
Explaining lightness illusions

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Abstract. Grey looks darker when set against white than when set against black. In some complex figures this illusion becomes startling, and can be shown to depend on the perceptual organisation of regions within the image. The most widely accepted explanations of such effects are based on the analysis of the junctions formed where the boundaries of nearby regions meet. Even theories where junctions are not the subject of special concern underline their importance as grouping cues. In this paper I present several new families of figures that challenge both views, and conclude that junctions do not play any crucial role in lightness estimation.

“‘You can show black is white by argument’,
said Filby, ‘but you will never convince me.’”

H G Wells, 1953 *The Time Machine*

1 Introduction

A piece of perfectly black paper, suspended in midair and illuminated by a beam of light in an otherwise dark room, looks white (Gelb 1929). The fact that it is, actually, black becomes apparent only when a larger surface of higher luminance, such as a piece of real white paper, is brought into the beam and placed behind the original black paper, so as to completely surround it. But as soon as the white paper is taken away the black surface goes back to white. Much as Filby in *The Time Machine*, our perceptual system will not let itself be convinced that white is black, however persuasive the argument is: a truly remarkable denial when, as in the case at hand, the argument is a visual, ostensive one.

The Gelb effect shows that the highest luminance in a scene appears white (the black paper looks white when it is the only illuminated surface in the room), and that any other luminances are seen in relationship to such white (the black paper looks black when viewed against the real white paper, which is now the highest luminance). The perceived shade of the paper, in other words, changes depending on the frame of reference: in the first case, the black paper can only be judged relative to the dark room, but in the second we add, by introducing the white paper, another, more local framework. From the standpoint of the anchoring model (Gilchrist et al 1999), the Gelb effect is a spectacular, but otherwise predictable, instance of the general principle that surface lightness is based on anchoring within perceptual groups.

The model says that a visual scene is segmented into perceptual groups, or frameworks, on the basis of Gestalt grouping principles (in this case, proximity). Within each framework, the role of anchor is assigned to the highest luminance, which is locally given a value of white, and the appearance of any darker region depends on its relationship to that white. A corollary rule is that any area that takes up more than half of the visual field tends to lighten, and the larger it becomes the lighter it appears. The final lightness of a given surface is a weighted average of the values computed for that surface within each framework.

Naturally, the notion of anchoring is not the only way to account for our perception of whites, greys, and blacks. Explanations based on the nature of contour junctions

(Todorović 1997; Zaidi et al 1997; see also Bressan 1997), on scission (Anderson 1997), on atmospheric boundaries (Adelson 2000), and on lightness–shadow invariance (Logvinenko 1999) have all been very recently invoked with reference to a number of lightness illusions.

In this paper I intend to offer counterexamples for each of these explanations. I shall then try to show that all these counterexamples can be handled by the anchoring theory, or a slightly modified version of it.

2 The split-spiral illusion

It has been claimed that, in order to assess the lightness of a visual object, we have to decompose it into a set of layers (intrinsic images), representing surface reflectance, illumination, and depth (see Bergström 1977; Barrow and Tenenbaum 1978; Gilchrist et al 1983; Adelson and Pentland 1990; and, of course, Helmholtz 1867/1962). For lack of other candidates, any such process would be based on edge interpretation, and more specifically on the analysis of the luminance configurations created where contours come together: T, Y, X, and Ψ junctions. Junctions would be used to identify and separate different atmospheres, where an atmosphere is the net effect of those viewing conditions (light, shadow, haze, glare, filters) that map reflectances into luminances. This, of course, may work fine in the real world, but when junctions do not actually correspond to atmospheric boundaries (as in the world of 2-D painted images) computations such as these will lead to lightness illusions. If the border dividing a dark field from a light field is seen, rather than as the reflectance edge it is, as the product of either a difference in illumination or a perturbation such as haze or a filter, the ‘true’ grey shade of objects sitting within each region will have to be recovered by discounting the atmospheric disturbance. Hence, an object on the dark field will be seen as lighter than an identical object on the light field, which is exactly what the phenomenon of simultaneous contrast amounts to.

Adelson (2000) has constructed a number of beautiful lightness illusions by making use of junctions that establish strong atmospheric boundaries between adjacent regions. However, I believe that the interpretation of these illusions in terms of atmospheric boundaries is, to adopt the expression he employs himself when referring to the Helmholtzian approach, an overkill.

