Abstract—When presented against a highly lit black background, dimly illuminated white paper strips appear white even when they are equiluminant with the background. Such an example of simultaneous lightness constancy cannot be accounted for by receptor gain control because of the equiluminance. Moreover, this demonstration shows that lightness cannot be reduced to ‘relative brightness’ as is widely believed.

Keywords: Lightness; brightness; luminance contrast; ratio rule; wallpaper illusion.

Objects are visible because they reflect light. Different objects often have different reflectances. Objects reflecting almost all of the incident light (across the visible part of the spectrum) appear white. Those reflecting only little or none of the light appear black. The perceptual continuum of various shades of grey (from white to black) is called lightness (Wyszecki and Stiles, 1982a, b). Yet when ambient illumination changes, white objects seem to remain white, and blacks remain looking black. This remarkable feature of human vision — called lightness constancy — poses a problem for visual science since the reflected light (the only direct source of visual information available) depends on both incident light and the object’s reflectivity (e.g. Brainard, 2003; Shevell, 2003).

One theory, quite popular among visual scientists, suggests that shifts in illumination are simply discounted by an adaptive gain control in receptors and possibly other visual neurons (Shapley and Enroth-Cugell, 1984; Whittle, 1994; Kingdom, 2003). Furthermore, it is generally believed that lightness is determined by relative rather than absolute luminance (e.g. the so-called ratio rule: Wallach, 1963) or by a luminance contrast, that are unaffected by illuminant changes. Despite the fact that the ratio rule has been criticized on experimental grounds (e.g. Arend and Sphehar, 1993), this belief has become so predominant that it is implied in a definition of

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lightness which is often characterized as ‘relative brightness’ (e.g. Wyszecki and Stiles, 1982b). However, the following demonstration shows, firstly, that lightness constancy can be observed without any change in gain control; and secondly, that a target may dramatically differ in lightness from its background even when the target and the background have the same luminance (thus, the same relative brightness).

In Fig. 1, vertical strips cut out of white paper are presented in front of a black background made of the same paper painted black. Four light sources (two on each side) provided spatially homogeneous illumination across both the strips and the background. While the background was illuminated by sources located at the side so as not to be blocked by the strips, the illumination gradients they produced almost cancelled each other out. Illumination of the strips and background were independently set to reflect equal amounts of light (50 cd/m²). Specifically, one of two light sources used to illuminate the strips was a digital projector driven by the 14 bit video card (VSG 2/4). This enabled us to control luminance and chromaticity of the light reflected from the strips with proper accuracy.

Despite their equiluminance, the strips appeared white and the background appeared black, thus exhibiting simultaneous lightness constancy, which cannot be accounted for by a change in gain control. Furthermore, when one looks through the strips and focuses on the background, a wallpaper phenomenon (Woodworth, 1938;
Logvinenko and Belopolski, 1994; Logvinenko et al., 2001) can be experienced. The strips are perceived to be located in the same plane as the background. Surprisingly, apart from changing their apparent location, the strips also change in appearance. They now appear to have nearly the same lightness as the background. Moreover, when the strips are perceived to be coplanar with the background they not only acquire the same shade of black as the background, but also appear to be under the same level of illumination as the background. Presumably, the illusory depth shift into a higher illuminated plane induces an illusion of a shift in the apparent level of illumination which, in turn, causes a change in the lightness of the strips (see Note 1).

When the strips were perceived as coplanar with the background, observers saw a slight difference in the lightness between the strips and the background because of the individual differences resulting from the semi-subjective nature of the definition of luminance (e.g. Wyszecki and Stiles, 1982a). To equate the individual luminance of the strips and their local background minor adjustment of the physical illumination of the strips was carried out for each observer using a minimally-distinct border (MDB) criterion (e.g. Kaiser and Boynton, 1996, p. 404). As a result, under the illusory location condition the strips appeared to be equiluminant with the background for all observers.

We used an asymmetric lightness-matching method to measure the lightness of the background and the strips (under both their veridical and illusory locations). A series of samples of grey from the Munsell neutral scale was mounted just above the black background so that both were under the same level of illumination (Fig. 1). Five observers were first asked to pick a Munsell sample which matched the shade of the strips, and then the background. The measurements were repeated three times (on different days) for each observer. The median Munsell matches for the strips and background under veridical perception were 8.75/ and 3.25/, respectively. Those under illusory locations were 4.25/ Munsell units. (In other words, the Munsell match was the same for the strips and the background when they were perceived in the same depth plane.) Thus, although the pattern of retinal illumination remains the same under veridical and illusory location of the strips, their lightness is perceived differently in the two cases.

Veridical perception (i.e. when the strips are perceived as white) is a challenge for any contrast-based theory of lightness perception (e.g. Whittle, 1994; Blakeslee and McCourt, 1999). Indeed, since the luminance contrast between the strips and the background is zero (see Note 2), such a theory would predict equal lightness for the strips and background. Contrary to this prediction the strips and the background gravitate towards opposite ends of the lightness scale.

