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Lightness, illumination, and gradients

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Abstract—The illumination interpretation approach claims that lightness illusions can be explained as misapplications of lightness constancy mechanisms, processes which usually enable veridical extraction of surface reflectance from luminance distributions by discounting illumination. In particular, luminance gradients are thought to provide cues about the interactions of light and surfaces. Several examples of strong lightness illusions are discussed for which explanations based on illumination interpretation can be proposed. In criticisms of this approach, a variety of demonstrations of similarly structured control displays are presented, which involve equivalent lightness effects that cannot readily be accounted for by illumination interpretation mechanisms. Furthermore, a number of known and novel displays are presented that demonstrate effects of gradients on the qualitative appearance of uniform regions. Finally, some simple simulations of neural effects of luminance distributions are discussed.

Keywords: Lightness; illumination; luminance gradients.

INTRODUCTION

It has been known since the times of Aristotle, Alhazen, and Leonardo (see Wade, 1998), that the visual appearance of a surface patch does not depend solely on the material composition of the patch itself and the light it reflects towards the observer, but also on the properties of its surround. For example, early in the 19th century, Johann Wolfgang von Goethe noted that ‘a gray image on black ground appears much lighter than the same image on white ground. When the two cases are placed next to each other, one can hardly persuade oneself that both images were painted from the same pot’ (see Trunz, 1981, p. 337). This particular effect was later named ‘simultaneous contrast’, and is depicted in many perception textbooks. A large variety of other context-induced achromatic color illusions were described and studied subsequently.

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There are several types of theoretical accounts of illusory contextual effects in perception. A popular approach is to regard them as results of inappropriate applications of visual mechanisms generally subserving veridical perception. Such mechanisms are needed to recover distal attributes of objects, because the corresponding proximal attributes are affected by various extraneous factors. For example, the projected, proximal size of an object depends not only on its distal size but also on its distance from the observer; proximal shape depends not only on distal shape but also on orientation; proximal motion on the retina depends not only on distal motion of the observed object but also on the motion of the eyeball; etc. In particular, the luminance of a surface patch, that is, the amount of visually effective light it projects onto the retina (which may be labeled as its 'proximal achromatic color'; see Todorović, 2002), depends not only on its reflectance (the percentage of light it reflects, or its 'distal achromatic color'), but also on its illumination (the extraneous factor involving the amount of light currently incident on the patch). However, in spite of such effects of extraneous factors on proximal attributes, usually perceptual constancies obtain, that is, distal properties are generally perceived more or less veridically. This suggests the existence of special visual mechanisms that compensate for the effects of extraneous factors. In color perception, these are the mechanisms that are supposed to recover constant surface reflectances from the incoming luminance distributions by discounting the effects of illumination.

One example of a theoretical account in which constancy mechanisms are hypothesized to generate non-veridical percepts involves size illusions. In this account it is assumed that depth cues in pictorial displays may trigger processes in the visual system that in everyday perception are activated by real 3D depth, so that the same mechanisms that standardly generate veridical percepts may, in this case through misapplication, cause visual illusions (see Gillam, 1998). For example, in the well-known Ponzo illusion, two target lines of equal size, flanked by two converging slanted lines, are perceived as of different length. The explanation is that perspective depth cues induced by the slanted lines indicate that the target lines are located at different distances, causing the further appearing target to look longer, as indeed it would be, had it been actually located further from the observer (see Palmer, 1999). In this way, constancies and illusions are elegantly and parsimoniously accounted for within the same theoretical framework. In the following I will first sketch such an account of achromatic color illusions, and will then proceed to criticize it.

In color perception this type of approach essentially goes back to Helmholtz. Although his original idea was formulated mainly with chromatic colors in mind, it can be readily applied in the achromatic domain as well. The achromatic color illusions under discussion here involve flat images exhibiting various reflectance distributions, observed under uniform illumination. However, they may be *interpreted* by the perceiver as depicting non-uniformly illuminated scenes. The basic assumption of this approach is that cues of illumination may trigger reflectance recovery mechanisms appropriate for corresponding real-world scenes, and in this way generate non-veridical percepts of image reflectances. For example, if two image patches of equal luminance are interpreted as receiving different amounts of illumination, then they may be perceived as having different reflectances, as indeed they would have in an actual non-uniformly illuminated scene. Such circumstances may provide the explanation of the phenomenon of simultaneous contrast, described above. If the observer of the display involving two equiluminous gray patches interprets one gray patch, together with its white background, as receiving higher illumination than the other gray patch and its dark background, then it follows that the first patch must have lower reflectance, in order to reflect the same amount of light as the second patch (see Hurvich and Jameson, 1966; Kingdom, 1999).

This type of explanation is formally closely analogous to the above account of the Ponzo size illusion: in both cases objects that have equal proximal attributes (such as size or color) are perceived as being different, supposedly due to effects of cues that convey the presence of different extraneous factors for the two objects (such as different distance or illumination). One potentially complicating factor for this type of account, that I will not address here in detail (but see Todorović, 2002, 2003c), is the need to distinguish between perceived distal attributes (such as perceived distal size or lightness) from perceived proximal attributes (such as perceived proximal size or brightness). Note that this type of account does not necessarily presuppose that scene interpretation is based on explicit, conscious deliberations by observers. Helmholtz already talked about ‘unconscious inferences’, implying that although such processes may be formally described as involving premises and conclusions, this does not mean that they need to be accessible to conscious awareness, or that they necessarily take the same form as logical reasoning or tap into higher cognitive processes. I will refer to putative processes of this type as *illumination interpretation mechanisms* (Kingdom, 2003a, b; Todorović, 2003a, b).

In recent years a number of authors have in various ways discussed the possibility that lightness phenomena in relatively complex flat displays may, at least in part, be due to mechanisms of this type (see Adelson, 1993, 2000; Agostini and Galmonte, 2002; Kingdom, 1997, 1999, 2003a, b; Knill and Kersten, 1991; Logvinenko, 1999, 2003; Logvinenko *et al.*, 2005; Purves and Lotto, 2003; Purves *et al.*, 2004; Schirillo and Shevell, 1997, 2002; Williams *et al.*, 1998a, b). I will deal with some of these approaches in a little more detail below. This class of accounts is only one among several different types of lightness theories. For example, an account of simultaneous contrast popular in textbooks bases this effect on actions of lateral inhibition processes or, equivalently, properties of neurons with concentric-antagonistic receptive fields. Although such a proposal in its simplest form has serious shortcomings (Gilchrist *et al.*, 1999), several much more complex computational models, based on and inspired by physiological data, have accounted for a number of lightness effects (Blakeslee and McCourt, 1997, 2003, 2004; Hong and Grossberg, 2004; Grossberg and Todorović, 1988; Kingdom and Moulden, 1992; Pessoa *et al.*, 1995). A variety of other theoretical approaches to lightness phenomena are also available (see e.g. Adelson, 2000; Anderson, 1997; Anderson and Winawer, 2005; Bressan, 2001; Gilchrist, 1988; Gilchrist and Economou, 2003; Gilchrist *et al.*, 1999; Whittle, 1994a, b). Although these different explanatory frameworks are generally theoretically opposed, they are not necessarily completely mutually exclusive in all respects, and any given effect might, in principle, be due to a combination of causes.

In this paper my aim is to critically examine the illumination interpretation account by starting from original stimulus images containing equiluminant target patches that look different, and whose difference may be plausibly accounted for through illumination interpretation mechanisms. The next step is to modify the structure of these stimuli in order to modulate particular illumination cues. If such a stimulus modification should be accompanied by corresponding changes in lightness, the illumination interpretation approach is corroborated; however, if strong manipulations of essential illumination cues fail to affect the lightness of critical targets, then the illumination interpretation account for these displays becomes problematic. It is this latter possibility that I will pursue in the following.

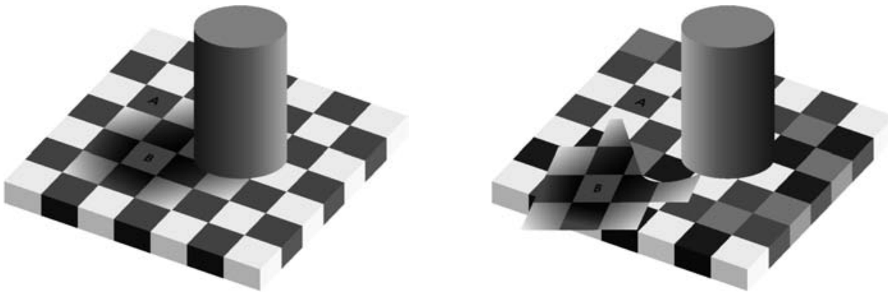
I have previously (Todorović, 1997, 2003a) used this strategy to challenge the illumination interpretation account of particular stimulus displays designed by Adelson (1993) and Kingdom (2003a); see also Kingdom's (2003b) reply and my reply to his reply Todorović (2003b), contained on the same CD as my first comment. In the present paper I will continue with such criticisms by addressing three among the strongest and most attractive recent lightness phenomena for which explanations based on the illumination interpretation can be and have been offered. These explanations turn out to be formally similar to the above account of classical simultaneous lightness contrast, except that the new displays are much more effective in conveying the represented scenes. As counter-examples, I will present a variety of similarly structured control displays that involve similar lightness effects but which, I will argue, cannot readily be accounted for by illumination interpretation mechanisms. I will not offer any comprehensive theory of lightness, but will claim that these particular effects can be better understood by concentrating on relatively local luminance relations and their effects on the visual system.

Natural scenes often contain *luminance gradients*, that is, regions in which luminance varies gradually over space. For example, gradients may appear at the edges of shadows (penumbras), as shading patterns on curved surfaces (due to smooth variations of surface orientation with respect to the light source), as consequences of the gradual decrease of illumination intensity with the increase of distance from the light source, or due to variations of light source intensity. Most of the displays that will be presented here involve luminance gradients, constructed using graphics software. According to the illumination interpretation account, these gradients may serve as image cues of illumination, which help trigger the corresponding interpretative mechanisms that are presumed to underlie the lightness effects. An alternative approach, which I will advocate, is that the lightness phenomena in these images are due to other structural aspects of the stimuli. This is not to deny that luminance gradients help establish the impression of illumination in these displays, but rather to question the causal role of illumination interpretation mechanisms in the generation of lightness effects exhibited in the images. Such arguments will be illustrated with displays presented in Figs 1 to 5, which involve detailed analyses of the illumination structure of a number of displays. Following that, I will discuss some additional phenomena involving gradients, which demonstrate that they may not only affect lightness, but also induce qualitative differences in surface appearance. Such analyses will be illustrated with displays presented in Figs 6 to 10. Figure 11 will present some effects involving chromatic gradients. Finally, some simple simulations of neural effects of luminance gradients will be illustrated with diagrams in Fig. 12. The presented lightness effects are informal demonstrations that have not yet been confirmed in published experiments. However, I hope that readers will find most of them robust enough to merit consideration.

THE CHECKERED SHADOW AND ITS DECONSTRUCTION

Figure 1a is a close replica of a now well-known image designed by Adelson (1995). It depicts a scene containing a horizontal checkered plane and a vertical cylinder, illuminated from the right. The two target patches A and B are uniform and have the same luminance, but their gray shades appear rather different. Within the illumination interpretation approach the explanation of this effect is straightforward, and involves the same logic as the above mentioned account of simultaneous contrast, but the argument for Adelson's image is more plausible because the illumination structure of the represented scene is more perceptually salient: in the conveyed scene patch B is readily interpreted as located within the shadow cast by the cylinder, whereas patch A appears normally illuminated. Based on information about the interaction of light and surfaces (accumulated individually or inherited through evolution), it can be concluded that since the patches are differently illuminated but have the same luminance, they must have different reflectances. The visual system automatically implements this conclusion, and therefore patch B comes to appear lighter gray but poorly lit, and patch A as well illuminated darker gray.

Figure 1b was designed as a control display to point out some problems with the above account. It conveys a similar scene as Fig. 1a, but with the shadow region, as it were, forcibly detached and artificially displaced from its natural position. This region in Fig. 1b contains all Fig. 1a patches that exhibit luminance gradients, preserving their exact luminance profiles, shapes, and mutual local spatial relations. I will call these two identical multi-patch regions in Figs 1a and 1b 'gradient regions'. Note that the two equiluminant target patches A and B in Fig. 1b appear differently light. However, in contrast to the gradient region in Fig. 1a, the gradient region in Fig. 1b lacks a number of features that are standardly associated with shadows.



(a) (b)

Figure 1. Lightness and depicted cast shadow. The target patches A and B have the same luminance, but A looks darker than B. In (a) this difference may be accounted for by the presence of the shadow, but in (b) this explanation is compromised. See text for details.

To begin, in Fig. 1a the gradient region surrounding patch B has the natural appearance of a shadow cast upon the ground, reminiscent of an immaterial transparent veil spread across a surface, whereas in Fig. 1b the corresponding region looks more like a thin, graspable material textured sheet lying upon or hovering above the plane. In consequence, whereas in Fig. 1a patches A and B are seen to belong to the same surface but to be differently illuminated, in Fig. 1b they are seen as belonging to different surfaces. Furthermore, in Fig. 1a the luminance gradients along the margins of the gradient region appear as the characteristic penumbra of a cast shadow, whereas in Fig. 1b the appearance of the same gradients as the shadow penumbra is disturbed, due to the presence of sharp luminance discontinuities all along the gradient region borders. A salient difference between the two gradient regions is that in Fig. 1a the checkered pattern outside of the gradient region continues smoothly into the checkered pattern within the region, which is a signature feature of shadows cast upon textured surfaces, whereas in Fig. 1b the patterns within and outside the gradient region clash with each other at the border of the region, both geometrically and photometrically. Furthermore, in Fig. 1a the average luminance within the gradient region is less than outside of it, which is a regular consequence of diminished illumination within shadows, whereas in Fig. 1b, due to the darkening of a few tiles on the plane outside of the gradient region, this is not necessarily the case. Whereas in Fig. 1a the two patches appear to belong to the same chess-board pattern, patch A being one of the many black checks and patch B one of the many white checks, but accidentally exposed to different illumination, in Fig. 1b the two patches belong to two different patterns. Also, in Fig. 1a the shadow casting cylinder appears as illuminated from the right, so that its darker, left side, interpreted as the attached shadow, is positioned near the gradient region, interpreted as the cast shadow, whereas in Fig. 1b the cylinder shading is inverted, its darker portion lying to the right, suggesting that illumination is coming from left, and that the gradient region is at the wrong side to be the shadow of the cylinder. Furthermore, in Fig. 1a the shape of the gradient region is in rough projective agreement with the shape of the shadow casting cylinder and the direction of illumination, whereas in Fig. 1b these projective relations are violated.