One of the figures devised by Adelson (2000) is a variant on the Koffka ring. This is a grey ring that sits half in a dark field, half in a light field, and looks roughly homogeneous in colour. When the two fields are moved slightly apart, however, the half-rings appear two different shades of grey. In Adelson’s version, the fields with the two half-rings are shifted vertically, so that the apparently darker half-ring on the right seems to be a continuation of the dark field on the left, and the apparently lighter half-ring on the left seems to be a continuation of the light field on the right. I present in figure 1 a variation on this theme, obtained by multiplying the rings. The shifted rings (top-right display) generate a spiral that looks continuous and partly overlaid by a greyish filter. Actually, the light elements on the left are the same grey as the dark elements on the right. Adelson’s explanation would be that the X-junctions along the middle vertical edge are consistent with transparency, and this edge becomes a powerful atmospheric boundary. The bottom-right display, however, shows that the impression of transparency plays no role: when this is removed by separating the two halves, the lightness illusion is equally strong.

To measure the lightness effects, I asked six observers to perform a matching task. The top-right and bottom-right displays of figure 1 were separately presented on a CRT screen, in random order, in alternation with other figures; each was shown twice. Below each pattern, on a white background, eight grey squares, numbered 1 to 8, were arranged horizontally. They represented increasing percentages of black in steps

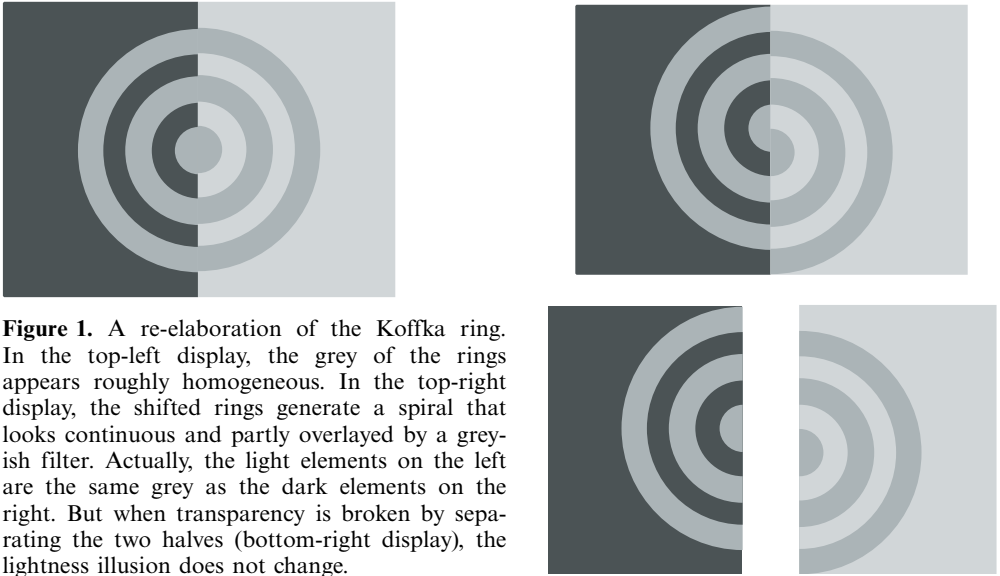


Figure 1. A re-elaboration of the Koffka ring. In the top-left display, the grey of the rings appears roughly homogeneous. In the top-right display, the shifted rings generate a spiral that looks continuous and partly overlaid by a greyish filter. Actually, the light elements on the left are the same grey as the dark elements on the right. But when transparency is broken by separating the two halves (bottom-right display), the lightness illusion does not change.

of 5% (from 10% to 45%). The grey of the two halves of the spiral was always 25% (on backgrounds of 65% and 15%), and corresponded to square number 4. For each display, the observers chose the grey squares that best matched the grey shades of the left and right half of the spiral (intermediate values, such as between 2 and 3, were also allowed); the difference between the matches chosen for the right and left half was taken as an estimate of the lightness illusion.

The data show that neither the left, nor the right halves of the spiral looked significantly different in the two figures. [Mean matches for the left halves: 2.33 (SD = 0.9) in the top-right display versus 2.25 (SD = 0.9) in the bottom-right display, $t_5 < 1$, ns. Mean matches for the right halves: 3.88 (SD = 0.9) in the top-right display versus 3.75 (SD = 0.8) in the bottom-right display, $t_5 < 1.2$, ns.] The resulting contrast illusions were identical (one-sample $t_5 < 1$, ns). Note that one cannot, as a means to rescue the explanation, appeal to some ‘dumb’ rule that applies to the X-junctions themselves, no matter whether the outcome actually involves perceptual transparency: there are no X-junctions in the split-spiral figure.

