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Dissimilarity of yellow-blue surfaces under neutral light sources differing in intensity: Separate contributions of light intensity and chroma

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Abstract

Observers viewed two side-by-side arrays each of which contained three yellow Munsell papers, three blue, and one neutral Munsell. Each array was illuminated uniformly and independently of the other. The neutral light source intensities were 1380, 125, or 20 lux. All six possible combinations of light intensities were set as illumination conditions. On each trial, observers were asked to rate the dissimilarity between each chip in one array and each chip in the other by using a 30-point scale. Each pair of surfaces in each illumination condition was judged five times. We analyzed this data using non-metric multi-dimensional scaling to determine how light intensity and surface chroma contributed to dissimilarity and how they interacted. Dissimilarities were captured by a three-dimensional configuration in which one dimension corresponded to differences in light intensity.

Keywords: Colour vision, Munsell papers, Dissimilarity, Multidimensional scaling, Surface-brightness

Introduction

When achromatic surfaces differing in albedo are viewed under the same, uniform illumination, their perceived lightnesses can readily be ordered along a one-dimensional scale (from black through different shades of grey to white). Katz (1935) conjectured that surfaces viewed under two different neutral illuminations, differing in intensity, could not be so readily ordered. Logvinenko and Maloney (2006) have recently confirmed this conjecture experimentally. They asked observers to rate the dissimilarity of seven achromatic surfaces viewed under the same or different illuminations. Using a combination of non-metric multi-dimensional and maximum likelihood scaling analyses, they showed that achromatic colors constitute a two-dimensional manifold with dimensions relating to surface albedo difference and to illumination intensity difference.

Under any single illumination, the surfaces fell along a slightly curved one-dimensional scale (a "layer") and the layers for three lighting conditions were parallel nested curves (Fig. 1). Layers corresponding to less intense illuminations were contracted compared to those for more intense. The dissimilarity between chips in the same layer was determined by the albedo ratio between the surfaces, that between the layers with the light intensity ratio. The difference between layers was referred to as "surface-brightness," that within layers as "surface-lightness."

In this article, we report on a similar study in which we attempt to establish whether the effects of illumination found by Logvinenko and Maloney (2006) for the achromatic colors are present in the chromatic domain. In our experiment, instead of the black-white continuum, we examined a yellow-blue continuum. We measured dissimilarities between all combinations of three yellow Munsell chips, three blue, and one neutral, illuminated by three different neutral lights. We analyzed the resulting data by non-metric multi-dimensional scaling. It is worth mentioning that while multi-dimensional analysis of Munsell papers has been done before (Indow, 1988); it has never been used to analyze the dissimilarities of Munsell papers under different illuminations.

Materials and methods

The experimental setup was effectively the same as in Logvinenko and Maloney (2006) except that (1) we used a different set of Munsell chips (10B5/12, 10B5/8, 10B6/4, N6.5, 2.5Y7/6, 2.5Y8/10, and 2.5Y8/16), and (2) we chose slightly different light intensities (1380, 125, and 20 lux). The chromaticity coordinates (CIE 1931) of the illuminant were $x = 0.4104$, $y = 0.4215$.

The rationale for the choice of surfaces was as follows. We wanted to employ more or less "pure" yellow and blue papers lying along a straight line in both colorimetric and perceptual spaces. As can be seen in Fig. 2a, the CIE 1931 chromaticity coordinates of the chosen chips are very close to collinear. In

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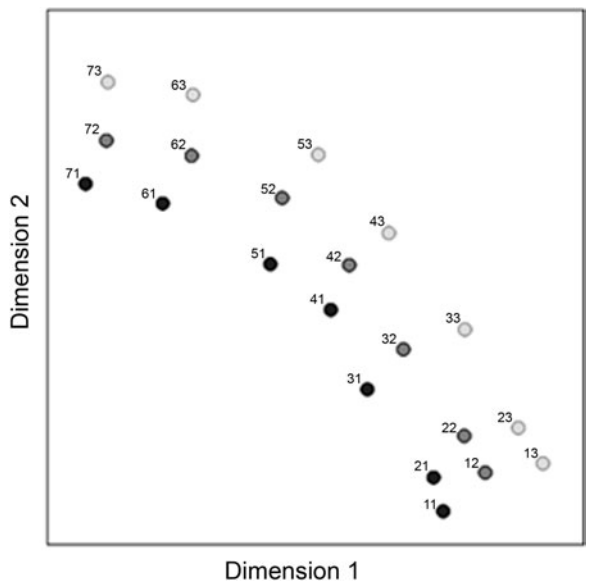

