On Achromatic Colour Appearance

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ABSTRACT

It was found that the same luminance border on the retina could bring about essentially different apparent contrast depending on whether it was perceived as an illumination (shadow) border or a material (reflectance) border. Specifically, it was found that, on average, observers judged the luminance ratio, produced by the reflectance edge, as apparently equal to more than twice the luminance ratio, produced by the illumination edge. This finding leads to the conclusion that observers are not able to evaluate the subjective intensity (brightness) of the light reflected from self-luminous objects in real scenes. We believe that in this experiment they evaluated the surface-brightness – a perceptual dimension of achromatic object (related) colours which is often confused with either brightness of the reflected light or an apparent illumination the object. We argue that lightness – another perceptual dimension of achromatic object (related) colours – cannot be reduced to (relative) brightness. Being independent of each other, these two dimensions - lightness and surface-brightness - provide a better frame reference for the description of the two-dimensional manifold of achromatic object (related) colours.

1. INTRODUCTION

While it is generally agreed that there are two achromatic attributes of perceived objects – lightness and brightness[1,2] – there is no consensus on their meaning. Brightness is usually defined as subjective intensity of the light reflected from an object, and lightness as the relative brightness[1,2]. Using the multidimensional scaling (MDS) technique, we recently confirmed that achromatic object (related) colours constitute a two-dimensional manifold[3]. However, neither of its two dimensions could be interpreted as brightness of reflected light.

In this experiment[3] observers were presented with two identical sets of seven Munsell chips (reflectances from 7.7% to 79%) on a random-dot background. The illumination of each of the two halves of the display was independently set at one of three levels: 175, 488, and 1694 lux. The task was to evaluate the dissimilarity between a pair of chips (one in each half) using a 30-point scale. Each pair was presented three times to each observer. A matrix of dissimilarities, averaged across observers and presentations, was used as an input into a non-metric MDS algorithm[4].

A MDS analysis yielded a two-dimensional fan-like pattern with three parallel arcs and seven converging radii. Chips with the same reflectance lay along a common radius. Chips with the same illumination lay along a common arc. The arcs length was found to contract when illumination decreased. For any fixed illuminant, the loci of achromatic colours for equi-illuminated surfaces form the one-dimensional continuum that might be interpreted as 'lightness'. However, differences in length and curvature between the arcs implied that each of the three levels of illumination employed in the experiment contained its own lightness continuum.

The data rule out luminance as a possible determinant of dissimilarity. Indeed, the objects with nearly the same luminance (46.5 and 52.2cd/m^2) made a pair with one of the largest dissimilarities. Therefore, neither luminance nor brightness ('subjective luminance') can be the second dimension of the achromatic object (related) colour manifold. This second dimension will be referred to as 'surface-brightness'. This should be considered as a dimension on its own, which should not be confused with either brightness of light (i.e., subjective intensity of light), or apparent illumination of an object. While being usually described in similar terms ("darker" – "lighter"), these dimensions are rather different from surface-brightness. Indeed, the main difference between surface-brightness and apparent illumination is that the former is a subjective (cognitive) characteristic of an illuminant whereas the latter is a perceptual attribute of a surface. The difference between surface-brightness and brightness of light was recently shown in an experiment where two equilluminant surfaces were shown to appear very different in surface-brightness[5]. In this experiment dimly illuminated white strips were presented against highly illuminated black background. The luminance (thus brightness) of the light reflected from the strips was the same as that from the background. However, the strips looked rather different from the background. Specifically, the strips appeared white but of low surface-brightness, whereas the background appeared black but of high surface-brightness.

It must be mentioned that the luminance difference produced by illumination was found to weigh considerably less than practically the same luminance difference produced by reflectance, when contributing to dissimilarity judgments[3]. This is in line with that shadows are usually under-estimated in 'every-day life' vision. Moreover, it has been reported by a number of researchers that after having turned into a pigmented area the shadow was always perceived blacker[6-8]. This leads to a conjecture that luminance contrast produced by an illumination edge may be somewhat discounted by the human visual system. This experiment attempts to illustrate and measure this illumination discounting.

2. METHOD

Experiment was divided into two parts. Twenty observers participated in the first part, and thirty seven in the second. While being familiar with the notions of luminance and luminance contrast, observers (students and members of staff of the department) were unaware of the purpose of the experiment. All they have normal or corrected to normal vision.