Adelson (personal communication) has remarked that, to get from one test region to the other in the bottom-right display of figure 1, one has to go across two boundaries instead of one, and one has to cover a larger distance. By providing better insulation between the two halves, these additions may be expected to enhance the effect and provide a compensation for the disappearance of junctions. To really challenge the role of junctions, then, one would have to keep the same proximity between the test patches, and allow the two regions to abut as they do in the top-right display. I will deal with this point by remodeling the criss-cross illusion.

3 The shrunken criss-cross illusion

The top-left display in figure 2 shows Adelson’s (2000) criss-cross illusion. The small tilted rectangles are all the same shade of grey, but those within the dark vertical stripes (that may be perceived as under a shadow or a filter) seem lighter. I have derived the top-right display from the original figure by sliding vertically alternate stripes. This manipulation has destroyed all the Ψ -junctions along the vertical edges, but the lightness difference between the small tilted rectangles is unchanged. Although one could claim that the T-junctions generated by shifting the stripes are still signaling

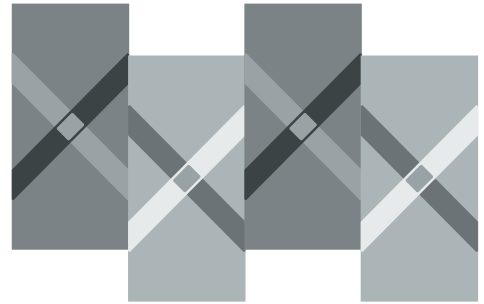
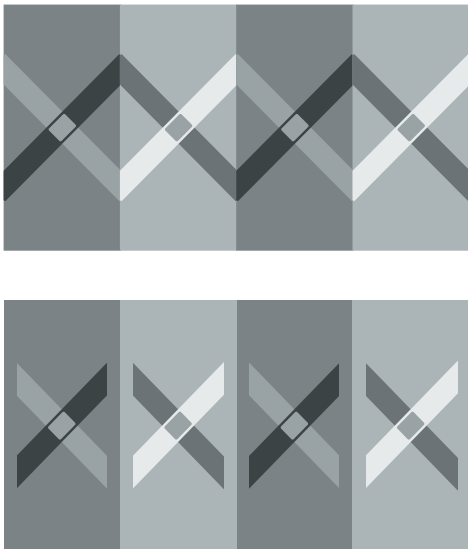


Figure 2. Top-left display: a redrawn version of the criss-cross illusion (Adelson 2000). The small tilted rectangles are all the same shade of grey. When the Ψ -junctions (top-right display), and even the T-junctions (bottom-left display) along the vertical edges of the panels are eliminated, the lightnesses of the small tilted rectangles appear essentially the same as in the original figure.

atmospheric boundaries, the bottom-left panel shows that the illusion is not disturbed by the disappearance of these T-junctions, either.

This image has been created by merely shortening the crossing bands. The distance that separates the test patches is unaltered, and no extra boundaries have been added between the stripes. Although the Ψ -junctions in the original display make for a much more sensational figure, the lightness illusion is identical.

4 The impossible-lighting wall-of-blocks

Logvinenko (1999) presented a modified version of Adelson's (1993) 'wall-of-blocks' where the sides of the blocks are filled by a luminance gradient (figure 3, top, shows a fragment of such a display). The tops of the blocks are all the same shade of grey, but those placed at the dark end of the gradient look much lighter than those placed at the light end. Note that, with the exception of the scission idea, all of the explanations mentioned so far could be expanded to predict this outcome. An account based on junctions [such as that advocated, for simpler displays, by Todorović (1997)] is the one that would need the largest adjustments. Where each block meets the two blocks behind it, a 6-junction, involving six regions separated by six branches, is generated.