Fig. 1. The non-metric MDS output configuration obtained by Logvinenko and Maloney (2006) for seven Munsell achromatic papers under three neutral illuminants differing in intensity. In each two-digit (nm) label, the first number indexes the surface ($n = 1, 2, \ldots 7$), the second indexes the illumination condition ($m = 1, 2, 3$).

Fig. 3. A sketch of the experimental setup. The display was the same as in Logvinenko and Maloney (2006). The neutral chip was in the centre, the others randomly arrange around it. Observers were provided with a 30-button response box. They were asked to press buttons to signal their responses to each pair of Munsell chips.

addition, these chips fell near a line in the configuration obtained by Indow (1988) using multi-dimensional scaling (Fig. 2b) and this choice of surfaces allowed us to compare our results to his. Since we wanted the end-point chips (yellow and blue) to be as subjectively dissimilar as possible, we included the chips of maximum Munsell chroma (10B5/12 and 2.5Y8/16). As these have different Munsell values, we chose the other chips of intermediate Munsell values to make the transition of Munsell value from one end-point to the other as smooth as possible.

Four normal trichromatic observers took part in the experiment. They sat at 1.9 m from the display (Fig. 3). As in the previous experiment (Logvinenko & Maloney, 2006), observers were asked to rate the perceived dissimilarity between all possible pairs of chips on the different halves of the display using a 30 point scale ranging from 0 to 29. The scale was anchored as follows. Observers were instructed to use 0 to rate a pairs of physically identical chips illuminated by the same light and to use the maximal rank for the most dissimilar pair, which, as preliminary experiments showed, corresponded to chips 2.5Y/8/16 illuminated by the brightest light, and 10B5/12 when illuminated by the dimmest light. This pair remained in the visual field of the observer (to anchor his or her judgment) throughout the experiment (Fig. 3) as a reference.

During one experimental session, the intensities of illumination of the two halves of the display were kept constant. On each trial, one of the 28 possible unordered surface pairs (these consisted of $21 = 7 \times 6/2$ pairs with distinct surfaces and seven with identical surfaces) were indicated by LEDs set next to the chips and the observer rated each pair. The pairs were presented in random order. All six possible combinations of three illuminations were repeated five times for a total of 840 trials per observer.