The main point of interest here is that although many characteristics of shadows which are respected in Fig. 1a are violated in Fig. 1b, the contrast between the lightnesses of target patches in Fig. 1b does not appear much weaker than in Fig. 1a. This poses a problem for the illumination interpretation account. For example, Purves *et al.* (2004), who support a variant of this approach, claim that '... any change relevant to the probable contribution of illumination, reflectance, and transmittance — no matter how subtle — should influence the apparent brightness and/or lightness of the elements in the scene' (p. 145). If the lightness illusion in Fig. 1a were indeed caused by processes based on information about the various types of interactions of light with objects, then one would expect the strength of the effect to vary proportionally with the degree of similarity of the image structure to ecologically valid features of shadows. The fact that in Fig. 1b many of these features are absent, indicating that the gradient region could not be a generic shadow, but that the lightness effect does not appear to be much diminished, casts doubt upon the relevance of the illumination interpretation account for these displays. One might imagine, though, that the gradient region in Fig. 1b is cut out from a similar pattern as the plane on which it rests, placed upon it, and then somehow subjected to shadowing precisely aimed to coincide with its boundaries, so that patch A would indeed be dark but well illuminated and patch B light but poorly illuminated; however, such a causal scenario would hardly be generalizible from everyday situations, that is, based on normal experience with lights and objects.

How can the lightness effects in these figures be accounted for, if the illumination interpretation is questioned? As pointed out by Adelson, in Fig. 1a the darker appearing patch A is surrounded by lighter patches, whereas the lighter appearing patch B is surrounded by darker patches; note that the same is true for Fig. 1b. I will call this type of relation between target patches and their backgrounds 'surround contrast constellations'. With respect to this feature, the structure of these displays is similar to classical simultaneous contrast, as described by Goethe, and may have a similar cause. I will not at this point enter into a discussion of various explanations of simultaneous contrast and its variants, but there are plenty alternatives to the illumination interpretation account, since most every theory of lightness is expected to address this classical effect. It should be noted that there are three differences of these displays from Goethe's variant. First, in the checkered displays the target patches are not completely surrounded by contrasting patches. Second, the background is not uniform but articulated, a feature known to enhance the strength of the contrast effect (Adelson, 2000). Finally, the displays involve luminance gradients in the vicinity of target patches. These features are shared with most subsequent figures discussed below.

A difficulty for the proper evaluation of the lightness effects in the preceding examples is the relative complexity of the transformation of Fig. 1a into 1b, which may affect not only the potential illumination cues but also many local luminance relations. Thus any eventual difference of appearance of targets in the two figures may not only be due to effects of stimulus variations on putative processes of illumination interpretation but also due to changes of the structure of local contrasts. Such potential confounds of illumination cues and structural features present serious threats to validity for many studies aiming to disentangle the sources of lightness phenomena (see Kingdom, 2003a, b; Todorović, 2003a, b). In the following sections I will use simpler and more controlled manipulations of both aspects of stimuli, thus enabling more focused analyses of their effects on the appearance of target patches.

THE GRADIENT WALL OF BLOCKS AND ITS SHADOW-INCOMPATIBLE VERSIONS

Figure 2a is a close replica of an ingenious display designed by Logvinenko (1999). It is composed of uniform patches and gradient patches (patches that contain vertically oriented luminance gradients). The figure was produced with graphics software by first constructing a layer of adjacent rectangular gradient patches, and then superimposing five rows of equiluminant uniform patches on top of the grid. There are two types of gradient patches: the 'dark' patches in which the shading varies from black to light gray (directed top to bottom and bottom to top in alternate rows), and the 'light' patches in which shading varies from white to dark gray (also directed top to bottom and bottom to top in alternate rows), arranged in a chessboard-like pattern. The uniform patches are diamond-shaped and have equal luminance. The point of the display is that the diamonds in odd rows look much darker than those in even rows.

How can this lightness difference be explained? Logvinenko (1999, 2003) has pointed out that this 2D display can be interpreted as depicting a 3D scene containing a wall of blocks exposed to a wave of illumination which changes intensity sinusoidally along the vertical axis, with the diamonds in odd rows receiving the strongest illumination and the diamonds in even rows receiving the weakest illumination. Given such an illumination structure, the explanation of the lightness effect within an illumination interpretation account is straightforward: the diamonds in odd rows are perceived as highly illuminated dark surfaces, whereas those in even rows are perceived as poorly illuminated light surfaces. This is essentially the same type of reasoning described above in the Helmholtzian account of simultaneous contrast and Adelson's checkered shadow. The difference involves only the particular geometric and photometric structure of Fig. 2a, in which the luminance gradients on the sides of the blocks presumably serve as cues of variable illumination. As noted before, such an explanation, and the term 'interpretation' that I use in describing this account, does not include the claim that observers actually consciously perform geometric and photometric calculations involving luminances, reflectances, spatial orientations, and illumination direction and intensity; instead,

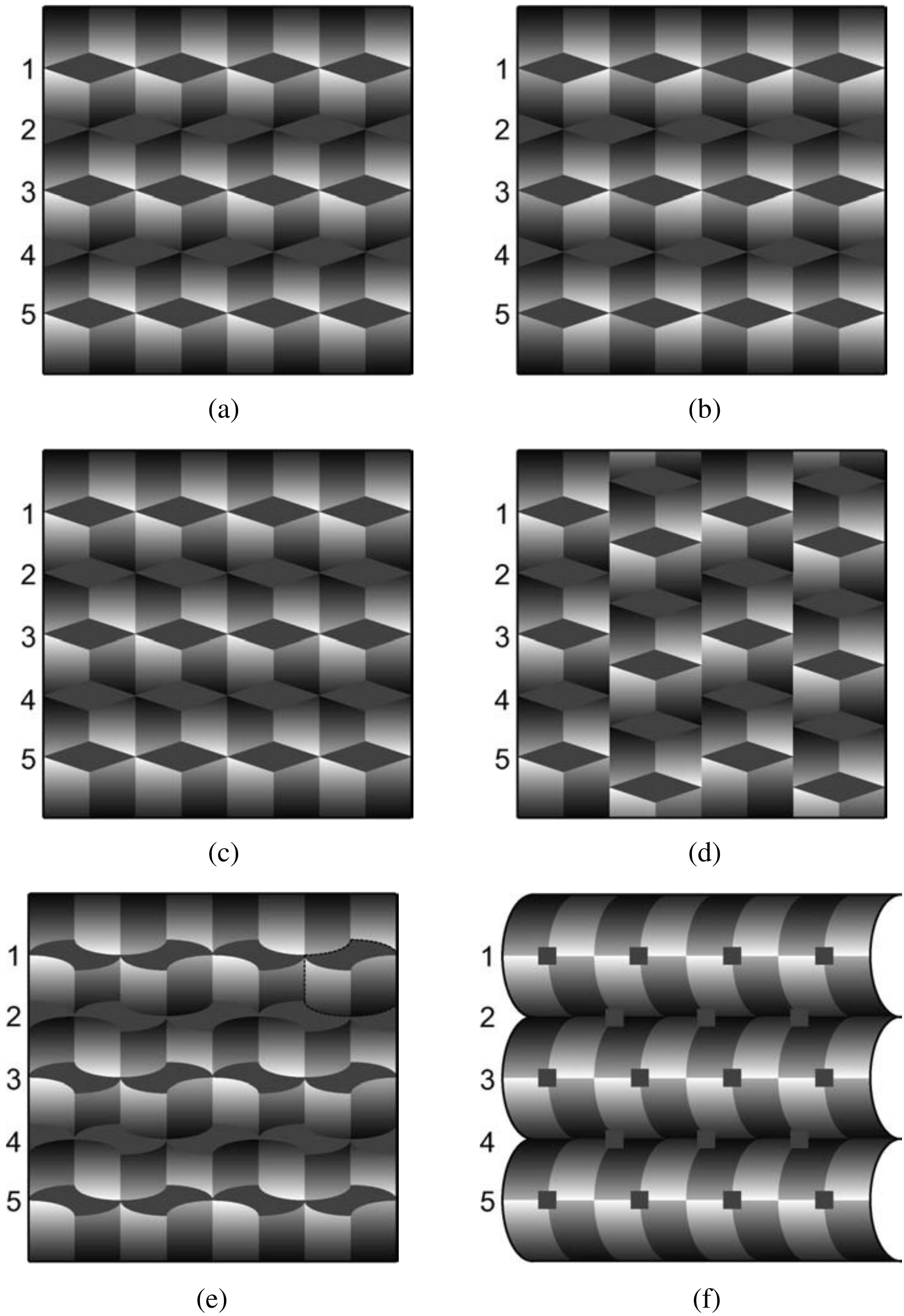


Figure 2. Lightness and depicted wave of illumination. The patches with the shapes of horizontally oriented diamonds in (a), (b), (c), and (d), as well as blades in (e) and small squares in (f) all have the same luminance, but those in odd rows look darker than those in even rows. The lightness difference in (a) may be accounted for by the presence of a wave of illumination falling upon a wall of blocks, but in other figures this type of explanation is less likely. See text for details.

their visual systems may be assumed to engage in analogous automatic, complex but reflex-like processing, only the results of which are accessible to consciousness.

The gradient wall of blocks and some related displays are labeled by Logvinenko (1999, 2003) as being *shadow-compatible*, meaning that there exists a pattern of illumination that can produce such a luminance pattern. However, this is not a very restrictive definition since 'every luminance pattern can, generally speaking, be produced by adjusting an illumination', so that this notion is to be applied 'from the human visual system point of view', such that shadow-incompatible displays are those for which 'the human visual system 'does not believe' that the pattern has been produced by the illumination' (Logvinenko, 2003, p. 723). An example of a shadow-incompatible display involves an array of blocks for which the illumination direction would have to be different for each adjacent block (Logvinenko, 1999, Fig. 11b). Although this feature could perhaps be defined more precisely, I will take shadow-compatibility to refer to representations of physically reasonably plausible 3D scenes involving a generally coherent illumination structure, the likes of which one might generically encounter in everyday environments. In contrast, shadow-incompatibility is a feature of 2D displays whose 3D interpretation would involve impossible or non-generic constellations of spatial shapes and illumination sources, highly unlikely to be produced in naturally occurring conditions. Logvinenko (1999, p. 812) has proposed that lightness illusions, such as in Fig. 2a, are generated only when luminance gradients are shadow-compatible. He has presented examples of displays related to Fig. 2a, which also contain luminance gradients, but which are not shadow-compatible, and in which the lightness illusion is reduced or lost, and has proposed that the decline of the strength of the illusion in such images is caused by the decline of shadow-compatibility (Logvinenko 1999, 2003).

Logvinenko's figure, itself based on a display by Adelson (1993), and used by him to challenge Adelson's theories of lightness phenomena, is a fruitful display paradigm which was, in turn, used by others to criticize Logvinenko's own explanation of his effect (Bressan, 2001; Todorović, 1999). For example, Fig. 2b, designed by Bressan (2001), is a variation of Logvinenko's figure in which the sides of blocks in every other row are interchanged. She pointed out that this figure portrays a shadow-incompatible wall of blocks, but that the illusory lightness difference between the diamonds in alternate rows is retained, challenging the explanation based on illumination interpretation. The wall of blocks in this figure is indeed shadow-incompatible, in the sense that its setup would necessitate a complex and unlikely constellation of illumination sources that change direction between different rows. Logvinenko (2003) has countered that Bressan's display can also be interpreted as conveying an alternative, shadow-compatible scene, which does not involve a wall of blocks. In this version the diamonds are patches freely floating in front of a corrugated background, and the scene is illuminated by a sinusoidal wave of light falling slightly from the side.

However, there is still a difficulty for the illumination interpretation account. The display in Fig. 2b is bi-stable, and with a little effort the observer may switch from one geometrical interpretation to the other, similar to observing a Necker cube. But note that the perceptual switch from Logvinenko's shadow-compatible scene to Bressan's shadow-incompatible one does not seem to have any effect on the perceived shades of the uniform diamonds. They appear equally light and dark in alternate rows, regardless of which of the two perceived 3D scenes they are part of. This is a problem, because one would expect that the presence/absence of shadow-compatibility should be accompanied by a corresponding presence/absence of the illusory lightness effect. Note that Logvinenko (2003) has insisted that this display is shadow-compatible by definition, simply because there exists at least one pattern of illumination that can produce the luminance pattern in question. Nevertheless, it seems that in order to be perceptually effective, it is not enough for a shadow-compatible interpretation to be just a valid theoretical possibility, but that it should also be actually realized in some way in the visual system of the perceiver. We know that it is realized when the observer perceives Fig. 2b accordingly, and in this case the lightness illusion might be accounted for as due to the illumination interpretation. But what happens when the percept switches to the shadow-incompatible variant and how can the unchanging lightness illusion be explained in that case? One might speculate that while consciously perceiving the shadow-incompatible interpretation, the visual system could also at the same time entertain the shadow-compatible one at some unconscious processing level, and use it for conscious lightness assignment in accord with the illumination interpretation approach, but this does not strike me as plausible.

I will now discuss some additional variations of Logvinenko's display (some variants of which were presented in Todorović, 1999) and argue that they also challenge the illumination interpretation account, because the lightness illusion persists unchanged in spite of shadow-incompatibility. Figure 2c was generated from Fig. 2a by simply vertically aligning the diamonds in even rows with those in odd rows. In this way portions of the underlying gradient patches were occluded and others were disoccluded, thus changing their visible shapes from parallelograms to trapezoids. Note that the lightness difference between the diamonds in alternate rows in Fig. 2c remains much the same as in the original Fig. 2a, and that, as in the original, there may exist an impression of a vertically oriented wave of illumination. However, the global geometrical structure of the conveyed scene has changed, and it is not easy to make sense of. Attending to regions around the diamonds conveys partial views of protruding or hollow blocks viewed either from above or below, or some bulging solids with trapezoidal lateral sides, but these impressions are fleeting and unstable because the stimulus geometry does not support them consistently. Therefore the display does not seem to be shadow-compatible, the reason being that, unlike in the previous two displays, there does not appear to exist a coherent 3D spatial structure for the shadow to be compatible with. Nevertheless, the lightness illusion remains steady, apparently oblivious to the inconsistent and fluctuating geometry. Figure 2d is obtained from Fig. 2c by vertically shifting alternate columns, a manipulation which, while maintaining the inconsistent geometry of

Fig. 2c, in addition destroys the sense of coherent illumination as well, and induces a more flat, mosaic-like impression. Nevertheless, the same lightness difference between the target diamonds is retained as in previous displays, again suggesting a dissociation of lightness and conveyed spatial structure in this class of displays.