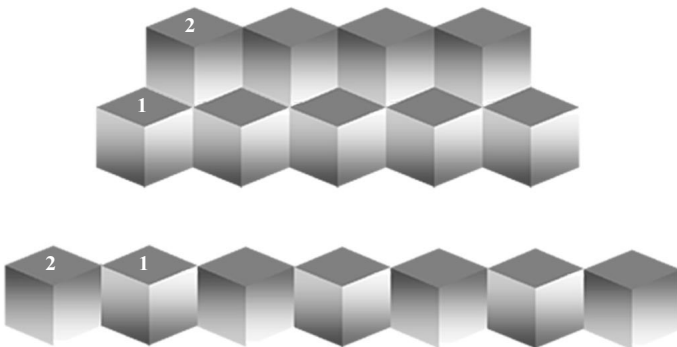


Figure 3. The tops of all blocks are the same shade of grey. The blocks differ only in relative position, but the lightness difference is reduced in the bottom display (after Logvinenko 1999).

The lightness of a patch is supposed to be a function of the ratio between its luminance and the luminance of the collinear region (that is, the region it shares a collinear edge with). The problem, with this type of 6-junction, is that no two adjacent regions are collinear. One would need to extend the rule to collinear triplets, and say, for example, that the lightness of the central region of a triplet is a weighted function of the ratios between its luminance and the luminances of its two collinear regions. In the wall-of-blocks, this approach would predict an illusion in the correct direction, although it would fall short of explaining why the effect is so much stronger in the variant with gradients.

Intrinsic image explanations, on the contrary, appear perfectly suited to account for the wall-of-blocks illusion: since perturbations such as illuminance gradients are discounted when estimating the ‘true’ grey shade of surfaces, the block tops apparently lying in the shadow must be lighter than those apparently lying in the sun. Logvinenko (1999) favours an explanation based on lightness–shadow invariance to the point of arguing that, in an image such as that shown in the bottom display of figure 3, the illusion vanishes because the illuminance distribution is incoherent—in his words, shadow-incompatible.

It is true that, in the gradient wall-of-blocks (of which the top display of figure 3 represents a fragment), there is at least a general impression that the light is coming from the right, since each block has a lighter side and a darker side and all the blocks are identically oriented. However, if one modifies the original figure by flipping the sides of each block in alternate rows (figure 4), such impression vanishes, and the illumination becomes incoherent, but the lightness illusion stays.

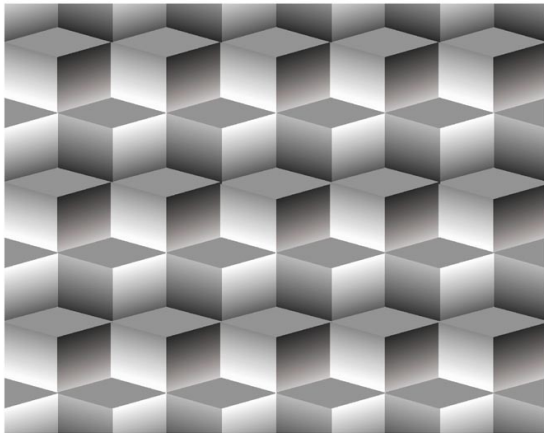


Figure 4. The impossible-lighting wall-of-blocks. The tops of all blocks are the same shade of grey.

Logvinenko (1999) has claimed that the difference between the top and bottom displays of figure 3 cannot be explained within the context of the anchoring theory (or of any other theory that ignores the notion of inappropriate shadowing). On the contrary, I believe that such a difference should be expected on at least two accounts. For one thing, the tops of all blocks of type 1 border with a gradient in the top display, and with no gradient at all (but only the white page) in the bottom display. Thus, any gradient-induced effect will be reduced by half for these blocks. Second, each of the same-type blocks in the top display belongs, by proximity, to a mid-level framework composed of four or five identical elements, whereas such a framework is totally absent in the bottom display. Even if one neglects the possible additional lightness homogenisation of these grey tops on account that their corners touch (a weaker version of the phenomenon observed in the unbroken Koffka ring), the above two circumstances are enough to predict a much smaller illusion in the bottom display.

5 The dungeon illusion

In the criss-cross, split-spiral, and wall-of-blocks illusions the grey elements that look lighter are those lying on the darker surround. What is remarkable in these displays is not the direction of the effect (the same as in simultaneous contrast), but its strength. In principle, the appearance of each grey patch could be predicted from the ratio of its luminance to the luminance of the field on which it lies (see Wallach 1948), if we only multiplied the ratio by a proper factor.