Observers were presented with a piece of dark grey paper (target) illuminated so that there was a vertical illumination edge across it (Fig 1). Luminance of the lit and shadowed halves was 41.5 and 4 cd/m^2, respectively. Hence, luminance ratio made by the illumination edge was 10.38. Observers were also presented with a series of 14 reflectance edges (bipartite rectangles in Fig. 1) made up of two adjacent squares one of which was printed with the same ink as that used to create the target (in the centre of Fig. 1). Reflectance of the second square varied in approximately equal steps so that luminance ratio varied from 1.47 to 9.43. In the first part of the experiment the reflectance edges were mounted only on the shadowed part of the display. In the second part the same 14 reflectance edges were mounted on both shadowed and lit part (as depicted in Fig. 1). The rationale was to ascertain whether the illumination of the reflectance edges affects the results.

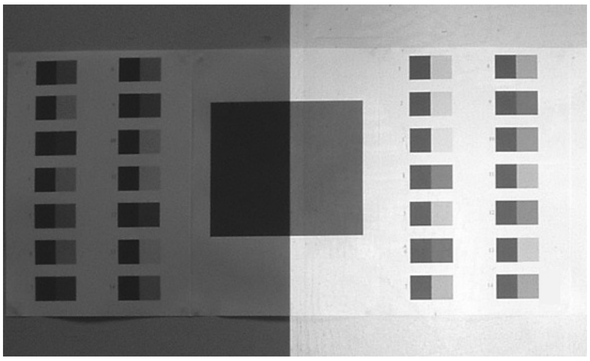

Figure 1: A photograph of the experimental display. A vertical border in the centre equally divided the display was created by the illumination (illumination border). All the other borders in the display were produced by ink. In reality the left hand side of the display did not look as dark as in this picture. Partly it was due to contrast compression made by the film; and partly due to discounting illumination edge which was the object of the present study.

The observers sat in a chair at 2 m from the stimulus display (30x65 cm). Vision was binocular. The task was to match luminance contrast. Specifically, they were asked to point out which of the reflectance edges had the same (or closest) luminance contrast as the illumination edge. In the first part one match was made by each observer. In the second part observers made two matches – one for the reflectance edges in shadow, and one in highlight.

In the end of the first part, after their matches were made, observers were informed that in reality all the 14 reflectance edges made the luminance contrast lower than that produced by the illumination edge. Eleven of twenty observers participated in the first part were also employed in the second part so as to find out if the knowledge of real luminance contrast of the illumination edge would affect their judgments.

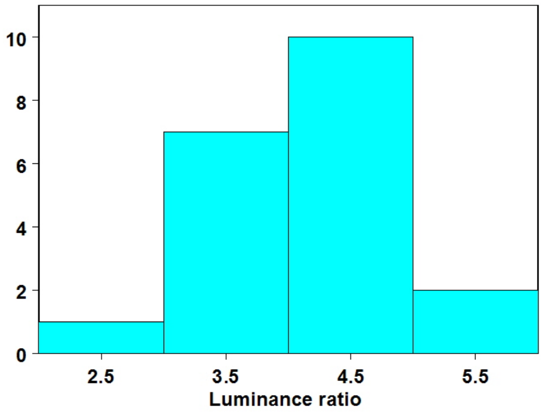

Figure 2: Luminance contrast matches made in the first part of the experiment. Horizontal axis is the luminance ratio produced by the reflectance border. Vertical axis is number of the observers who matched the corresponding luminance ratio to the luminance ratio produced by the illumination edge.

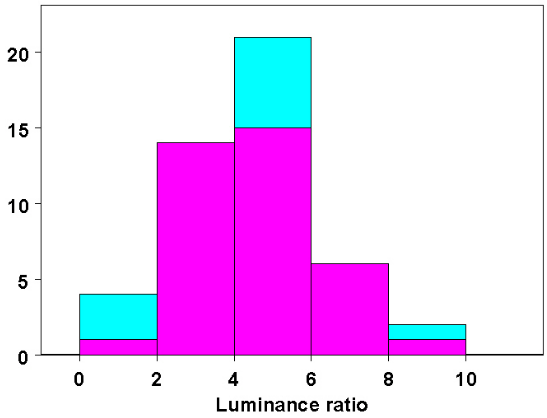

Figure 3: Two histograms (for the shadowed and lit halves of the display in figure 1) of luminance contrast matches made by 37 observers in the second part of the experiment. Axes are the same as in figure 2.