Figure 2e is a modification of Fig. 2a in which the original diamonds were transformed by caving in and bulging out their sides, making them look somewhat like blades. Note that the lightnesses of the blades are much the same as the lightnesses of the corresponding diamonds in Fig. 2a and in the other preceding figures. However, the 3D spatial interpretation of the represented scene is again different, as the original cubical components of the wall in Fig. 2a have morphed into various curved 3D blocks. Closer inspection reveals that, unlike the blocks in Fig. 2a, many of the curved blocks are geometrically and photometrically ambiguous. For example, consider the block near the top right corner of the display, indicated by the dotted outline, which is replicated at several other places in the figure. Its visible portions include the blade-shaped top and a left side of higher average luminance than the right side. However, its top and bottom portions are incongruent: note that in the bottom part its shape appears to be cylindrically convex, so that its left and right halves seem to have different reflectance, whereas in the top part the shape appears partly convex and partly concave, so that the two halves seem to be illuminated differently. Note also that although much of the time the blocks are perceived as observed from above, thus exposing blade-shaped tops to view, occasionally portions of the display exhibit perceptual inversions, appearing as blocks with blade-shaped bottoms observed from below, generated by 'borrowing' their sides from three neighboring normally oriented blocks; similar effects may also be noted in previous figures. In sum, neither the geometric structure or spatial orientation, nor the nature of illumination, nor the reflectance pattern of the components of the scene appear to be well defined or to remain steady, and yet the lightness illusion involving the blades seems unchanged and fairly constant in prolonged viewing, although one might have expected some fluctuations, were it to depend on the unstable structure of the perceived scene.

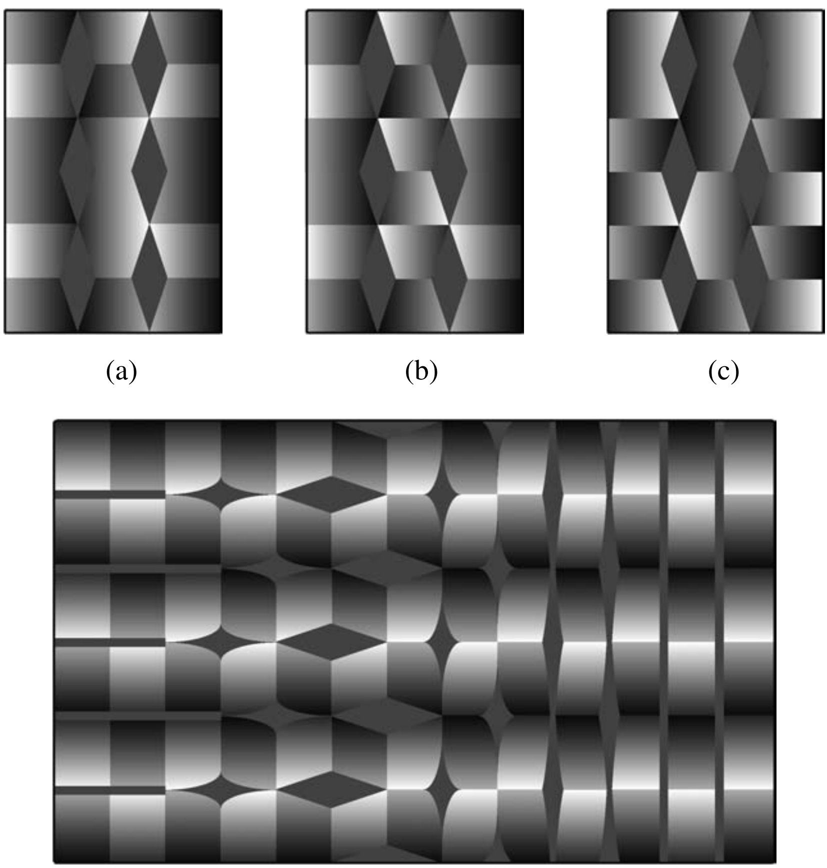
Figure 2f is still another variation of Fig. 2a, in which the diamonds have shrunk into small squares centered at the same locations as the original diamonds, and the underlying gradient patches were transformed by curving their sides. Note that the lightness difference between the alternate rows of squares appears much the same as the difference between the diamonds in other figures. However, the spatial structure of the represented scene is not only rather different from previous displays, but unlike them it is also clear and coherent: the figure dominantly conveys the appearance of three semi-cylindrical convex checkered surfaces, with a set of vertically oriented small squares pasted on or located directly in front of them; there is also an alternative, also coherent spatial interpretation, in which the three surfaces are concave, but it is fleeting and hard to maintain. Note that the lightnesses of the squares are the same in both spatial interpretations. Closer inspection reveals that the conveyed illumination of the dominant interpretation of the scene is rather straightforward: the lightest portions of the semi-cylinders are the ones most in front, and they get darker as they curve back, all of which can be accounted for by assuming a spatially uniform light field illuminating the surface from the front and falling perpendicularly upon the horizontal midlines of the three surfaces; a similar account applies for the alternate spatial interpretation. Given such a pattern of illumination, the increased average luminance corresponding to highlights at the three horizontal midlines (where the darker appearing squares are located), and the reduced average luminance corresponding to the joints of the surfaces (where the lighter appearing squares are located) are not due to the variation of the intensity of the light source, as in Fig. 2a, but due to the curvature of the surfaces. The important point to note is that given that the illumination is uniform and that all the small squares appear to have the same spatial pose, it follows that all of the squares in all rows receive the *same* amount of illumination from the light source. This is in contrast to the diamonds in Fig. 2a, in which alternate rows were interpreted as receiving *different* amounts of illumination. The upshot of this analysis is that the lightness differences between the squares in this figure, in either of the two spatial interpretations, cannot be accounted for in the same way as the lightness differences between diamonds in Fig. 2a, that is, that the dark ones appear well illuminated, and the light ones poorly illuminated.

In sum, the displays in Fig. 2 suggest a dissociation of shadow-compatibility and lightness. Although the lightness illusion is present in shadow-compatible displays in accord with the illumination interpretation account (Fig. 2a and one interpretation of Fig. 2b), it is retained in a shadow-incompatible display (Fig. 2b in the other interpretation), in spatially ambiguous displays which are also shadow-incompatible (Figs 2c, d, e), as well as in a display which *is* shadow-compatible and non-ambiguous (Fig. 2f), but in which the illusion cannot be explained through illumination interpretation mechanisms. The implication is that shadow-compatibility as such does not appear to be a relevant determining factor of lightness perception in this class of displays.

How then can the lightness effects in these figures be accounted for? The structure of the luminance relations of the target patches and their immediate surrounds in Fig. 2a was pointed out by Logvinenko (1999) and Bressan (2001). Each diamond patch is bordered by two dark and two light gradient patches, such that the lighter appearing diamonds in even rows are flanked at all four sides by the *darker* ends of the gradient patches (black ends of the dark gradient patches and dark gray ends of the light gradient patches), whereas the equiluminant darker appearing diamonds in odd rows are flanked at all four sides by the *lighter* ends of the gradient patches (white and light gray ends). Note that this is another variant of a surround contrast constellation, which characterizes both the classical simultaneous contrast display and the target patches in Figs 1a and 1b. This local feature is shared by all target patches in all six displays in Fig. 2, despite their differences in other respects.

If the presence of the lightness illusion in Fig. 2 displays depends on the existence of the surround contrast constellation, then manipulations of this feature should affect the strength of the illusion. This is indeed the case. For example, Bressan (2003b) has noted that a wall of block display constructed by Logvinenko (2003), which involves a much smaller lightness difference between two sets of diamonds than in Fig. 2a (an effect which Logvinenko attributed to shadow-incompatibility), may instead be related to the fact that in this figure one set of diamonds is flanked at only three sides by lighter gradient ends and by the darker gradient end at the remaining side, and *vice versa* for the other diamond set. In other words, weakening of the surround contrast is associated with a weakening of the lightness difference.

This type of manipulation of the surround contrast is illustrated here in three displays in Fig. 3, which develop further the observations by Bressan (2003a), presented in her Fig. B. All three displays consist of two columns of diamond-shaped uniform patches, superimposed upon three columns of gradient patches, with horizontally oriented luminance gradients. The three diamonds in the left column of Fig. 3a are all flanked at all four sides by darker (two black and two



(a) (b) (c)

(d)

Figure 3. Further variations of displays from Fig. 2. See text for details.

dark gray) gradient ends, in three different spatial arrangements, whereas the three diamonds in the right column are all flanked by four lighter (two white and two light gray) ends, also in three different spatial arrangements. Note that in this figure there is a strong lightness difference between the two diamond columns, similar to the corresponding difference in displays in Fig. 2. Figure 3b was obtained from Fig. 3a by flipping the direction of three out of six gradients in the middle column of gradient patches. Therefore, each of the three diamonds in the left diamond column is now flanked at only three sides by darker (two black and one dark gray) gradient ends and at one side by a lighter (white) end, in various spatial arrangements, whereas the three diamonds in the right column are flanked at three sides by lighter (two light gray and one white) ends and at one side by a darker (dark gray) end, also in different arrangements. Thus here the surround contrast constellations for the diamonds are mixed, whereas in Fig. 3a the contrast has consistent direction at all four sides. In consequence, the difference in the appearance of the diamonds is appreciably smaller than in Fig. 3a, although the diamonds in the left column still look somewhat lighter than those in the right column. Finally, in Fig. 3c the diamonds in the left column are flanked by two white and two black gradient ends, in different arrangements, and the diamonds in the right column are flanked by two dark gray and two light gray ends. The differences between their lightnesses are negligible, in accordance with the fact that all diamonds involve opposed surround contrast constellations.

Figure 3d is constructed in the same general manner as the displays in Fig. 2, and consists of a bottom layer involving a chessboard-like arrangement of gradient patches, over which a top layer involving several types of uniform patches is superimposed. The figure contains a portion of the original Logvinenko wall-of-blocks display with uniform diamond tops, located slightly to the left from the central vertical axis; the rest of the figure demonstrates the consequences of certain geometrical transformations of the diamonds, directed towards the two ends of the figure. Thus in the direction towards the right end of the figure the diamonds are transformed into physically uniform vertical stripes, whereas towards the left end they are transformed into physically uniform horizontal stripes. Note how the 3D relief in the left-center of the figure gives way to different flat mosaic-like impressions towards the left and right end. In the left half of the figure the patches in different rows are kept segregated from each other, whereas proceeding towards the right end the patches get increasingly closer, then touch, and finally fuse into vertical stripes. This geometrical difference is accompanied by different lightness effects. In the left half, the patches exhibit discretely different uniform lightness levels, whereas in the right half there appears a non-uniformity in the perceived color of the patches, as they keep crossing increasingly more surround luminance levels, culminating in the wavelike variation of lightness in the vertical stripes.

The described manipulations serve to relate the wall of blocks illusion to some other lightness effects reported in the literature. The strong lightness illusion in the equiluminant horizontal stripes in the left end is reminiscent of another display by Logvinenko (1999, his Fig. 8a), as well as a figure studied by Agostini and Galmonte (2002), although they all used a single type of inducing gradients, whereas the present effect uses two types (dark and light), and a somewhat different geometric constellation. On the other hand, the appearance of induced illusory gratings in the uniform vertical stripes at the right end is closely related to the grating induction effect of McCourt (1982), except, again, for differences in grating types and geometric configurations.

How can the lightness effects in Fig. 3d be accounted for? Three possibilities may be considered. One approach is to regard them as versions of the grating induction effect and classical simultaneous contrast, basically involving variants of surround contrast constellations. The apparently somewhat weaker lightness illusion in the vertical than in the horizontal stripes may be due to the smaller area of contact of the vertical stripes with extreme luminance levels of the gradients. Another approach is to explain all effects on the basis of shadow-compatibility. One problem for this approach is how to plausibly account for the appearance of illusory gratings in the physically uniform vertical stripes. Finally, both principles of explanation may together be applied to the figure, with shadow compatibility, say, dominating in the left portion and grating induction in the right portion. However, it seems to me that a uniform principle of explanation of all lightness effects in this figure is preferable, especially as it was deliberately constructed with the aim of showing how effects otherwise considered as diverse may in fact be regarded as variations on basically the same theme, involving interactions of gradients with uniform patches.

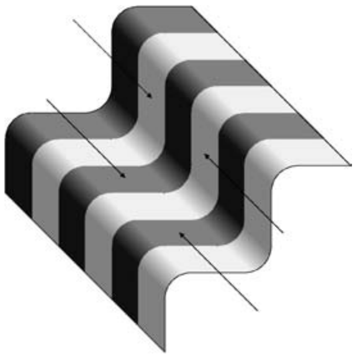
THE CURVED STAIRCASE AND ITS VARIATIONS

Figure 4a is based on a remarkable display published by Purves and Lotto (2003, their Fig. 3.9), but uses a slightly different geometrical layout. The depicted object looks like a smoothly curved striped staircase. The dominant appearance is as if it is viewed from above, but the surface may also perceptually invert and appear as if viewed from below; in the first spatial interpretation the illumination also appears as coming from above, and in the alternative interpretation as coming from below. Figure 4b is my variation that has the same structure, except that it is checkered rather than striped. Both staircases have two vertical planar portions and two horizontal ones (‘steps’) and three rounded portions (‘knees’); in the dominant spatial interpretation, the two outer knees appear convex and the middle, inner knee appears concave, but the directions of curvature are reversed in the alternative percept. The effect of interest here is that the four target regions indicated by arrows have the same uniform luminance, but the two located on the horizontal steps look darker than the two located on the vertical steps.