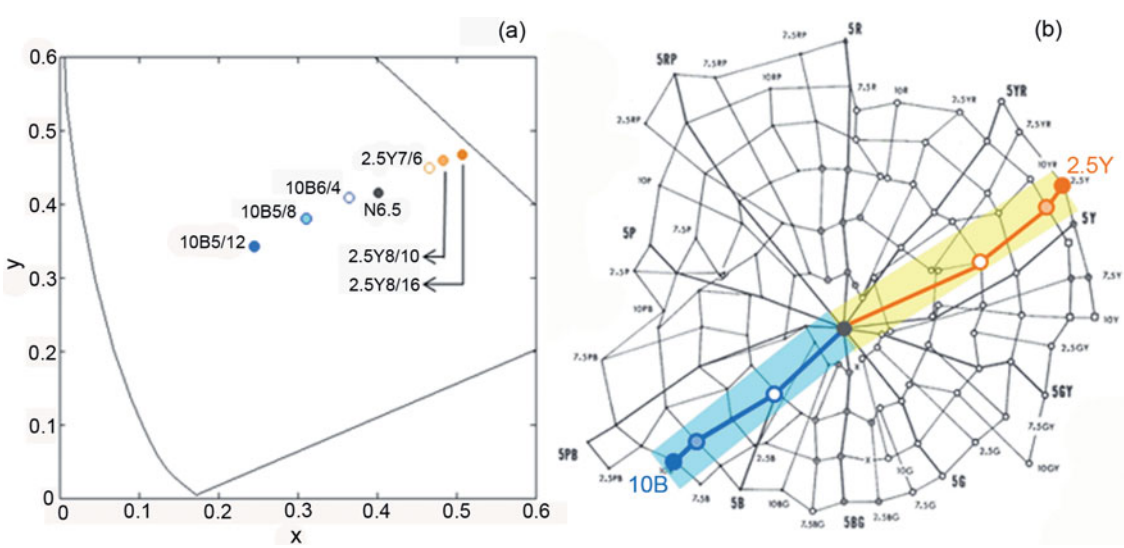

Fig. 2. Munsell papers used in the present study as presented (**a**) in the CIE 1931 chromaticity diagram and (**b**) in the space as derived by Indow (1988) using non-metric multidimensional scaling.

Results

The dissimilarity judgment from the four observers was averaged and analyzed using a non-metric MDS algorithm (Cox & Cox, 2001). Fig. 4 shows two different views of the output configuration obtained when the number of dimensions was three (stress 0.024). When the number of dimensions was decreased to two, stress increased by a factor of two (0.047). Based on stress alone, it is not obvious whether we should select the two-dimensional solution or the three-dimensional solution. Other analyses described next allow us to reject the two-dimensional solution.

We performed a permutation test to test whether the layers (as seen in Fig. 4a) were ordered randomly as they would be if there were no separation between layers in the third dimension. A perfect ordering would have all corresponding points in the layers 1,2,3 in the order 123 from top to bottom along the vertical axis in Fig. 4a or all in the order 321 (the same order with the picture upside down). There are only two chips out of order (10B5/8, 10B5/4) with the layers ordered 1, 2, 3 from bottom to top. The probability of getting this close to a perfect 123 or 321 ordering by chance is less than 0.0001. The effect of the illumination intensity changes is, therefore, real (see Tversky & Hutchinson, 1986 for discussion of the use of diagnostic tests in non-metric MDS).

Note that in the three-dimensional solution lines (solid, dotted, or dashed in order of increasing intensity) connect the symbols representing the Munsell papers illuminated by the same light. The first view (Fig. 4a) clearly shows three separate layers each of which corresponds to a single light intensity. The three layers corresponding to the seven surfaces are roughly parallel. The second view (Fig. 4b) shows that the three equi-illuminated layers are virtually identical. Hence, in contrast with the outcome of the achromatic study (Logvinenko & Maloney, 2006) no effect of illumination on the length of the equi-illuminated contours was found.

Logvinenko and Maloney (2006) could compute the relative influence of changes in light intensity and changes in log surface albedo since both could be measured in equivalent units. Since chroma and light intensity changes are not in comparable units, we cannot repeat this computation here. It is, however, evident that changes in chroma across the gamut considered had much greater effect than a 70-fold increase in illumination intensity. Indeed, the separation between the brightest and dimmest layers in Fig. 4a was found to be 22% of the averaged distance between the most dissimilar papers (i.e., 2.5Y/8/16 and 10B5/12). Surprisingly, the separation produced by light intensities 20 and 125 lux (i.e., 0.8 log unit difference) was found to be more than three times as much as that produced by light intensities 125 and 1380 lux (i.e., 1.04 log unit difference). This is in contrast with the results of Logvinenko and Maloney (2006) where the separations between equidistant (on the log scale) lights were found to be equal.

Discussion

Logvinenko and Maloney (2006) found that the points corresponding to seven neutral surfaces under any single illumination fell along a slightly-curved one-dimensional layer and that the layers for three lighting conditions were parallel nested curves (Fig. 1). Layers corresponding to less intense illuminations were contracted relative to those for more intense. In the present study, we also found that surfaces fell along parallel, curved layers but the separations between layers were not equal. Moreover, the layers show no evidence of contraction or expansion with change in light intensity.