3. RESULTS

The distribution of observers' matches made in the first part is presented in Fig. 2. They fell into the luminance ratio range 2.50 – 5.61 with the mean being 4.29. The distributions of observers' matches made in the second part are presented in Fig. 3. The Wilcoxon signed-rank test showed no significant difference between these two distributions, i.e., matches made in the shadow and highlight, ($Z = 0.961$, $p = 0.34$). Hence, the illumination of the reflectance edges did not matter. Eleven observers participated in both parts of the experiment showed no significant difference between the matches made in the two parts ($Z = 1.29$, $p = 0.20$). Therefore, a prior knowledge of real luminance ratio did not affect observers' judgments. Combining the results from both parts of the experiment we get the mean luminance ratio match equal to 4.73. Therefore, on average, observers judged the luminance ratio, produced by the reflectance edge, as apparently equal to a 2.2 times higher luminance ratio, produced by the illumination edge. In other words, luminance contrast produced by an illumination edge was discounted by a factor of 2.2.

4. DISCUSSION

It turned out that in spite of direct instruction our observers did not base their matches on luminance contrast. Indeed, if they did, then there would no underestimation of the luminance contrast produced by the illumination edge. In other words, our observers were unable to match the luminance contrast. Therefore, they based their matches on the other perceptual dimensions.

One might suggest then that observers matched lightness contrast to surface-brightness contrast. Being presented with (i) an illumination edge which was mainly perceived as surface-brightness edge, and (ii) a reflectance edge which was mainly perceived as lightness edge, and being unable to evaluate the luminance contrast of reflected light, the observers matched the lightness contrast at the reflectance edge to the surface-brightness at the illumination edge. If this is the case, then our results simply suggest that the luminance contrast transfer function for lightness (i.e., lightness vs. luminance contrast response function) is steeper than that for surface brightness. That is, the same luminance contrast brings about lightness contrast approximately 2.2 times larger than surface brightness contrast. This is quite understandable from an ecological point of view since the range of luminance ratios produced by illumination edges in real scenes may be much broader than that produced by reflectance edges.

The observers' inability to match luminance contrast in this experiment means that they were unable to evaluate the intensity of the light reflected from a natural scene. It should be noted that we do not claim that human observers cannot match luminance contrast at all. The human ability to match luminance contrast of self-luminous targets (e.g. those presented on CRT displays) is well known. However, it could be argued from this study that the human ability to estimate the intensity of the light reflected from real objects in real scenes is rather poor.

When a luminance pattern is perceived as a self-luminance object (light mode) then there is just one achromatic dimension – brightness (of light). When a luminance pattern is perceived as an object (object mode) there are two achromatic dimensions – lightness and surface-brightness. This experiment shows that brightness of light can be assessed only in the light mode. In the object mode observers cannot estimate the brightness of the (reflected) light. Being unable to do so, they attempt to do what they can, i.e. they match the lightness contrast to the surface-brightness contrast.

If this is the case, then brightness of reflected light should be excluded from the list of the dimensions of achromatic object (related) colours. Moreover, we believe that the definition of lightness as relative brightness (of reflected light) should also be reconsidered since it reduces lightness to brightness (of reflected light) which is inaccessible in the object mode. In fact, such reducing lightness to brightness reduces the number of the dimension of the achromatic object (related) colour manifold to just one. Besides, lightness cannot be reduced to relative brightness because the lightness continuum has two extremes (black and white), amounting topologically to an interval, whereas brightness has only one extreme (darkness), being topologically a ray. So is relative brightness which is nothing more than brightness expressed in terms of a particular unit of measurement.

5. CONCLUSIONS

The achromatic object (related) colours constitute the two-dimensional manifold the dimensions of which are lightness and surface-brightness. When the reflectance of the surface changes, its colour changes mainly in lightness. When the illumination of a surface changes, its colour changes mainly in surface-brightness. White and black are the two end points of the lightness continuum. The lightness continuum is different for different levels of illumination. Specifically, when the illumination gets dimmer the lightness continuum contracts, shrinking to a point in the limit (i.e., there is no difference between black and white in the complete darkness). Therefore, the two-dimensional manifold of achromatic object (related) colours consists of a series of different one-dimensional continua, which are ordered in relation to their surface-brightness.

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