Other classes of illusion, on the contrary, represent direct pieces of evidence against a local-contrast account. These examples take typically one of two forms. In the 'same ratio' form, the ratio rule predicts no contrast effect. Region A and region B have identical borders, but because of a difference in the way the two regions relate to the rest of the image, region A looks darker. Benary's cross (1924) and Wolff's concentric annuli (1934; see also Shapley and Reid 1985) belong to this class. In the 'wrong ratio' form, the ratio rule predicts a contrast effect in the opposite direction. Region A has longer black than white borders and region B the other way around, but region A looks darker. White's effect (1979) and Todorović's overlapping squares (1997) are members of this group.

A more radical example of the 'wrong ratio' form is a checkerboard pattern where one black square and one noncontiguous white square have been replaced by two identical grey squares (De Valois and De Valois 1988). The grey square that replaces the white one (and only borders with black, though it has a common corner with white) looks perhaps slightly darker than the other, rather than lighter as it should. The 'reverse contrast' effect (Economou et al 1998) is a more compelling case where one grey bar surrounded by black, but perceptually belonging to a set of parallel white bars, looks darker than a second grey bar which is surrounded by white, but belongs to a set of black bars. As in the checkerboard effect, however, the perceptual difference between the two greys tends to be modest, and sometimes even reverses to ordinary contrast.

I propose the two displays in figure 5 (the dungeon illusion) as extreme and prototypical instances for each category. The top display is an example of 'same ratio' effect where all the elements forming regions A and B are totally surrounded by black, but region A looks distinctly darker. Region A is the set of small grey squares arranged in the shape of a diamond in the left figure; region B is the same set in the right figure. The bottom display is an example of the 'wrong ratio' class where the elements forming region A entirely border (and have a common corner) with black and the elements forming region B entirely border (and have a common corner) with light grey, but region A looks darker.

A local-contrast account fails in both cases. This is not simply a matter of how much stretching the meaning of 'local' can bear. If the figure is considerably enlarged, or watched from a shorter distance, the central square of the left diamond still appears darker than the corresponding square on the right: but the closest white square can be now more than three degrees of visual angle away, and the mean intervening luminance is either the same as (top display), or lower than (bottom display), the luminance that separates the right diamond from its closest dark square.

The junction account would seem to have little to say on the dungeon illusion, on the grounds that no T, Y, X, and Ψ junctions can be found in figure 5. For the same reason, an approach based on atmospheric boundaries, or lightness–shadow invariance, or scission, appears to fail, too. Incidentally, note that the scission hypothesis advocated by Anderson (1997), whose starting point is a contrast change along aligned contours, does not apply to any of our figures.

How can we explain the dungeon illusion? If one looks through the grid, as if into a prison from the outside, what one sees is an amodally completed diamond sitting on a light (left displays), or dark (right displays) background. Take the same-ratio version:

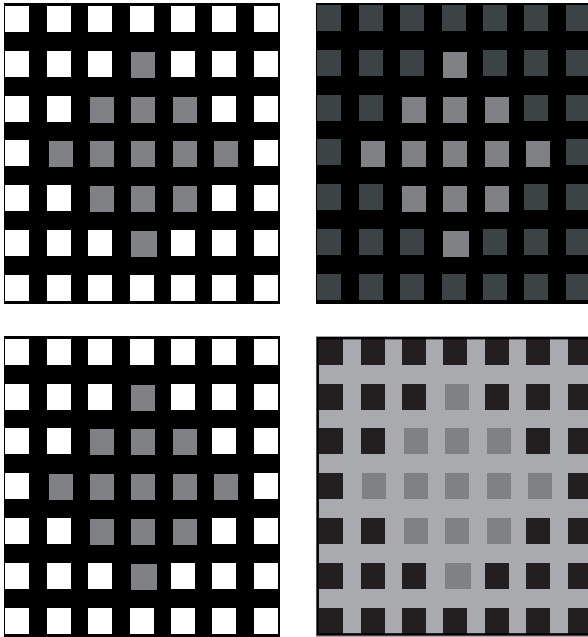


Figure 5. Top display: the dungeon illusion, in its ‘same-ratio’ version. The small grey squares that form the two diamonds are all the same shade of grey, and are all completely surrounded by black areas, but the diamond that appears to lie on the white background (left) looks darker. Bottom display: the dungeon illusion, in its ‘wrong-ratio’ version. The small grey squares that form the two diamonds are all the same shade of grey, but the diamond whose elements are completely surrounded by black areas (left) looks darker. The effects are stronger when the displays are viewed from a distance.