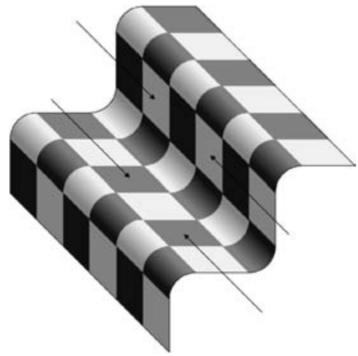
The luminance distributions in the two displays are clarified in Figs 4g to 4i. As depicted in Fig. 4g, the surfaces can be described through a curved grid, with six zigzagging columns, numbered 1 to 6, and seven rows, denoted by A to G. The luminance distributions along odd-numbered columns are mutually identical, as are the luminance distributions along even-numbered columns. Thick lines are depicted along two columns — a dashed one along column 2 as a representative of even numbered columns, and a full line along column 5 as a representative of odd numbered columns. The luminance distributions along these lines are schematically represented in Fig. 4h (for Fig. 4a), and in Fig. 4i (for Fig. 4b). The seven dashed line segments in the graph in Fig. 4h depict the luminance distribution along column 2 as the dashed line passes across seven rows (A to G), whereas the full line segments correspond in the same way to column 5. It can be seen that luminance along the steps (rows A, C, E, G) is uniform, involving three levels denoted as low, mid, and high, and that it is monotonic along the knees (rows: B — bottom outer knee, D — inner knee, F — top outer knee), which exhibit luminance gradients between the uniform levels. The two equiluminant, medium luminance patches at positions E2 and C5 in the grid are indicated by arrows in the graph in Fig. 4h. Turning to the graph in Fig. 4i, it can be seen that it is the same as in Fig. 4h, except that the full and dashed monotonic segments are switched. In other words, Fig. 4b was produced from Fig. 4a by interchanging the ‘dark knees’ (involving the gradient from low to medium luminance) and the ‘light knees’ (gradient from medium to high luminance) throughout the display, with the uniform patches forming the steps retaining their luminance levels.

Note that both the striped and the checkered staircase are shadow-compatible, as they evoke clear and consistent impressions of objects having a particular 3D geometry, painted with a particular achromatic texture, and exposed to uniform illumination (coming from above or below, depending on the spatial interpretation). Attending to the structure of the lighting, it is readily apparent that the horizontal steps receive a high level of illumination, that the vertical steps receive a lesser amount (consistent with subtending a sharper angle with respect to the direction of illumination), and that the luminance gradients across the knees correspond reasonably to the gradual change of surface orientation between the horizontal and the vertical steps. Of course, photographs of similar real surfaces under real illumination would likely have luminance structures of higher complexity, involving more complicated gradients, inter-reflections between surfaces, highlights, irregularities, etc. Note also that Fig. 4b is related to Fig. 1a, in that both involve checkered patterns which contain equiluminant regions that appear to receive different amounts of illumination; the difference is that in Fig. 1a this impression is due to conveyed variation of incoming illumination (shadow), whereas in Fig. 4b the impression is due to conveyed 3D surface curvature.

Purves and associates have developed a theoretical framework in which lightness percepts are based on the relative frequency of occurrence of all possible sources of the stimuli witnessed in the past (for detailed accounts of theory and data see Purves and Lotto, 2003; Purves *et al.*, 2004; Williams *et al.*, 1998a, b). Within this framework, the explanation of the lightness effect in the Purves and Lotto (2003) figure, referred to above, of which of Fig. 4a is a close variant, can essentially be based on the same idea as the illumination interpretation accounts of effects in



(a)



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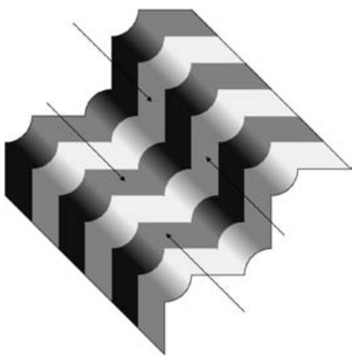

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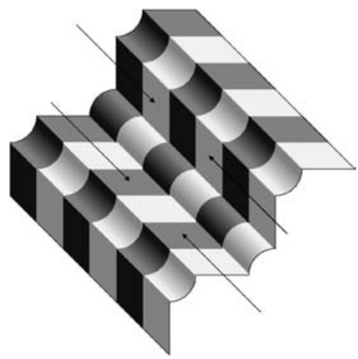

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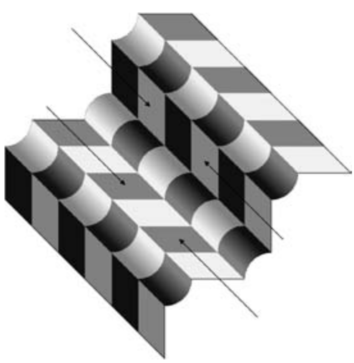

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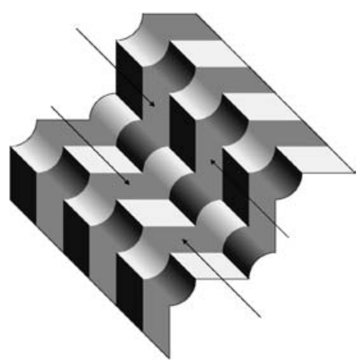
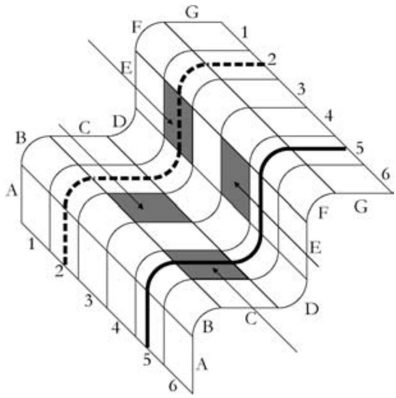
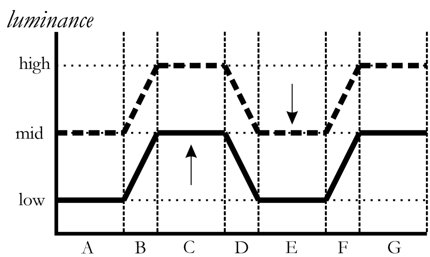


(f)

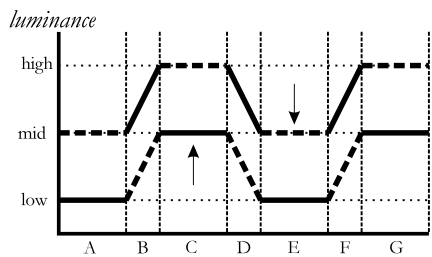
Figure 4. Lightness and depicted 3D shape. The target patches, pointed at by arrows, all have the same luminance, but patches in the horizontal plane look darker than the patches in the vertical plane. In (a) and (b) this difference may be accounted for by the presence of shading on a curved body illuminated by a homogeneous light source, but in (c), (d), (e), and (f) this explanation is less likely. Display (g) is a spatial scheme of figures (a) and (b), used for subsequent graphs that represent the luminance distributions of the previous displays, along two indicated lines. Display (h) is the graph of the luminance distribution of (a) and (c), display (i) is the graph for (b) and (e), display (j) is the graph for (d), and display (k) is the graph for (f). See text for details.



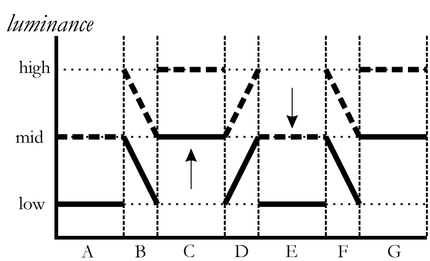
(g)



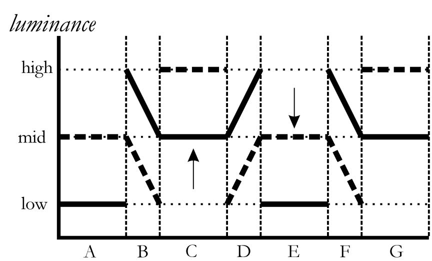
(h)



(i)



(j)



(k)

Figure 4. (Continued).

Figs 1a and 2a: the lightness difference between the targets can be explained by supposing that observers interpret the horizontal targets as well illuminated dark regions, and the vertical targets as poorly illuminated light regions. The same explanation can be applied to my version, Fig. 4b.

I will now present some simple geometric and photometric transformations of these two displays that convey objects with less straightforward shape and illumination, and challenge the illumination interpretation account of the lightness effects. These transformations apply only to the knees of the figures, and leave the steps unchanged. Figure 4c was generated from Fig. 4a by a geometric change, involving flipping the curvature of the contours of all knees. In Fig. 4d a photometric change was added, involving flipping the directions of the luminance gradient across the knees as well. Figures 4e and 4f were generated in analogous manner from Fig. 4b. The luminance distributions of Figs 4c and 4e are the same as for Figs 4a and 4b, respectively. The luminance distribution for Fig. 4d is presented in the graph in Fig. 4j, and was obtained from Fig. 4h by flipping the orientation of all monotonic segments of the graphs. The luminance distribution for Fig. 4f is presented in the graph in Fig. 4k, and was obtained from Fig. 4i in the same way, by flipping all monotonic segments.

In the following I will analyze the structure of displays 4c to 4f and relate it to the appearance of the target patches. Consider Fig. 4d first. It represents a different geometric object than Fig. 4a, because the formerly convex knees appear concave, and *vice versa* (although persistent observers may fleetingly re-invert them). The transitions between the steps and knees, which are geometrically and photometrically smooth in Fig. 4a, are abrupt in Fig. 4d. Nevertheless, because both the curvatures of the knees and the directions of their luminance gradients were inverted concomitantly, the conveyed object is just as shadow-compatible as the one in Fig. 4a, and can in all details be consistently interpreted as a striped stair-like (or perhaps butterfly-like) structure, with horizontal planar portions being well lit and vertical planar portions being poorly lit. In particular, note how the variation of luminance across all knees fits with this interpretation, in that the conveyed illumination is consistent with the way light falls upon the planar portions: the knees are most illuminated along those portions in which their orientation is most nearly horizontal, and as they curve away from this orientation, they gradually become least illuminated along those portions which are most nearly vertical. However, in spite of the same geo-photometrical logic, it appears that, compared to Fig. 4a, the lightness difference between target regions is somewhat diminished.

Turning now to Fig. 4c, note that flipping the curvatures of the knee contours without also flipping the directions of gradients within the knees (as was done in Fig. 4d) induces a deterioration of cohesion of both the spatial and the illumination structure of the conveyed scene. Due to the change in geometry, the inner knee which in the dominant interpretation appears concave in Fig. 4a, tends to appear convex in Fig. 4c. In consequence, the luminance variation across it, being the same as in Fig. 4a, conveys an illumination change inconsistent with the illumination of the adjoining horizontal and vertical steps (in contrast to Figs 1a and 1d, in which the illumination is consistent across steps and knees). The same conflict, but in reverse, involves the two outer knees. The global shape of the depicted body appears less well defined than in Fig. 4d, because the abrupt change of spatial orientation between planar and curved portions of the surface is not accompanied by correspondingly abrupt changes in luminance. Furthermore, the percept of the depicted object is unstable, in that the outer knees may relatively easily invert and appear convex. Nevertheless, in spite of these geo-photometric inconsistencies, the lightness illusion seems stable and appears much the same as in Fig. 4a. In sum, in comparison to Fig. 4a, Fig. 4c appears less shadow-compatible but exhibits a similar lightness illusion, whereas Fig. 4d appears equally shadow-compatible, but exhibits a diminished illusion.

Consider now Fig. 4e, and note that the lightness difference between the targets appears relatively strong, and much the same as in Fig. 4b. However, the display poses similar interpretational problems as Fig. 4c, presenting them in a perhaps more salient form. In the dominant spatial interpretation, the inner knee appears convex and the outer knees concave, just as in Fig. 4d, but inverted compared to Fig. 4b. However, the luminance variations across the knees are inconsistent with the luminance across the steps: although for the steps the illumination seems to come from above, so that the horizontal steps appear well illuminated and the vertical steps appear more weakly illuminated, for knees the illumination seems to come from left rather than from above, because they appear least illuminated when they are most nearly horizontal and best illuminated when they are most nearly vertical. Furthermore, similar to Fig. 4c, the percept of the depicted object is unstable, in that the outer knees may relatively easily invert and temporarily appear convex, just as the inner knee. When all knees thus appear convex, the spatial structure of the object looks contorted and its parts seem oddly geometrically incongruent with each other, since the outer knees and the inner knee, although parallel in 2D, do not appear parallel in 3D. However, note that these geometrical instabilities do not affect the lightness illusion in the least. In sum, in contrast to Fig. 4b which is shadow-compatible, in that its geometry and photometry are mutually consistent, Fig. 4e is shadow-incompatible, but the lightness illusion in both figures has the same strength.

Finally, consider Fig. 4f. It differs from Fig. 4e only in that the gradient directions across all knees are inverted. This seemingly modest change has caused a surprisingly drastic difference in the global structure of the figure, as well as in the local appearance of the target regions, whose lightness difference has greatly diminished, compared to Fig. 4e. Because the spatial interpretation of this display is somewhat unclear, it does not present a challenge to the illumination interpretation account.

To summarize the preceding discussions, although the illumination interpretation account applies rather naturally to Figs 4a and 4b, which are both shadow-compatible and both show the lightness illusion, it is challenged in the related Figs 4c, 4d, and 4e, because the presence of shadow-compatibility is dissociated from the strength of the illusion. Contrary to the predictions based on shadow-compatibility, according to which the strength of the illusion should be retained in the shadow-compatible Fig. 4d and reduced in the shadow-incompatible Figs 4c and 4e, the illusion in fact persists largely unchanged in the shadow-incompatible displays, but appears somewhat diminished in the shadow-compatible display.

How may the lightness effects in these figures be accounted for? Consider first Figs 4b and 4e. Taken together, they present perhaps the most direct challenge to the illumination interpretation account in this figure set, because they exhibit clear and strong identical lightness effects, although one figure is shadow-compatible and the other is not. Note that in both these figures the lighter appearing targets are surrounded at all four sides by darker patches, whereas the darker appearing targets are surrounded at all four sides by lighter patches. This is another case of a surround contrast constellation. Figure 4e differs from Fig. 4b through the flip of knee curvatures, a manipulation which affects the interpretation of the global spatial structure and illumination of the represented object, but does not change the surround relations of the target patches.

