Logvinenko & Maloney, 2006), was also observed in the chromatic domain in the present experiment. Specifically, the same difference in the CIE chromaticity was, generally, judged as less dissimilar when it was produced by illumination difference than by paper difference. For example,
the dissimilarity between the neutral paper (black cross in Fig. 7) and the yellow paper 2.5Y8/16 (circle in the black line in Fig. 7) lit by the neutral light, is larger by a factor of 4.15 than that between the neutral papers illuminated by the neutral (black cross in Fig. 7) and yellow (yellow cross in Fig. 7) lights. However, in Fig. 3a the distance between the black cross and the yellow circle makes a ratio of 1.45 with the distance between the black and yellow crosses. Dividing the ratio of dissimilarities – 4.15 – by the ratio of chromaticity differences – 1.45 – we get an index of 2.86, which shows how much more effective material difference is as compared to lighting difference. We will refer to this as the \textit{index of lighting discounting}. The index of lighting discounting can be expressed more formally as follows. Let us consider two papers, \(a\) and \(b\), and two lights, \(l\) and \(m\) such that the reflected lights produced by (i) paper \(a\) lit by light \(l\) (written \((a, l)\)); (ii) paper \(b\) lit by light \(l\) (written \((b, l)\)); and (iii) paper \(a\) lit by light \(m\) (written \((a, m)\)); lie on a straight line in the CIE chromaticity diagram. Denote \(D((a, l); (b, l))\) the dissimilarity between the stimuli \((a, l)\) and \((b, l)\). Then the following ratio is taken as the \textit{index of lighting discounting}:

\[
\frac{D((a, l); (b, l))}{D((a, l); (a, m))}
\]

where \(D((a, l); (b, l))\) stands for the chromaticity difference (i.e., the distance in the chromaticity diagram) between the stimuli \((a, l)\) and \((b, l)\).

The index of lighting discounting is even larger – 18.1 – for the blue (10B5/12) and neutral papers under the blue light, and the neutral papers under the neutral and the blue lights. This is because the chromaticity differences for these pairs are in an inverse order as compared to the dissimilarities. Specifically, the ratio of dissimilarities for these pairs equals 2.17, whereas the ratio of chromaticity differences is 0.12 (see Fig. 3a).

4. Discussion

Multidimensional scaling of subjective dissimilarities between yellow–blue Munsell papers lit by yellow–blue lights reveals two yellow–blue continua. One yellow–blue continuum correlates with the papers’ spectral reflectance (referred to as \textit{material yellow–blue continuum}), the other with the light spectral power distribution (referred to as \textit{lighting yellow–blue continuum}). Such a dual representation of the yellow–blue continuum follows up from and encompasses the previous findings of there being two achromatic dimensions of object colour (lightness and surface-brightness) which had been obtained with the same method (Logvinenko & Maloney, 2006). Specifically, it was found that lightness correlated with surface albedo, and surface-brightness with the intensity of the incident light. Lightness and material yellow–blue continuum on the one hand, and surface-brightness and lighting yellow–blue continuum on the other, constitute what we call \textit{material and lighting dimensions} of object colour.

Both surface-brightness and the lighting yellow–blue continuum have been found to be related to light. Does it mean that the lighting dimensions represent the colour of light? If this is the case, which light: incident or reflected? As for reflected light, it has long been tradition to believe that there is a dual mental representation of the external world, according to which sensations represent proximal stimulation (i.e., the reflected light), and perceptions distal stimulation (i.e., objects). From this point of view one might argue that the lighting dimensions represent the light reflected from an object. Within such a conceptual framework, surface-brightness might have been treated simply as the brightness of reflected light. However, Logvinenko and Maloney (2006) provided strong evidence for surface-brightness being different from the brightness of reflected light. Likewise, as shown above, the lighting yellow–blue continuum does not correlate with the chromaticity of the reflected light. In other words, our results are more in line with the Gibsonian stance that we can see everything but light (Gibson, 1979). At any rate, the lighting dimensions of an object’s colour cannot be reduced to the colour of the light reflected from that object.