only the background changes. This means that the lightness of the grey diamond must be assessed relative to it. (The only alternative would be claiming that, for example, the white background darkens the part of the black grid that lies on it, the darkening diffuses to the whole grid, and in turn lightens the diamond. Even if we gloss over the logical loop of basing one lightness assessment upon another lightness assessment, any such account predicts an effect in the wrong direction.) But if we assume that the diamond and the background on which it appears to lie form a perceptual group, and that the diamond’s lightness is computed within it, we should indeed observe a lightening of the diamond on the dark background. (Being the highest luminance in this framework, such diamond is locally assigned a value of white.) The same applies to the wrong-ratio figure.

This also explains why the dungeon illusion is stronger, and more stable, than previously reported instances of reverse contrast, such as Economou et al’s (1998): there, as observed by Gilchrist (personal communication), each target grey bar participates in two local frameworks, one including the flanking bars and one including only the black or white background. Thus, we expect a tension between its grouping with the flanking bars (leading to reverse contrast) and its grouping with the background (leading to ordinary contrast). The same holds in principle for the dungeon illusion, but here, because of the highly symmetrical and repetitive structure, the target squares group much more easily with the remaining squares than with the intervening regions. Indeed, the latter combine into a grid, which is viewed as in front, and has little perceptual dealing with the diamond other than partially occluding it; yet, this depth-ordering is by no means necessary to see the effect.

6 Anatomy of a snake

The anchoring model accounts very nicely for all the illusions we have discussed so far. The patch that looks a lighter shade of grey represents its local framework's highest luminance in the criss-cross illusion (shrunk and unshrunk), in the spiral illusion (split and unsplit), and in the wall-of-blocks (in either its possible or impossible lighting). Yet there has been no mention, so far, of the reason why the lightness illusions seen in such figures should be so much stronger than simultaneous contrast. I will address this problem by dissecting a snake.

The snake illusion (Somers and Adelson 1997) is shown in the top-left display of figure 6. The grey diamonds are identical, and their local contrast relations with their surrounds are the same as in the top-right display (the 'anti-snake'). Here, however, the illusion virtually vanishes—since, according to Adelson (2000), there are no X-junctions and no sense of transparency. To measure the lightness effects, I asked six observers to perform a matching task. The snake, the anti-snake, and the other four displays of figure 6 were separately presented on a CRT screen, in random order; each was shown twice. Expressed as percentages of black, the grey levels used to fill the various regions were 20% and 65% for figures with two greys; 0% 20%, 65%, and 80% for figures with four greys. The only exception was the reversed-contrast snake (middle-right

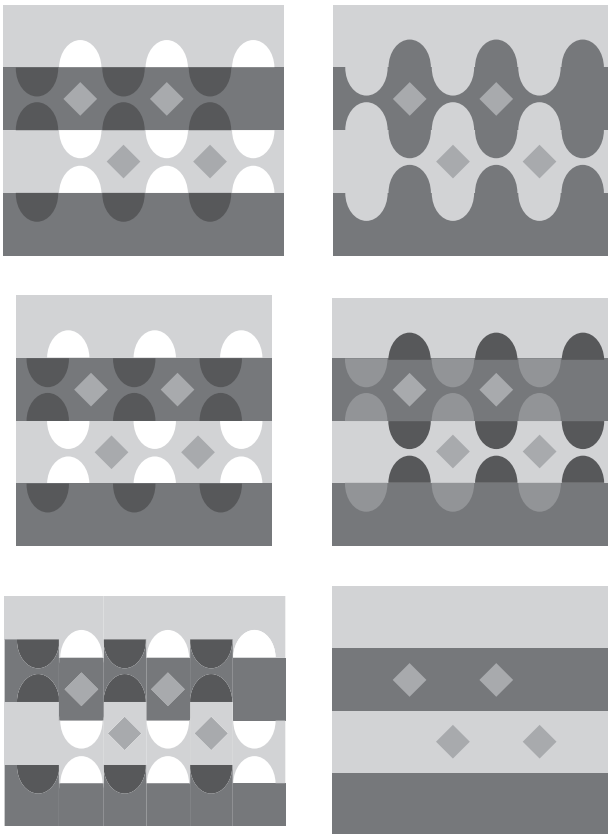


Figure 6. Top-left display: the snake illusion (redrawn after Adelson 2000). All diamonds are identical. Top-right display: the anti-snake (redrawn after Adelson 2000). The diamonds and their local surrounds are the same shades of grey as in the snake illusion. The X-junctions along the horizontal contours (and the corresponding sense of transparency) are neither sufficient (middle-right display), nor necessary (middle-left) for the lightness illusion to come about. But if the diamonds are forced to group differently (bottom-left display), the illusion is not stronger than standard simultaneous contrast (bottom-right display).