Consider now Figs 4a and 4c. In both of them the vertical, lighter appearing targets are flanked at two longer sides by darker patches, whereas the horizontal, darker appearing targets are flanked at two longer sides by lighter patches. These configurations are *partial* surround contrast constellations, as they involve only two sides of the targets. At the other two sides the targets blend continuously into gradients, the lighter appearing targets into light gradients and the darker appearing targets into dark gradients. One way in which such constellations might contribute to the lightness illusion could be as follows. Suppose that there is a tendency towards increased uniformity of lightness within continuous regions, such as the stripes in Figs 4a and 4c that may contain gradients but no abrupt luminance changes. The neural basis for such a tendency might consist in lateral facillitory interactions, similar to filling-in processes, confined within stimulus regions delineated by luminance steps (see Grossberg and Todorović, 1988; Pessoa and DeWeerd, 2003). Note that the horizontal targets have the highest luminance within dark stripes, and that the vertical targets have the lowest luminance within the light stripes. If such a homogenizing tendency were at work, its effect would be to shift the lightness of all portions within a stripe towards the mean of the stripe, thus decreasing the lightness of the horizontal target patches and increasing the lightness of the vertical target patches. I will label such conditions ‘surround assimilation constellations’. Thus the target patches in these figures exhibit both partial surround contrast and assimilation constellations. These constellations are congruent, in that the vertical targets are expected to lighten and the horizontal targets to darken both through contrast and assimilation of this type. Note that neither of the two postulated contributing factors depends on the curvature of the knees, which means that no difference is predicted between the effects in Figs 4a and 4c, unlike in the illumination interpretation account, which should predict a smaller effect in Fig. 4c, because of shadow-incompatibility.

Consider now Fig. 4d. Note that the vertical targets are bordered at their two longer sides by darker patches and at their two shorter sides by lighter patches, and that opposite relations hold for the horizontal targets. Therefore all targets are adjoined on their short and long sides by regions of oppositely directed contrasts, thus exhibiting incongruent partial surround contrast constellations. In consequence, compared to Figs 4a and 4c, a decrease of the lightness difference between the targets is expected, its exact amount depending on the relative strength of the two opposing tendencies.

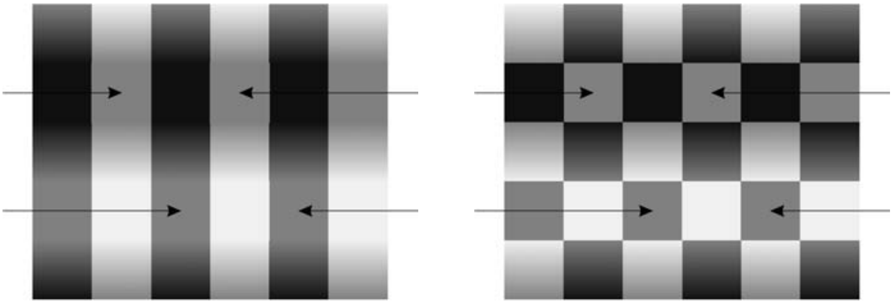
Finally, consider Fig. 4f. Note that, as in Figs 4a and 4c, the surround constellation of the targets involves both contrast and assimilation. However, here these two factors are incongruent, in that the horizontal targets should be darkened by contrast but lightened by assimilation, and *vice versa* for the vertical targets. Therefore the prediction is that the difference in appearance of the vertical and horizontal targets should be small, as is indeed the case.

Figures 5a to 5d are geometrical variants of Figs 4a and 4b, using rectangular (5a, 5b) and circular (5c, 5d) arrangements of similar basic elements, both in striped and in checkered versions. As in Figs 4a and 4b, the equiluminant target regions, indicated by arrows, look different, though the effect appears weaker for Fig. 5a. Compared to Figs 4a and 4b, the shapes and local relations between individual patches are changed only modestly, but the global constellations are rather different, and Figs 5a to 5d look much flatter. However, there may still exist impressions of surface undulation, coupled with impressions of some linear or circular variations of surface illumination. Therefore one might still argue for an illumination interpretation account of the lightness effects, involving light but poorly lit and dark but well lit targets.

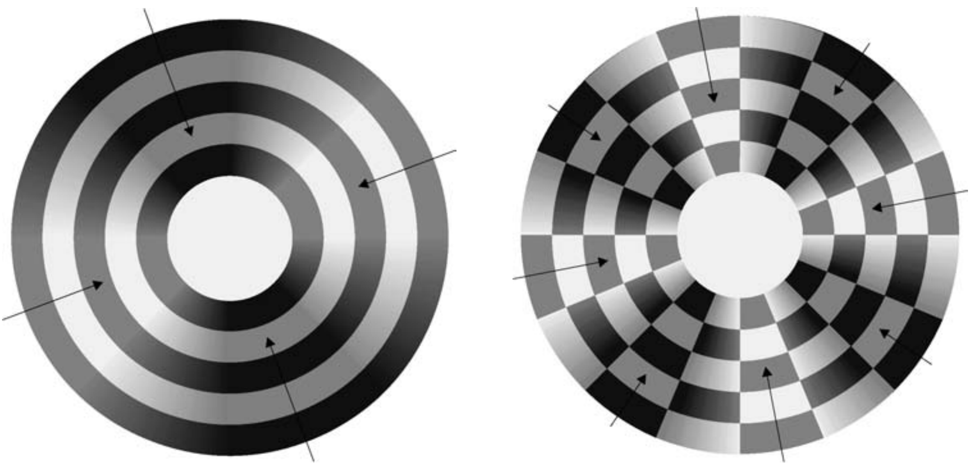
I will challenge the illumination interpretation account for these figures in a different way than in Fig. 4, by using stereoscopic presentations. Figures 5e and 5f provide stereoscopic versions of Figs 5b and 5c. In Fig. 5e the two rows containing the target patches are shifted laterally and occupy a different stereoscopic depth plane than the rest of the figure. As the reader may confirm using free fusion, the lightness effect remains much the same as in non-stereoscopic observation, although the impression of illumination upon a common plane is disrupted, a fact which should disrupt the illumination interpretation. In Fig. 5f, some of the rings are shifted laterally, generating a radically changed geometrical structure of the represented scene, as observed stereoscopically. As the reader may confirm, stereoscopic views provide impressions of upright coaxial cylinders or truncated cones viewed from above, resting on a plane disk, with the cylinders/cones looking light and the disk dark, or *vice versa*. However, the lightness difference between the target regions appears much the same as in the non-stereoscopic view, although it is hard to think of a plausible way to account for it, in the stereoscopically conveyed scene, in terms of some interaction of illumination and geometry.

INTERIM DISCUSSION

To summarize briefly the preceding displays and arguments: I have presented a number of close replicas or slight variations of three influential displays — Adelson's checkered shadow (Fig. 1a), Logvinenko's gradient wall of blocks (Fig. 2a), and Purves and Lotto's smooth staircase (Fig. 4a) — and have also contributed a few designs of my own (Figs 4b, and 5b to 5d), which all involve strong lightness illusions for which plausible illumination interpretation explanations can be proposed.



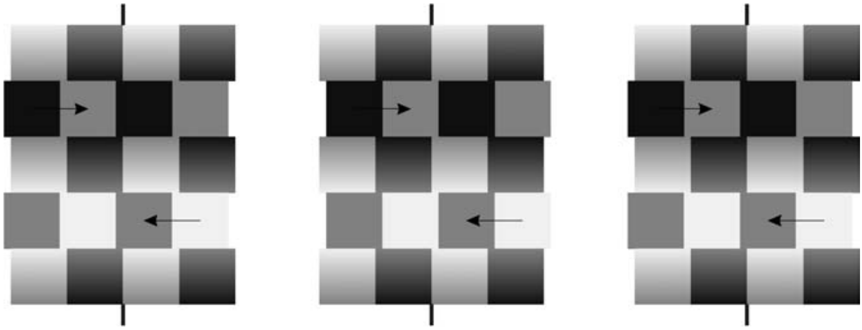
(a) (b)



(c) (d)

Figure 5. Displays (a) and (c) are geometrical variants of display 4(a), and displays (b) and (d) are geometrical variants of display 4(b). The target patches, pointed at by arrows, all have the same luminance, but look different. Displays (e) and (f) are stereoscopic variants of displays (b) and (c), in which the perceived geometry is different than in non-stereoscopic displays but the lightness effect is retained. See text for details.

I have also mustered a host of carefully constructed ‘counter-illusions’, that is, control variants of these images whose purpose was to challenge such explanations in various ways. I believe that the presented evidence, although it certainly would need to be backed by experiments, argues against the possibility that this class of illusions could be accounted for solely based on the notion of illumination interpretation, at least in the way that I have interpreted this notion. However, this conclusion does not mean that the general relevance of illumination in the perception of lightness is brought into doubt. It is well established that appreciation of illumination is a decisive factor for lightness determination in 3D scenes involving real depth and real light sources (Kardos, 1934; Gilchrist, 1977, 1988; Gilchrist *et al*., 1999). The topic under consideration here is not the overall role of illumination but rather whether processes activated in real scenes contribute to lightness determination in pictorial



(e)

(f)

Figure 5. (Continued).

displays such as those presented in this paper, which are flat and uniformly illuminated, but convey depth and variable illumination through static pictorial cues. Note that a robust cue for illumination variation in real scenes, in contrast to pictorial displays, is the fact that the value of the ratio of maximum to minimum luminance may far exceed the value found in images, which may rise only up to about 30 : 1.

One might argue that whereas illumination interpretation may not be the sole cause of these lightness illusions, it still may be one of its determinants, among other contributing factors. The idea is that while one may accept that factors like the surround contrast constellation may affect lightness, still illumination interpretation would add something over and above other causes of appearance of image patches. While this remains a general possibility, according to the arguments I have presented even this more modest proposal is brought into doubt for the displays analyzed here. Note that I have discussed a number of cases in which the illusion in the original display appears to be plausibly accounted for through illumination interpretation, but where in the modified, control display this interpretation is challenged, although the illusion itself remains unaffected. I would argue that in such a case, given that both the structural aspects of the display as well as the illumination cues are well controlled, it is not only that the illusion in the modified display cannot be accounted for as being caused by illumination interpretation; in addition, its presence in the original display cannot have been, even in part, due to this cause either. This is because, had illumination interpretation played any role there, the reduction of illumination cues in the modified display should have caused a reduction in the illusion strength, but it did not. For an example of analogous reasoning, suppose that it is first established that a mixture of substances X and Y causes drowsiness, but that a subsequent study shows that X alone causes the same amount the drowsiness; then one would not argue that in the first experiment Y might have affected the outcome to some extent, over and above X, but would more parsimoniously conclude that Y had no effect on drowsiness whatsoever.

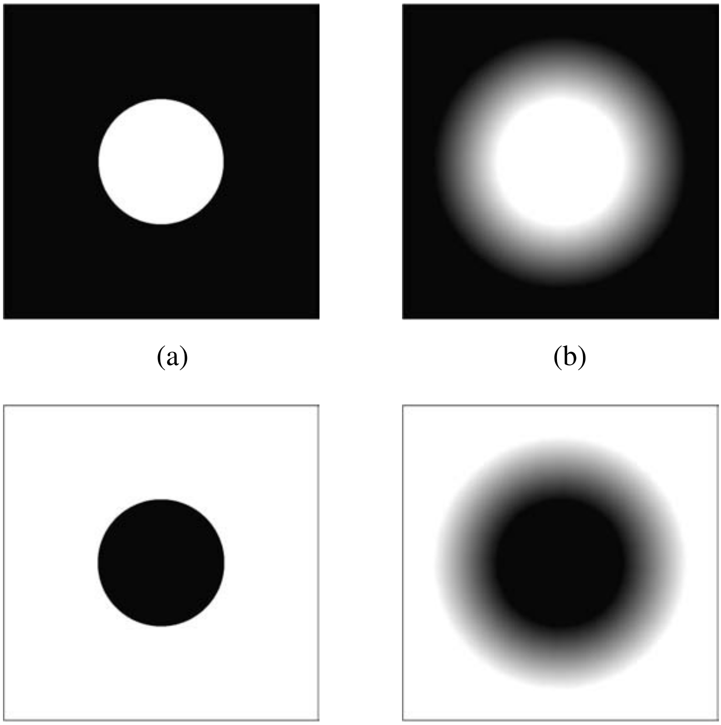
A different line of argument against my criticisms would be to abandon the general notion that illumination interpretation is based on detailed appreciation of ecologically valid, mutually consistent cues for illumination, acquired through prolonged observations of all environmental regularities concerning the interactions of light and surface shapes and their reflectance patterns over the whole visual field. Alternatively, the putative illumination interpretation mechanisms might use only some and not all potentially valid cues, which could be rough rather than optically accurate in detail, and / or provide spatially local rather than globally consistent heuristic indications of illumination. In that case, the manipulation of illumination cues which may be physically appropriate but are not actually used by the visual system would have little perceptual relevance, detailed agreement with optical regularities would not be necessary for such mechanisms to do their job, and they might not be bothered by displays containing shadow-incompatibilities of the sort that I have analyzed here. Thus, as I have argued in more detail in discussing another set of images in Todorović (2003a, b), rather than refuting the illumination interpretation account, the counter-examples that I have marshalled against it might only serve to amend it, pointing out the limitations of the global, all-encompassing variant of illumination interpretation, by suggesting which image features such mechanisms are less likely to respond to.