Another difference between the present results and those in the previous achromatic study is that there appears to be some degree of clustering of surfaces by color category ("yellow," "neutral," and "blue"). While achromatic Munsell chips were found to be more or less evenly distributed along the equi-illuminated layer (Fig. 1), there seems to be a large gap between the neutral chip and the chromatic ones in Fig. 4. We computed the maximum dissimilarity within each cluster of three chips of the same chromaticity (yellow or blue) for each lighting intensity and compared it to the minimum separation of a chip in each cluster to the neutral chip, again for each lighting intensity. The distance from each chromatic cluster to the neutral point was significantly greater that that within

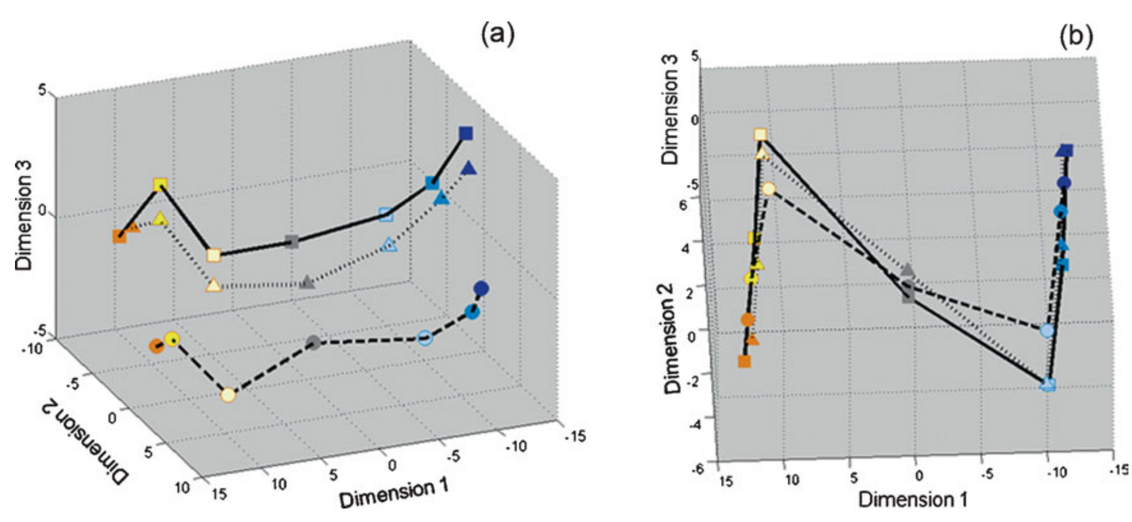

Fig. 4. Two views of the same three-dimensional output configuration. Circles (connected by the dashed line) represent the chips illuminated by light of 20 lux; triangles (with dotted line) 125 lux, and squares (with solid line) 1380 lux. Dark shaded blue symbols represent Munsell paper 10B5/12; light blue, 10B5/8; light shaded blue, 10B6/4; grey, N6.5; light shaded yellow, 2.5Y7/6; yellow, 2.5Y8/10; and dark shaded yellow, 2.5Y8/16.

each chromatic cluster ($t(22) = 3.26$; $p < .004$), a result that is even more striking when we realize that we are comparing the "two-step" dissimilarity within the chromatic clusters to the "single-step" from each cluster to neutral. We emphasize that this analysis was performed directly on the dissimilarity data. The dissimilarities within chromatic clusters are much smaller (by a factor of 3.55) than those between each cluster and the neutral chip. The spacing of corresponding points in Indow's (1988) solution (Fig. 2b) does not exhibit such a "categorical" effect.

The curved yellow-blue layers found in our study are also in sharp contrast with the near-linearity of the points corresponding to the same chips in Indow's (1988) experiment (Fig. 2b). We conjecture that the evident categorical structure (yellow, blue, neutral) in our stimuli led to this result and that in an experiment such as Indow's (1988) with a large variety of surfaces of different hues, any categorical effect would be reduced.

We have found that illuminant intensity differences affect dissimilarity for both achromatic and chromatic surface and that their effect is simply as an additive contribution to dissimilarity. Specifically, when illumination changes the layer moves along a specific dimension in the perceptual space remaining parallel to itself. It is plausible that it is the same dimension as in the previous achromatic study (Logvinenko & Maloney, 2006) which was referred to as surface-brightness there. Of course, the chromaticity of the illumination can also be varied and it will be interesting to see how changes in chromaticity affect dissimilarity in future experiments.

Acknowledgments

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