display), where the light half-ellipses were 50% rather than 0%. The grey of the target diamonds was always 40%. Below each pattern, on a white background, twelve grey squares, numbered 1 to 12, were arranged in two horizontal rows of six. They represented increasing percentages of black in steps of 5% (from 10% to 65%). For each display, the observers chose the grey squares that best matched the grey shade of the top and bottom diamonds; the difference between these values was taken as an estimate of the lightness illusion.

The data, shown in table 1, indicate that the lightness illusion is significantly stronger than standard simultaneous contrast (portrayed in the bottom-right display: $t_5 = 4.8$, $p = 0.005$) in the snake, and significantly weaker than simultaneous contrast ($t_5 = -3.5$, $p = 0.017$) in the anti-snake; indeed, not different from zero in the latter case (one-sample $t < 1$, ns). Now, the snake survives certain forms of injury but not others. In the middle-left display, I have chopped it up along its length, and shifted every second stripe: the X-junctions and the sense of transparency have gone, but the illusion (stronger than simultaneous contrast, $t_5 = 4.2$, $p = 0.009$) has abated only slightly. The middle-right display illustrates the symmetrical, complementary case: the X-junctions and sense of transparency are present, but the illusion is not. Here I have reversed the contrast polarity of the external and internal half-ellipses, by darkening the former and lightening the latter. The illusion is now not larger than standard simultaneous contrast ($t < 1$, ns). Note that this manipulation has transformed the ‘sign-preserving’ X-junctions of the snake into ‘single-reversing’ X-junctions. This implies that, while in the original snake one could see, in principle, either a transparent dark stripe over opaque wavy regions or transparent wavy regions over an

Table 1. The first six rows (experiment 1) show mean matches and standard deviation (in parentheses) for the top and bottom diamonds of the six displays presented in figure 6, and for the difference between them, taken as an estimate of illusion magnitude. Each value is an average across six observers and two trials. The two bottom rows (experiment 2) show the same data for the simultaneous-contrast configuration depicted in figure 6, bottom-right display, and for a stand-alone version of the ‘articulated anti-snake’ (shown in figure 7, central section of the bottom panel). Each value is an average across seven observers. Data for the simultaneous-contrast configuration were independently obtained in both experiments, to permit paired comparisons with the rest of the data in each experiment. Values 1 to 12 indicate the 12 matching squares, from 1 (10% black) to 12 (65% black), so higher values stand for darker greys. The correct match was always 7.

Stimulus	Top diamonds	Bottom diamonds	Illusion magnitude
Snake (figure 6, top left)	2.04 (0.70)	8.17 (1.37)	6.13 (1.59)
Anti-snake (figure 6, top right)	4.54 (1.27)	4.33 (0.63)	-0.21 (1.59)
Horizontally shifted snake (figure 6, middle left)	2.96 (0.70)	7.50 (1.15)	4.54 (0.93)
Reversed-contrast snake (figure 6, middle right)	3.25 (0.76)	4.67 (0.75)	1.42 (0.41)
Vertically shifted snake (figure 6, bottom left)	3.58 (1.01)	5.54 (1.07)	1.96 (0.40)
Simultaneous contrast (figure 6, bottom right)	3.88 (1.06)	5.67 (0.79)	1.79 (0.81)
Simultaneous contrast (replication)	3.79 (0.68)	5.32 (0.76)	1.54 (0.78)
Articulated anti-snake (figure 7, bottom display, central section)	5.00 (1.26)	4.79 (0.91)	-0.21 (1.11)

opaque stripe, in this variant the dark stripe is unambiguously seen as a filter covering the regions underneath. If any mechanism is at work to discount the murky medium in the original snake figure (causing the illusion), that is all the more reason why such a mechanism should be labouring in this figure, too.