It is indeed possible that illumination interpretation mechanisms might not be based on elegant, comprehensive, and interconnected statistics but on rough, primitive, and isolated bag-of-tricks type heuristics. However, I see several problems with this explanatory strategy. For example, the visual system is known to otherwise exhibit exquisite sensitivity to some aspects of interactions of luminance and geometry, such as in shape-from-shading interpretation processes, and it seems surprising that it should forsake this sensitivity in the process of lightness assignment. Furthermore, the original simplicity, elegance, and parsimony of the illumination interpretation notion, such as in explaining the effects in Figs 1a, 2a, 4a and 4b, would be compromised by such a move, which would make the theory more flexible but less testable. A premier task for its proponents would be to propose and check which among the many potentially available optical features of illumination might actually be causally effective in lightness perception in flat images, and which might not. It would also be interesting to know why the visual system should use some cues rather than others, instead, say, the other way around, given that all are potentially available. The cues actually used would presumably be those which are most robust and useful, but the question is which ones would those be, and whether they are indeed picked up by the visual system. In the preceding discussions I have argued that a number of plausible illumination cues do not actually affect lightness. It remains to demonstrate which ones do. Furthermore, an additional task would be to show that a putative heuristic illumination cue is in fact based on regularities concerning illumination, and is not just spuriously correlated with such regularities in particular displays, so that it could be disassociated from them in suitable control displays, as I have shown here. If in assessing lightness the visual system is not thought to respond to illumination in a comprehensive manner, but only particular illumination heuristics are deemed effective, whereas other, potentially similarly informative, are not, then one would need additional arguments to back up the claim that the effective ones are actually based on interpreting illumination.

QUALITATIVE EFFECTS OF LUMINANCE GRADIENTS

The preceding displays have, in one way or the other, involved the role of luminance gradients in the determination of lightness of uniform regions. In the following I will present replicas, variants, as well as some new designs which demonstrate that gradients may affect not only the lightness but also the mode or quality of appearance of uniform regions (Beck, 1972). Basic effects of this type were reported by Evans (1959), Fry (1931), Kanizsa (1980), MacLeod (1947), and Zavagno (1999). Here the phenomenon will be demonstrated by comparing similar displays with and without gradients, as in Fig. 6. Figure 6a presents a white disk on black ground with a sharp, step-shaped luminance border. Figure 6b presents the same disk, but surrounded by a ramp-shaped luminance ring, in the form of a luminance gradient between the white figure and the dark background; faint Mach rings bordering the ramp region may be noted. Approximate luminance profiles of the two displays are presented in Fig. 12 as stimuli labeled Inc1 and Inc2. Analogous images involving luminance inverses of these figures are presented in Figs 6c and 6d.

The phenomenon of interest here is that disks of identical luminance appear qualitatively somewhat different, depending on whether they are delimited by a sharp border or a gradient. However, it is not straightforward to express this difference verbally. To contrast their appearances, describing the interior surfaces of the step-bordered disks (Figs 6a and 6c) one might use terms like *clear* or *opaque* (and perhaps also *hard*, *cold*, *compact*, *smooth*, and *planar*), whereas the interior surfaces of the ramp-bordered disks (Figs 6b and 6d) may be said to look more *hazy* or *fuzzy* (and perhaps also, in contrast to Figs 6a and 6c, as *softer, warmer, diffuse, wooly*, and *ruffled*). In the following I will mainly refer to this effect as the 'clear *vs.* hazy' distinction. Furthermore, in the white ramp-bordered disk there is also some sense of *translucency* and *luminosity* or *glow*, whereas in the dark ramp-bordered disk the corresponding quality is hard to label. There also appears to be a lightness difference between the equiluminant step-bordered and ramp-bordered disks, but because of the qualitative differences in their appearance, its direction is somewhat



(a) (b)

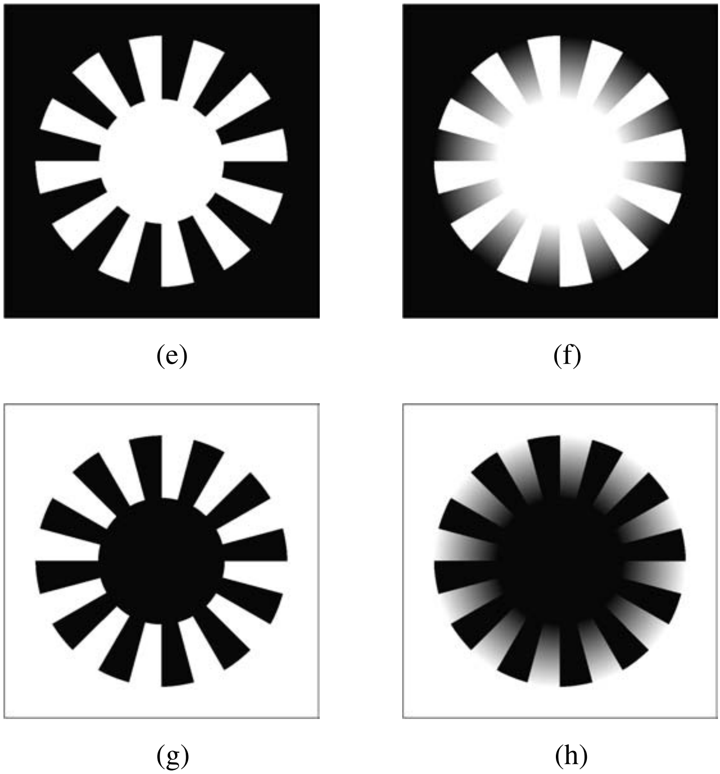
(c) (d)

Figure 6. Effects of luminance gradients on qualitative appearance, part I. Sharp-bordered patches with full (a, c) or partial (e, g) borders look qualitatively different than corresponding ramp-bordered patches with full (b, d) or partial (f, h) borders. See text for details.

hard to pin down unambiguously. However, MacLeod (1947), who used gray disks, found that ramp-bordered disks on white background looked lighter and on black background looked darker than corresponding gray step-bordered disks. This is in accord with the homogenizing tendency, postulated in analyses in previous sections. I will now draw connections between these and several other effects, some related to ones reported before and some new.

Figures 6e and 6g present modifications of Figs 6a and 6c, involving the introduction of trapezoidal stripes oriented perpendicular to the disks, which have the same luminance as the disks, that is, they are white in Fig. 6e and black in Fig. 6g. The disks are now physically defined only along 50% of their perimeters, but perceptually one still has a relatively clear impression of their presence, although half of their contour is virtual. This is a variant of the well-known Ehrenstein illusion (Ehrenstein, 1941; Spillmann *et al.*, 1976). Identical uniform trapezoidal stripes are also introduced in Figs 6b and 6d to form Figs 6f and 6h, respectively, making the corresponding disks semi-virtual as well.

The effect to be noted here is that the difference in appearance between step-bordered and ramp-bordered semi-virtual disks is rather similar to the difference



(e) (f) (g) (h)

Figure 6. (Continued).

between corresponding real disks, in that the clear *vs.* hazy distinction again applies, and the white disk again looks luminous. The effects present in Figs 6f and 6h are versions of phenomena originally reported in several variations by Zavagno (1999), and are related to a phenomenon described earlier by Kennedy (1976). The juxtaposition of Figs 6f and 6h with Figs 6b and 6d serves to point out the close similarity between these effects, suggesting similar mechanisms behind them. Note also how the virtual contours of the disks in Figs 6e and 6g are replaced by some dust-like impressions within the physically uniform trapezoidal stripes in Figs 6f and 6h. One may speculate that both the sharp virtual contours and the spread-out virtual dust are based on the same neural mechanisms, triggered in the first case by the real sharp luminance edges and in the second by the real luminance gradients.

Another format for demonstrating the effects of gradients on qualitative appearance, as well as for linking them to effects on lightness, is used in Fig. 7. It contains three sets of figures, each composed of three displays. Each display consists of five columns of three non-uniform oval disks; columns 1, 3, and 5 are identical, and columns 2 and 4 are their mirror images. The effects of interest in all displays do not concern the disks themselves but the uniform backgrounds surrounding them, in the four interspaces between the five columns, numbered 1 to 4 and pointed at

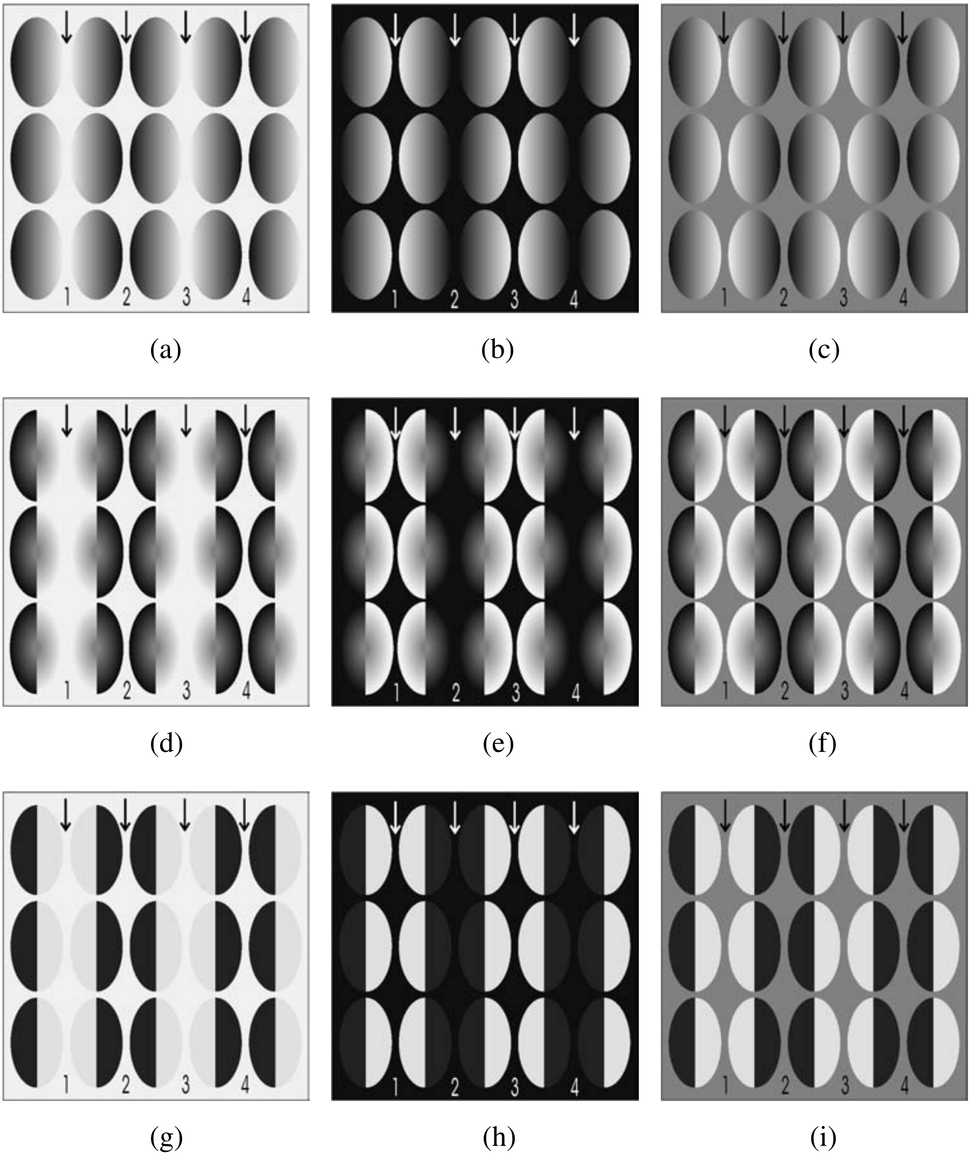


Figure 7. Effects of luminance gradients on qualitative appearance, part II. Three types of inducing elements are placed on white, black, and gray backgrounds. The clear versus hazy contrast is strong on white backgrounds and somewhat weaker on black backgrounds, but it disappears on gray backgrounds, which only involve lightness effects. See text for details.

by arrows. Note that some of the effects may appear more salient if viewed on the computer screen.

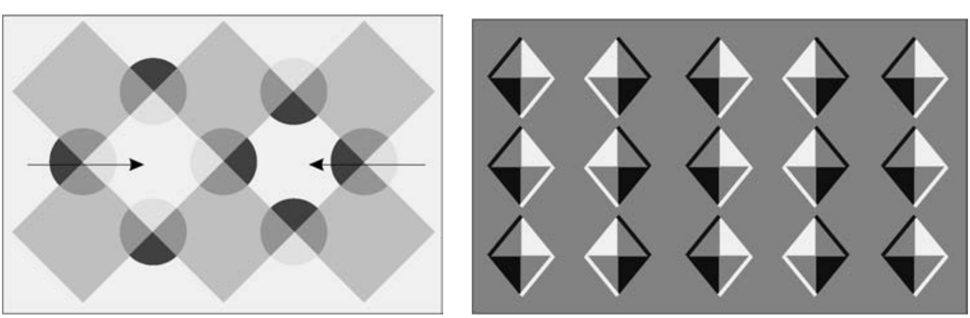
The disks in the first set of displays, Figs 7a, 7b, and 7c, contain horizontal luminance gradients spanning the range from black to white; the directions of the gradients alternate between neighboring columns of ovals, being (from left to right) dark to light in the first column, light to dark in the second, etc. The disks and their arrangement in all three figures are identical, and only the shade of the background varies, being white in Fig. 7a, black in Fig. 7b, and gray in Fig. 7c. The difference in the appearance of disks, which is not of immediate concern in this section, is likely due to surround contrast constellations. What is of interest is that although all backgrounds have uniform luminance they do not appear uniform, and this non-uniformity is different in different figures. In particular, note that in Fig. 7a, where the background is white, impressions of whitish haze as well as glow appear within the odd-numbered interspaces, at places where the white ends of the disk gradients blend into the uniform white background, whereas within the even-numbered interspaces the background looks clear. In Fig. 7b, which contains identical ovals, but on black background, the locations of appearance of hazy and clear portions are switched, compared to Fig. 7a: blackish haze appears within the even-numbered interspaces, at places where the black gradient ends blend into the black background, whereas the background looks clear within the odd-numbered interspaces; however, the appearance of haze may be less salient than in Fig. 7a. In Fig. 7c the background has intermediate luminance and the gradient ends do not blend into it. In consequence, the clear *vs.* hazy difference has vanished, giving way to a lightness difference, such that the background within the odd-numbered interspaces looks darker than the background within the even-numbered interspaces. Note that this is still another variant of a surround contrast constellation, in that the background regions bordering the lighter gradient ends appear darker than those bordering the darker gradient ends. Thus the lightness effects in Fig. 7c are related to the corresponding effects in several previous figures involving surround contrast constellations.