Moreover, this demonstration may also be problematic for many other theories of lightness perception. For instance, anchoring theory (Gilchrist et al., 1999) suggests that lightness is derived from normalizing luminance using the maximum luminance of a frame. Since the luminance of the strips is practically equal to that of the background, and the entire scene (i.e. the global frame in Gilchrist’s terms)
is equiluminant, the anchor for any local frame should be the same. Therefore, this theory also predicts that the strips and the background should have the same lightness. Furthermore, anchoring theory, along with the contrast-based theories, predicts a single lightness value for a given luminance value. Thus, these theories cannot account for the most important feature of this demonstration — that the same luminance in the same retinal image may produce two very different lightness values.

All of these theories completely ignore apparent illumination, although this feature is closely interrelated with lightness. Indeed, it has already been established that the same luminance border can be perceived as a lightness edge in one perceptual context and an apparent illumination edge (e.g. shadow) in another (Gilchrist, 1977; Logvinenko and Menshikova, 1994; Adelson and Pentland, 1996). Furthermore, lightness and apparent illumination edges produced by the same luminance edge were shown to have opposite contrasts (Logvinenko and Menshikova, 1994). The same reciprocal relationship between the lightness and apparent illumination edges can be observed in Fig. 1 under veridical perception. White strips made a positive lightness contrast with the black background, whereas dimly illuminated strips made a negative apparent illumination contrast with the brightly illuminated background (see Note 3).

It should be noted, however, that the term ‘apparent illumination’ is somewhat misleading in the present context. Indeed, apparent illumination is generally understood as a characteristic of either the illuminant or the ambient illumination. It is inferred rather than perceived. However, when the strips change their apparent location they not only change in apparent illumination but they change along another perceptual dimension of achromatic colour which is perceived (not inferred). Although there is no consensus on a definition of this second dimension, bi-dimensionality of achromatic colour was unquestionable for Hering (1874), Katz (1935, 1999), Evans (1964), Heggelund (1974) and many others. That lightness is not the only dimension of achromatic colour has recently been supported by the multi-dimensional analysis of achromatic colours (Logvinenko and Maloney, in press). Specifically, it was shown that similarity judgments of Munsell grey chips under different illumination are essentially two dimensional. We believed that these measurements were based on lightness and the second dimension, which we refer to as surface-brightness (Logvinenko and Maloney, in press). It seems that this second dimension is very close to what Katz called ‘pronouncedness’ (Katz, 1935, 1999), though there is an important difference. Specifically, Katz believed that in the dimmer illumination, the white and light greys became less pronounced but the black and dark greys more pronounced (Katz, 1935, 1999, pp. 79–81). The latter is in apparent contradiction with our finding that surface-brightness always decreases when the illumination is reduced (Logvinenko and Maloney, in press).

While surface-brightness usually correlates with apparent illumination the two concepts are phenomenologically different. Surface-brightness is a perceptual dimension of an object rather than a characteristic of either the ambient or direct
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illumination. Of course, when the physical illumination of an object is altered, surface-brightness is what mainly changes. However, as our demonstration shows, surface-brightness may significantly change even when the physical illumination of the scene is constant. Indeed, we believe that the apparent depth shift causes simultaneously a decrease in lightness and an increase in surface-brightness rather than apparent illumination because the actual illumination of the scene remains the same.

It should be also noted that being a perceptual attribute of an object, surface-brightness should not be confused with the brightness of light (i.e., the subjective intensity of light). There is no reason to doubt that brightness of the light reflected from the strips remains the same under both their veridical and illusory location. Still, the surface-brightness of the strips is much higher during the illusory perception.

Thus, contrary to the common interpretation that luminance is just transformed into lightness; luminance is bifurcated into two perceptual dimensions — lightness and surface-brightness. Particularly, any luminance edge produces a lightness edge and a surface-brightness edge, which are coupled in space. Note that, in our demonstration, the pair of coupled lightness/surface-brightness edges can emerge from an edge with practically zero luminance contrast. In other words, an equiluminant (according to the MDB criteria) rectangle on the retina is segmented into two patterns (the strips and the rest) of different lightness and surface-brightness. As the luminance is practically the same for both patterns, this segmentation can hardly be based on luminance contrast. Thus, luminance contrast is not necessary for the segmentation of a scene into different lightness and surface-brightness patterns.

What features of the retinal pattern, then, cause the segmentation of the equiluminant scene? It should be noted that there was a small unavoidable difference in the reflectance profiles of the black paper of the background and the white paper of the strips, which might result in the scene segmentation. Although the background was made of the same paper as the strips, the background paper was painted black. Painting produced a slight difference in chromaticity of the light reflected from the strips and the background. A digital projector was used to minimize this difference. However, we found that even after the CIE chromaticity coordinates, as measured with a spectroradiometer, were equated for the strips and the background, the former was clearly perceived as a pattern distinct from the latter.