Alternatively, one might argue that the lighting dimensions are the perceptual correlates of ambient illumination. It is an old idea that along with surface reflectance which is perceptually represented as object colour, illumination is also represented in our perception. For instance, summarising many earlier works, Mausfeld argued that there had to be a dual coding in the human visual system: for reflectance, and for illumination (Mausfeld, 1998, 2003). A recent study of chromatic simultaneous contrast by Ekroll, Faul, Niederee, and Richter (2002) has triggered more interest in this idea. For instance, MacLeod (2003) claimed that their findings could be accounted for by assuming the dual, that is, the six-dimensional representation of colour. Specifically, three colour dimensions were suggested to represent object colour, and another three illumination colour.

If the lighting dimensions were the colour dimensions of apparent illumination we would be able to judge the colour of illumination independently of the object colour. In other words, any real

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3 Different generations of scientists used different terms to describe the duality of visual experience in question (Hatfield & Epstein 1979); ‘sensation and perception’ (Reid 1785/1969); ‘sensory core and perceptual context’ (Titchener 1906); ‘primary image and perceptual image’ (Helmholtz 1867); ‘visual field and visual world’ (Gibson 1950); and ‘unasserted and asserted colour’ (Arend 1994) – to mention a few.
object lit by a real light source would bring about three object colour dimensions and three illumination colour dimensions. However, it is known that apparent illumination is not easy to assess in a single illuminant scene. For example, inexperienced observers usually find it hard to believe that the white walls in a room with an incandescent lamp are being illuminated by a rather yellowish light. Experimental investigation into our ability to estimate illumination intensity showed that observers’ judgments of apparent illumination were very rough and unstable (Beck, 1972; Kozaki, 1973; Rutherford & Brainard, 2002).

As is known from visual photometry, whilst we are not good at evaluating the absolute intensity of light, our ability to see the difference between two differently illuminated regions is remarkably accurate. Moreover, observers can readily distinguish a change in a scene produced by a material change from that made by an illumination change (Craven & Foster, 1992; Foster et al., 2001). We believe that it is the immediate phenomenological difference between material and lighting dimensions that make such differentiation possible. Therefore, lighting dimensions emerge only when there are at least two regions of different illumination. This contradicts the idea that the colour appearance dimensionality of a scene can be split into two independent triplets of colour dimensions: three material dimensions encoding reflectance, and three lighting dimensions encoding illumination.

We believe that lighting colour dimensions emerge in our experiment not because there are two independent three-dimensional manifolds: an object colour manifold and an illumination colour manifold, but because the object colour manifold varies with illumination. In other words, whilst remaining three-dimensional, the object colour manifold is different for different illumination. The difference between the two views can be illustrated with the following example. A rectangle can be thought as a Cartesian product of two intervals. A point in it can be specified with two coordinates – each within each interval. At the same time the rectangle can be considered as a family of intervals (e.g., its horizontal cross-sections). A trapezoid can be represented as a family of different intervals but not as a product of two intervals. We argue that the object colour manifold comprises a three-dimensional family of three-dimensional manifolds of material colour, such that it cannot be represented as a Cartesian product of two three-dimensional colour manifolds.

Assume now that we are not aware of the shape of the trapezoid; and we can observe only a sample from the family of horizontal cross-sections of the trapezoid. When the sample consists of just one interval one cannot say at what height this cross-section is made. This is an analogue of our inability to evaluate apparent illumination in a single illuminant scene. Given two different sample intervals, one can infer which corresponds to a higher cross-section ordering the intervals with respect to length. This illustrates our ability to judge which of two illuminations is brighter or yellowish, and the like. Generally, there is a colour order across the family of all the three-dimensional manifolds of object colour.