The second set of displays, Figs 7d, 7e, and 7f, is similarly structured, but involves ovals with luminance gradients directed radially instead of horizontally, starting out as middle gray in the center and proceeding towards black in one half of the oval and towards white in the other half. This feature enables the disks to blend into the background along half of their perimeter, rather than only at one point, as in Figs 7a and 7b. As in the first set of figures, all three displays contain identical ovals and only the background is different, being white in Fig. 7d, black in Fig. 7e, and gray in Fig. 7f (in which the structure of the ovals may be appreciated most easily, since they do not blend into the background at either end). The induced haze effects in the backgrounds in Figs 7d and 7e appear at the same locations as in Figs 7a and 7b, but are uniform throughout and rather strong, although haze may appear more saliently on the white background. Furthermore, in both Figs 7d and 7e the impression of haze is accompanied by impressions of transparency, in the form of translucent vertical stripes. In contrast, on the intermediate luminance background (Fig. 7f) both the haze and the transparency have disappeared, and are replaced by a lightness illusion involving the interspaces, which has a similar structure as the effect in Fig. 7c, and is associated with a similar type of surround contrast constellation.

The luminance gradients in all preceding figures were relatively smooth, involving dozens of gray levels. The question arises whether similar effects can be produced by coarser gradients. I will only present one case of the coarsest possible ‘gradient’, which is a simple luminance step involving only two gray levels. Figures 7g, 7h and 7i use bi-colored ovals involving luminance steps whose direction corresponds to the global direction of luminance change of the gradients in preceding sets of figures, being dark to light in the first column of ovals, light to dark in the second, etc. The ovals are identical in all three figures, but the background is white in Fig. 7g, black in Fig. 7h, and gray in Fig. 7i. The effects of interest here are as follows. In Fig. 7g uniform whitish haze as well as impressions of transparency appear, located in the same interspaces as the corresponding effects in Figs 7a and 7d; however, the impression of glow is absent. Similar, though less salient effects, may be noticed by inspecting Fig. 7h and comparing it with Figs 7b and 7e. Finally, in Fig. 7i, both haze and transparency are gone, and are replaced by a lightness illusion involving a surround contrast constellation, similar as in Figs 7c and 7f. The appearance of perceived transparency in Figs 7d, 7e, 7g and 7h is consistent with the classical Metelli rules, in that the luminance contrasts within the transparent portions are smaller than outside of them; however, transparency cannot be directly deduced from the rules because there are no X-junctions in the displays.

In sum, the displays in Fig. 7 demonstrate that luminance gradients may induce qualitative differences in the appearance of uniform regions, such as haze and transparency, if they blend into them (Figs 7a, 7b, 7d, 7e), in which case glow also appears, or show low edge contrast (Figs 7g, 7h), in which case there is no glow, but not when the contrast is high (Figs 7c, 7f, 7i), in which case they may instead induce lightness differences, depending on surround contrast constellations.

For comparison, note that very similar impressions of haze and transparency can be observed in Fig. 8a, which is a replica of a display devised by Adelson (2000, Fig. 24.17), who linked the appearance of these effects to the presence of particular X-junctions. However, such junctions are absent in Fig. 7g, which indicates that they are not strictly needed to generate impressions of transparency and haze in



(a) (b)

Figure 8. Two figures by Adelson (1993, 2000), used for comparisons with Figs 7g and 7i. See text for details.

this type of displays, and that simple luminance steps may suffice, combined with decreased figure-ground edge contrasts. It is also interesting to compare the displays involving backgrounds of intermediate luminance to Fig. 8b, which is based on another display by Adelson (1993, Fig. 4c). It contains a set of relatively complex figures, arranged in five columns of three elements each, similar as for the displays in Fig. 7. The background has uniform luminance, but involves a similar lightness illusion within interspaces as in Figs 7c, 7f, and 7i. Adelson (whose original figure shows a somewhat stronger lightness difference, probably because the elements touch vertically) has explained this effect by invoking a variant of the illumination interpretation account, linking it to the impression of transparency in his display. However, a closer analysis of Fig. 8b reveals that it, like Figs 7c, 7f, and 7i, involves a surround contrast constellation (albeit of a somewhat more intricate variety), in that the darker appearing portions of the background are bordered by lighter halves of the figural elements, and *vice versa*.

Figure 9 presents another set of figures demonstrating the qualitative effects of gradients. Consider first Fig. 9a, a display that roughly resembles a window consisting of a wooden frame and three vertical window panes; the frame contains uniform regions, which look planar, and gradients, which convey 3D relief. The uniform regions in the display have the same luminance, but the frame region, which blends into the gradients, looks hazy, whereas the three panes look clear. A similar difference can be noted between the corresponding regions in Fig. 9b, which is the luminance inverse of Fig. 9a. Furthermore, in these displays the lightness difference between the equiluminant hazy (frame) and clear (panes) portions appears more salient than in previous displays, in that the clear white portions look lighter than the hazy white portions (Fig. 9a), whereas the clear black portions look darker than the hazy black portions (Fig. 9b); this is probably due to surround contrast constellations involving the panes. The luminance profiles and the lightness effects in these figures are related to some variants of the Craik-O'Brien-Cornsweet effect (see Todorović, 1987).

Figures 9c and 9d are versions of Figs 9a and 9b that use a very coarse luminance gradient involving only two levels (light gray — dark gray). Note that in these coarse-gradient displays similar differences between the frame and the panes obtain as in the fine-gradient displays, though both the lightness difference and the haze effect appear somewhat reduced. These displays suggest a relation of the presented phenomena to the watercolor effect (Pinna *et al.*, 2001). Figure 9e presents an originally chromatic example of this effect, which was converted to gray scale, and Fig. 9f presents the corresponding luminance inverse. The achromatization has decreased the strength of the original chromatic effect, but a difference between 'frame' and 'panes' regions may still be noticed, especially if viewed on the computer screen. A close inspection of these figures reveals their geometrical and photometrical similarities to Figs 9c and 9d, including the presence and direction of the coarse gradients. The structural similarities between the displays and the phenomenal similarities of the effects presented in Fig. 9 suggest that they may all

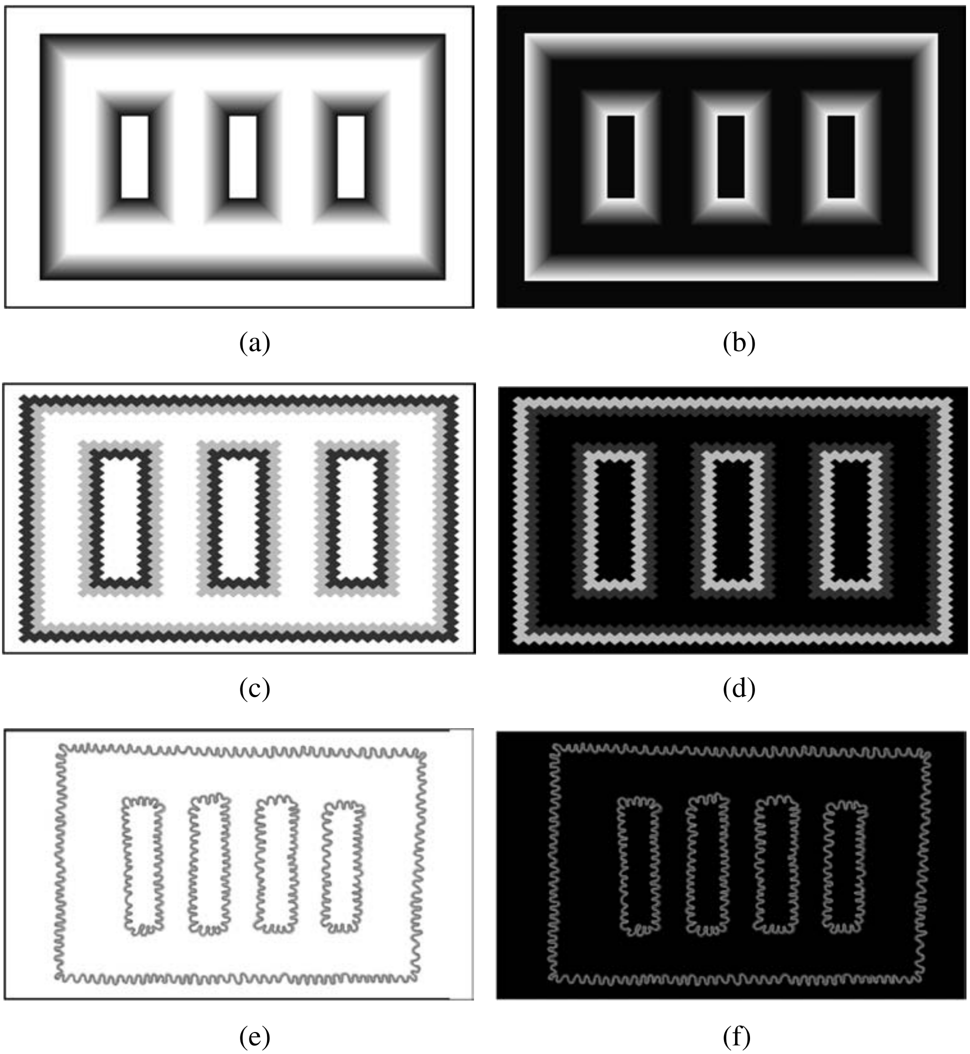


Figure 9. Effects of luminance gradients on qualitative appearance, part III. The haze effect seems strongest for broad and fine gradients (a, b), weaker for broad and coarse gradients (c, d), and weaker still for narrow and coarse gradients (e, f). See text for details.

be caused by common mechanisms based on gradients, either fine-grained or coarse, bordering uniform regions and displaying different luminance contrasts with them.

Figure 10 contains the final set of displays in this section, serving to summarize similarities and differences between many preceding figures, involving a display format useful for a comparative overview of the effects. Consider first Figs 10a, 10b, and 10c. The patches labeled A and B are equiluminant uniform gray targets which appear differently light. The targets are mostly surrounded by gradient patches; the arrows within the gradient patches indicate the directions of luminance increase. These figures have close structural relations to various displays in Figs 1 to 5. Thus

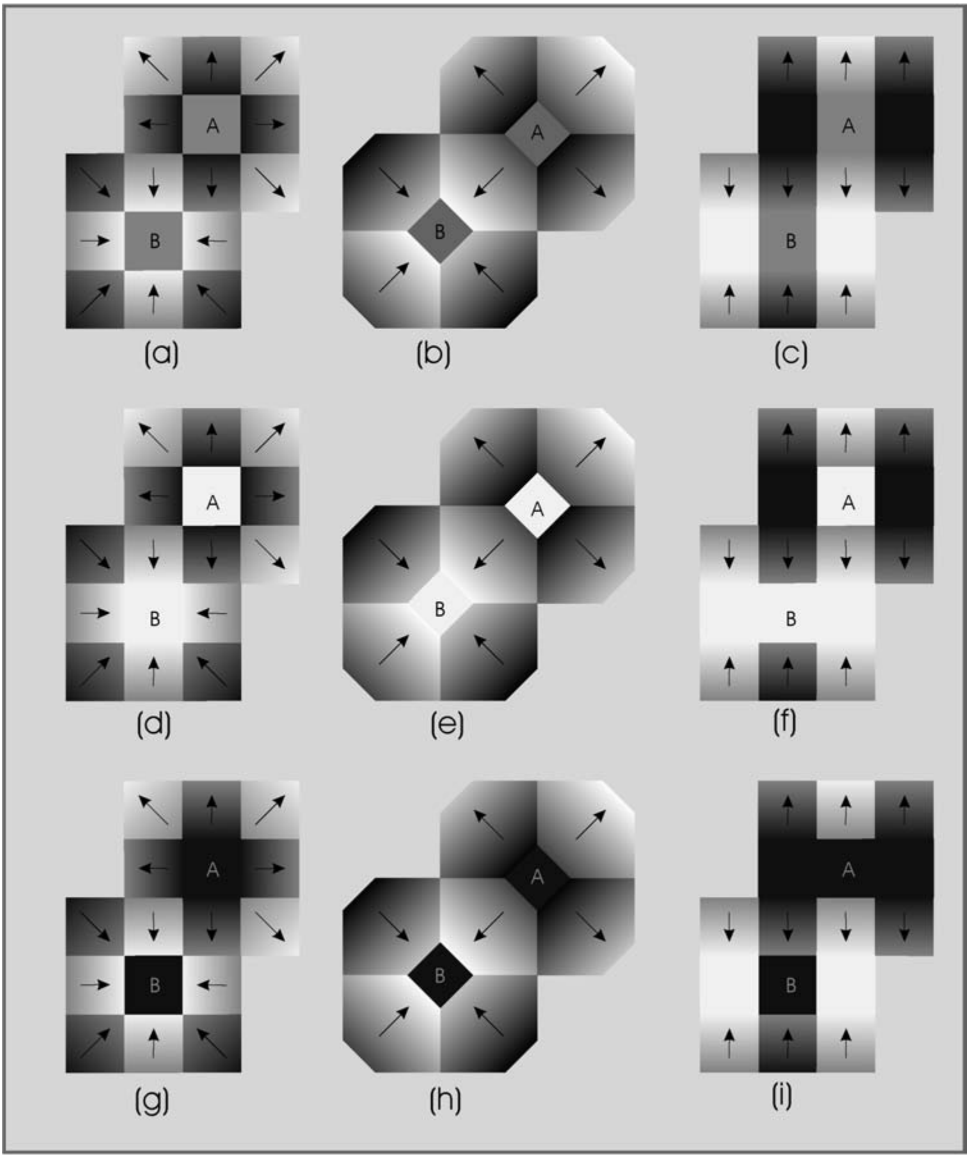


Figure 10. Targets of three luminance levels in different contexts. Gray targets: displays (a), (b), and (c). White targets: displays (d), (e), and (f). Black targets: displays (g), (h), and (i). See text for details.

Fig. 10a is related to Figs 1, 4b, 4e, 5b, and 5d; Fig. 10b is related to displays in Figs 2 and 3; and Fig. 10c is related to Figs 4a, 4c, 5a and 5c. Comparing the three figures brings out the structural similarities and differences between the three main types of lightness illusion displays discussed in this paper. The main differences between them are as follows: in Fig. 10a the target patches are bordered at their four sides by a single type of gradient, with luminance increasing towards the darker appearing target and away from the lighter appearing target, involving surround contrast constellations; in Fig. 10b the target patches are bordered at their sides by two types of gradients, but both types are increasing towards the darker appearing target and away from the lighter appearing target, in another surround contrast constellation; in Fig. 10c the target patches are bordered at their two sides by the same type of gradient, blending into them in a surround assimilation constellation, and at the other two sides by uniform patches, in a surround contrast constellation congruent with the surround assimilation constellation.