Moreover, we asked our observers to adjust the CIE coordinates of the strips so that they had the same colour as the background. While this considerably reduced the chromaticity difference, the observers proved to be unable to achieve a total identity between the strips and the background. The strips always looked distinct from the background. We believe that this might have been due to the difference in micro-texture evoked from painting.

One might argue that equating the chromaticity and luminance could only be done to a certain degree of accuracy. Consequently, as mentioned above, a small error in
residual luminance due to approximation between the strips and the background could, in theory, result in this segmentation. While the residual difference in luminance due to measurement error could, strictly speaking, bring about the segmentation of the strips and background, it cannot account for the large difference in lightness between the strips and background observed under normal vision. Indeed, a small difference in luminance should induce only a small difference in lightness (which was indeed observed, but only during illusory perception of the display).

It does not follow, however, that luminance contrast has no role in lightness perception. On the contrary, its role is important as it determines the relationship between the lightness and surface-brightness. While luminance contrast does not determine the specific value of either lightness or surface-brightness per se, it dictates their relative proportions; in this way lightness and surface-brightness are interrelated. Indeed, our experiment clearly indicates that there is a reciprocal relationship between lightness and surface-brightness (referred to as lightness/surface-brightness invariance).

It should be said that a reciprocal relationship between lightness and apparent illumination has long been suggested (e.g. Koffka, 1935; Beck, 1972; Adelson and Pentland, 1996; Logvinenko, 1997). Moreover, it is implicitly assumed in some accounts of colour perception (e.g. Brainard et al., 1997). However, direct experimental tests have brought somewhat controversial results, leading to both supporting evidence and evidence against it (for review see, e.g. Beck, 1972; Logvinenko and Menshikova, 1994; Rutherford and Brainard, 2002). The experimental criticisms have mainly been based on the fact that subjective estimates of the ambient illumination do not follow a reciprocal relationship with lightness. However, if surface-brightness, rather than apparent illumination, is cojoined with lightness in a reciprocal relationship, an experimental test should include measurements of surface-brightness rather than estimates of the ambient illumination which, as our demonstration shows, can be quite different. Until such a test is done, the lightness/surface-brightness invariance can be considered a plausible hypothesis.

Note that the lightness/surface-brightness invariance implies that when surface-brightness in a scene is constant the lightness ratio (contrast) should be equal to the luminance ratio (contrast) (Logvinenko, 1997). If a scene is partitioned into several areas where each region of surface-brightness is kept constant, the lightness ratio will equal the luminance ratio when derived from within a single area, but not from different ones. For example, in Fig. 1, the luminance ratio between the strips and the background is equal to 1 whereas the lightness ratio between them was found to be much greater than 1 under veridical perception. Therefore, the ratio rule (Wallach, 1963) can be valid only within areas of equal surface-brightness (see Note 4).

Hence, partitioning a scene into equally illuminated frames is important for computing lightness. As established recently, the human visual system uses some cues to distinguish illumination borders from material (reflectance) ones, and thus to establish areas of equal illumination (Logvinenko et al., in press). Further
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investigation into such cues may shed a new light not only on how illumination, but also how achromatic color, is perceived by the human visual system.

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NOTES

1. It has already been established that a change in apparent depth, resulting in a change in apparent illumination, may, in turn, cause a corresponding change in lightness (Gilchrist, 1977; Knill and Kersten, 1991; Logvinenko and Menshikova, 1994). However, this is the first time that such a lightness shift has been induced by a ‘misjudgment of illumination’ — a term coined by Herman von Helmholtz (1867) — under equiluminance conditions. It should also be noted that it is the shift into an area of higher illumination rather than coplanarity of the strips and background per se that causes the change in lightness. Indeed, the same lightness shift can be observed when the strips have been moved slightly forward from the background plane since the whole volume around the background is perceived as much more illuminated than the strips. Moreover, the same effect is observed even when the strips are rotated around a vertical axis from a position originally parallel to the background and therefore cannot be perceived as being coplanar with it.

2. Admittedly, there might have been micro-fluctuations of the local luminance contrast along the strips/background border due to texture inhomogeneity which prevented the strips and the background from merging into a single apparently homogeneous rectangle. However, since these micro-fluctuations were random and so small that they could not be resolved by the spectroradiometer, we shall say that the luminance contrast was practically zero.

3. We use the following formula for evaluating the contrast here: \((S - B)/B\), where \(S\) and \(B\) stand for the lightness (or apparent illumination) of the strips and background respectively.

4. Having said this, one must admit that a definition of lightness based on the ratio rule (i.e. relative brightness) should be reconsidered. Generally, the use of relative units does not change the nature of the entity in question. Brightness remains brightness irrespective of the units used. Length remains length whether measured in meters or feet. The lightness continuum has two endpoints (black and white), whereas the brightness continuum only one (complete darkness). In other words, they have different topological structure. Hence, lightness cannot be reduced to relative brightness since relative brightness remains to be open at one end while the lightness continuum is topologically similar to an interval.
REFERENCES