There is abundant evidence that the object colour manifold does not remain the same when illumination varies. For instance, Logvinenko and Maloney (2006) found that the lightness continuum shrinks when illumination gets darker. Many previous authors (e.g., Helmholtz, 1867; Katz, 1935) pointed out that object colours looked peculiar under chromatic illumination (for a review see Mausfeld, 1998). All this shows that the colour manifold can hardly be represented as a Cartesian product of two three-dimensional colour manifolds. Yet, it can be considered as a bundle of three-dimensional object colour manifolds ordered with respect to the three additional (lighting) colour dimensions.

An important question immediately arises. How are the material and lighting dimensions related? In particular, are the material and lighting hues perceptually different? For example, when we see a bluish shade and a blue pigmented stain are these two blues, in principle, same or different? The answer comes from experiments and demonstrations in which an apparent reversal of spatial relief of a surface made shadows (lighting) turn into apparently pigmented (material) areas (Logvinenko & Menshikova, 1994; Mach, 1959). After the apparent depth reversal the darkened area of shadow was perceived as a black stain. As known, black is not just the lack of light (i.e., darkening) (Volbrecht & Kliegl, 1998), it is an achromatic hue which is absent in the palette of lighting hues. Thus, an important difference between the material and lighting hue palettes is that the former is much broader than the latter. Lighting hues do not include, say, brown, olive, black and many others that can be observed only as material hues. Formally speaking, one can say that the material hues form a two-dimensional manifold, whereas the lighting hues make a one-dimensional continuum. The difference between the two palettes of hues is well known, and usually is referred to as that between related and unrelated colour axes (e.g., Kaiser & Boynton, 1996). It should be borne in mind, however, that both material and lighting hues are attributed to an object. Both are experienced not in isolation but in multicoloured scenes. Therefore, strictly speaking, both should be recognised as ‘related’ within this dichotomy.

Note that even those hues which are included in both the hue palettes are experienced in different ways. As shown in our experiment, a yellow–blue material shift is perceived rather differently from a yellow–blue lighting shift even though the reflected lights have the same CIE tristimulus coordinates. Lighting discounting, as described above, results in the lighting shift appearing less pronounced than the material shift.

It must be emphasised that material blue and lighting blue hues are qualitatively different colour experiences. For instance, one cannot experience the material blue and yellow hues in the same place and at the same time, since they make an opponent pair (Hering, 1874/1964). However, as shown in our experiment, the material blue hue can readily be perceived simultaneously with a yellow lighting hue.

The co-existence of the lighting and material dimensions of object colour sheds light on the controversial issue of asymmetric colour matching (when an observer is asked to establish a colour match for an object under different illuminations). While the problems with asymmetric colour matching in experiments on colour constancy are well recognised (e.g., Brainard, Brunt, & Speigle, 1997), the nature of these problems still remains unclear (Foster, 2003). As pointed out in the Introduction, we believe that it is the unavoidable difference in the lighting dimensions caused by differences in the illumination that makes an asymmetric colour match impossible out of principle. Therefore, the colour constancy problem should be reconsidered because the colour of an object, strictly speaking, always changes (in lighting dimensions) when its illumination changes. Yet, it may happen that the object colour remains constant as far as material dimensions are concerned. Therefore, distinguishing between material and lighting dimensions of object colour can help to conceptualise a hitherto enigmatic experience familiar to everyone who studied colour constancy: when illumination alters the colour of an object changes and remains constant at the same time.

Finally, both material and lighting dimensions were found to contribute to the dissimilarity judgments. However, the contribution from the material dimensions was found to be considerably stronger than from the lighting dimensions (lighting discounting). This finding might have an impact on colour metric formulae. Indeed, it follows that the same CIE chromaticity difference will produce a rather different subjective distance (dissimilarity) depending on whether this chromaticity difference is perceptually implemented in terms of material or lighting dimensions.
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