Figures 10a, 10b, and 10c are transformed into Figs 10d, 10e, and 10f, respectively, by substituting the gray targets with white ones, and into Figs 10g, 10h, and 10i, respectively, by substituting the gray targets with black ones. These figures have structural similarities with various displays in Figs 6, 7, and 9. Thus Figs 10d, 10e (which is similar to Fig. 8 in Bressan, 2001), and 10f, are related to Figs 6a, 6b, 6e, 6f, 7a, 7d, and 9a, whereas Figs 10g, 10h, and 10i, are related to Figs 6c, 6d, 6g, 6h, 7b, 7e, and 9b. In particular, note the appearance of the clear *vs.* hazy distinction in the targets in Figs 10d and 10g, where clearness is associated with surround contrast constellations (A-target in Fig. 10d and B-target in Fig. 10g) and haziness with surround assimilation constellations, that is, gradients blending into targets (B-target in Fig. 10d and A-target in Fig. 10g). Note also that the A-targets in all displays generally look lighter than the corresponding B-targets.

CHROMATIC GRADIENT EFFECTS

All effects presented up to now were achromatic. Little is known about the corresponding phenomena involving chromatic gradients. One example is presented in Fig. 11a. It consists of a bouquet of curved 'burning arrows', with a gradient from violet to orange at their tips; this color pair was used in the watercolor effect, and seemed to create the strongest perceptual effect among those that were tried. The background is physically white throughout, but compared with its appearance in the periphery and between the violet arrow tails, the center of the figure assumes a faintly glowing yellowish tinge. This phenomenon may be regarded as a chromatic variant of Zavagno's (1999) haze effect, and as a gradient version of the Ehrenstein (1941) illusion, and it is also related to the watercolor effect and displays studied by Da Pos and Bressan (2003). Note that the effect involves color assimilation, in the sense that the induced color in the center is similar to the adjoining color of the tips of the arrows.

Another chromatic assimilation effect is presented in Fig. 11b. It is composed of 'flowers' with 'petals' involving a violet-orange gradient, placed on a physically uniform white background. Note that in the regions of confluence of violet petal

Figure 11. (See color plate IX) Chromatic gradient effects. In both displays the backgrounds are uniform and achromatic, but show chromatic tinges at places of confluence of chromatic gradients. See text for details.

ends the background takes on a faint violet tinge, whereas in the regions of confluence of orange petal ends it takes on a faint orange tinge. An additional effect may be noticed if the display is treated as an auto-stereoscopic image, and the neighboring flowers, involving oppositely directed color gradients, are dichoptically superposed. Using free fusion, the reader may confirm that in the stereo image there is little rivalry and that the colors tend to fuse rather well, such that color variety is reduced and the flowers appear more uniform (though uniformity varies with different computer screens); this is unlike in achromatic versions of the image, not presented here, involving black-white gradients instead of violent-orange ones, which are very hard to fuse and are strongly rivalrous (see Hovis, 1989 for a review of dichoptic color mixing). Furthermore, the color tinges, which are induced into the background in non-stereoscopic viewing, completely disappear in the stereoscopic percept. The reason for this may be either that the induced colors are first generated and then dichoptically fused, or that they are not generated at all at the binocular processing stage.

SIMPLE NEURAL SIMULATIONS

In this paper I have argued against the role of illumination interpretation mechanisms in lightness illusions in flat images. However, regardless whether the presence of luminance gradients does or does not trigger illumination interpretation processes, it is of interest to study the reactions of neurons in the visual system to various configurations of gradients, and compare them to responses to abrupt luminance changes. Figure 12 presents computer simulations of reactions of 1D layers of processing units with on-center off-surround receptive fields to six selected stimuli. Input luminance profiles and corresponding examples of stimuli are depicted in the left-hand column. All stimuli contained a centrally located uniform target region with medium luminance level (L = 0.8, indicated by a horizontal dashed line); the position of the targets within the stimuli is indicated as lying between two narrow-dotted vertical lines. The targets were either increments (Inc1, Inc2, and Inc3) or decrements (Dec1, Dec2, and Dec3), that is, they had either higher or lower luminance levels than the immediately adjoining portions of the stimuli. The luminance profiles of the decrements were the same as for the corresponding increments, except for being mirrored upwards about the L = 0.8 horizontal line. The targets had inner and outer surrounds. The outer surrounds (lying outside of wide-dotted vertical lines), had low luminance level (L = 0.5) for the increments, and high luminance levels (L = 1) for the decrements. The inner surrounds (lying between wide-dotted and narrow-dotted vertical lines), had luminance levels that were either equal to those of the outer surrounds (Inc1, Dec1), or involved linear luminance gradients that either connected the outer surrounds and the targets smoothly (Inc2, Dec2), or had inverted profiles, involving abrupt luminance jumps (Inc3, Dec3). The Inc1-Dec1 and the Inc3-Dec3 pair involve surround contrast constellations for

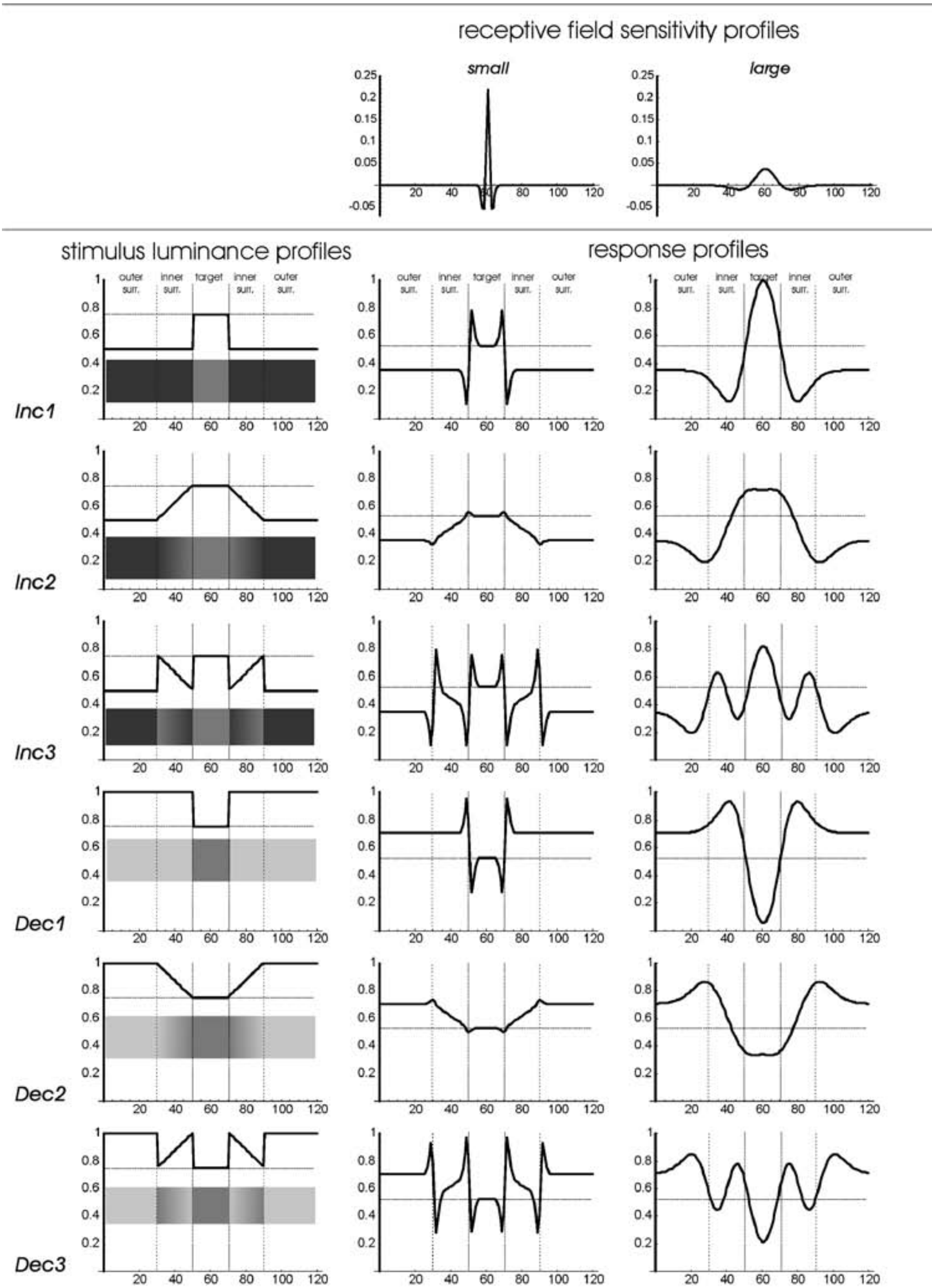


Figure 12. Modeling reactions of layers of two types of on-center neural units to six stimuli. See text for details.

target regions, and the Inc2-Dec2 pair involves a surround assimilation constellation.

The sensitivity profiles of the processing units were defined as differences of two Gaussians, one tall and narrow for the center and the other shorter and wider for the surround. The surround Gaussian was scaled to 90%, making the receptive fields volume-unbalanced (having a positive integral). The consequence of this is that the units exhibited sensitivity to absolute luminance levels, that is, they had positive outputs to uniform stimuli, since the positive reaction of the center was not fully matched by the negative reaction of the surround (see Croner and Kaplan, 1995). Two types of processing units were used, depicted at the top right of Fig. 12, one with small receptive field size (center and surround space constants equal to 1 and 2, respectively) and the other with large receptive field size (six times larger center and surround space constants), very roughly analogous to ganglion P-cells and M-cells. The responses of the unit layers were computed as convolutions of their sensitivity profiles with the stimulus distributions. The 12 resulting output profiles (6 stimulus profiles $\times 2$ receptive field profiles) were subsequently normalized by dividing them by the maximum reaction of all profiles.

Consider first the reactions of small-field units to increments, depicted in the top three graphs in the middle column in Fig. 12. Stimulus Inc1 represents a light patch on darker background (such as in Fig. 6a). The corresponding response profile involves the familiar pattern of overshoots and undershoots associated with the two luminance edges. Note the larger reaction to the target interior than to the background, due to the volume-imbalance of the receptive fields; a completely balanced receptive field would produce zero output for uniform patches of any level. The second stimulus, Inc2, involves linear gradients that blend into uniform regions (such as in Fig. 6b, in portions of striped displays in Figs 4 and 5, and in portions of Figs 9a, 9b and 10). The corresponding regions of the response profile exhibit similar neural gradients. This is another feature due to receptive field imbalance, since volume-balanced units would produce zero outputs for linear gradients (this can be seen by noting that the action of balanced difference-of-Gaussians units resembles taking the second derivative, and the second derivative of any linear function is zero). Note also the rather modest overshoots and undershoots in the response profile. In contrast, the response to stimulus Inc3, involving non-blending gradients (similar to luminance distributions in many portions of displays in Figs 2 to 5 and Figs 9a, 9b and 10), exhibits both neural gradients (as for Inc2) as well as strong overshoots and undershoots (as for Inc1). Turning to decrements, note that Dec1 is similar to Fig. 6c, Dec2 is similar to Fig. 6d and portions of striped displays in Figs 4 and 5 and in Figs 9a, 9b and 10, and Dec3 is similar to portions of displays in Figs 2 to 5 and Figs 9a, 9b and 10. The response profiles of the small-field layer to these stimuli (depicted in the bottom three graphs in the middle column) are mirror images of corresponding profiles for increments.

Are these response profiles relevant for understanding the lightness illusions in images exhibiting similar corresponding luminance profiles? Consider Inc1 and

Dec1, which, regarded together, form the classical simultaneous contrast display. Note that the levels of the response profiles corresponding to target interiors, indicated by dashed horizontal lines, are identical for the two stimuli (and indeed for all six stimuli); however, the presence of the overshoots for Inc1 and undershoots for Dec1 agrees with the direction of the lightness effect in simultaneous contrast (the same patch looks lighter on darker ground than on lighter ground). Thus subsequent processing, roughly corresponding to averaging or smoothing or diffusion confined within the target region, bounded by increments or decrements, would predict the form of the phenomenon (see Hong and Grossberg, 2004; Grossberg and Todorović, 1988). A similar analysis applies to targets in Inc3 and Dec3, but the targets in Inc2 and Dec2 would be predicted to look quite similar.

Consider now the response profiles of the large-field unit layer, depicted in the right-hand column of Fig. 12. Compared to the response profile of small-field units for Inc1, in the response profile of large-field units to the same stimulus the undershoots are much wider, and the two overshoots have merged into a single large overshoot within the target region, strongly exceeding the level of the response within the target interior of the small-field units, indicated by the dashed horizontal line; the response profile for Dec1 is the mirror image of the response to Inc1. Thus the average response within the target region is significantly larger for Inc1 than for Dec1, which again corresponds to the direction of the lightness illusion in the standard simultaneous contrast display. A simple average of the somewhat complementary small-field and large-field response profiles would provide a robust prediction of simultaneous contrast, even without any subsequent diffusion processes within the target regions (though the diffusion would provide more uniform output levels). A similar analysis applies for the Inc3-Dec3 pair. Furthermore, in contrast to small-field simulations, there is a stronger reaction to the target in Inc2 than in Dec2, although the difference is smaller than for the Inc1-Dec1 pair, which is in agreement with MacLeod's (1947) data. The importance of units with large receptive fields for computational models of lightness phenomena was recently stressed and analyzed, in different ways, by Blakeslee and McCourt (2004) and by Hong and Grossberg (2004).

The presented simulations fall far short of a computational model of effects discussed in this paper. Among other shortcomings, they are not 2D, they do not address the clear *vs.* hazy difference, and they do not explain the sometimes surprising strength of the gradient-induced effects. Furthermore, they are unsuitable for the treatment of a class of lightness effects which run counter to predictions based on surround contrast constellations, such as the White effect and related phenomena (see Todorović, 1997). However, most full-fledged models include related types of processing units among their building blocks. Therefore a close analysis of the response profiles and the particular combinations of overshoots/undershoots and gradual reactions present in them may provide insights for future models of effects of luminance gradients on uniform regions.

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