If junctions and transparency have no bearing on the effect, why does the snake (either intact or chopped) lead to a lightness illusion so much larger than simultaneous contrast? The anchoring theory's answer (Gilchrist et al 1999) is that the final lightness of a region is a weighted average of the lightness values assigned to it in each of the frameworks it belongs to. The weight of each of these values depends on the framework's strength, which reflects its size and articulation (roughly, the number of parts it is composed of). The stronger the framework within which the illusion occurs, the heavier the weighting in favour of that anchoring, and the stronger the illusion. Now, the framework of interest in the snake-family figures appears to be the stripe on which each diamond lies: in the simultaneous-contrast pattern, such framework has a very poor articulation—no parts at all, in fact. Thus, it might simply be that the diamonds do receive locally different lightness assignments, but these weigh quite little at the averaging stage. Here we expect in fact a local/global weighting heavily shifted in favour of global anchoring, and in the global framework (ie in relationship to the white page) the diamonds are computed as identically grey. Yet, articulation by itself cannot be the answer: all potential frameworks in the inert snake of the middle-right display are every bit as articulated as in the original one.

Consider now the dark stripe in the original snake figure. It contains six half-ellipses, all darker than the stripe. The half-ellipses and the grey surface above and below them group together by good continuation of the curved sections of their contours. They belong together in the sense that they represent a single object (partly covered by a dark filter). However, the half-ellipses also group with the stripe by good continuation of the straight sections of their contours, and I am going to suggest that this is the relevant grouping in the lightness-anchoring process. [In agreement with this view, it has recently been shown that, when straight contours are put in competition with crooked contours, it is the former that dominate lightness illusions: see Adelson and Somers (2000).] The snake cut into horizontal shreds proves that this idea is not pure speculation. Here, the reduction of X-junctions to T-junctions forces the half-ellipses to group with the stripe they lie on. The bulk of the lightness illusion is unaltered, showing that this is the effective grouping in the original figure, too.

A control test is displayed in the bottom-left figure. Here, the original snake has been sliced into vertical stripes, and these have been alternately shifted up and down. The good continuation between the half-ellipses and the stripes has gone. The lightness difference between the diamonds has sensibly declined, and is now not appreciably stronger than simultaneous contrast ($t < 1$, ns).

Taken together, these visual arguments suggest that the larger illusion magnitude in the snake, relative to simultaneous contrast, stems from the fact that the framework within which the diamonds receive different lightness values contains the half-ellipses; and that these half-ellipses represent further decrements within the decremental stripe, and increments within the incremental stripe.

The geophotometric relationship between the two displays is represented in the top panel of figure 7, where the snake sloughs its skin. As can be seen, this change is essentially a decolourisation. The bottom panel shows that the transmutation of the snake into the anti-snake is of an altogether different nature: the contrast polarities of the half-ellipses must reverse. If this is done at the beginning of the sloughing process, the snake turns into a fully articulated anti-snake (middle section), of which the original anti-snake (right section) portrays a special case. Here, the half-ellipses have faded to the colour of the regions above and below them, and are thus only partially defined:

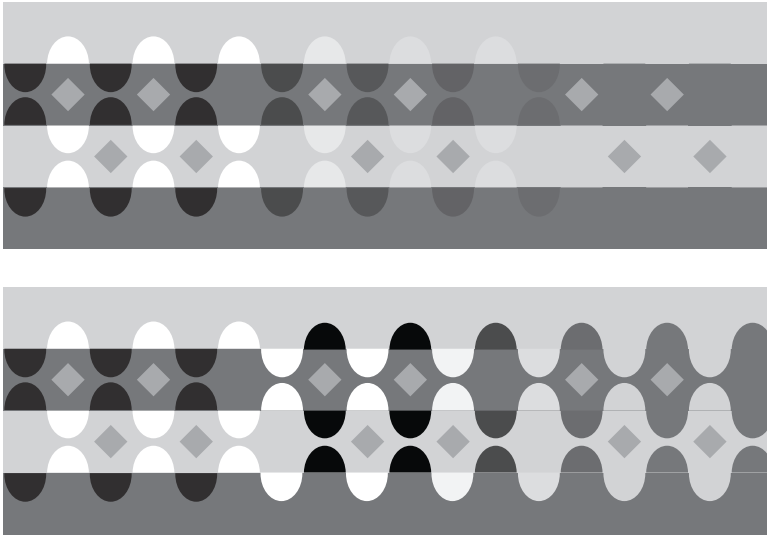


Figure 7. The snake sloughs its skin. Top display, left to right: the turning of the snake into a simultaneous-contrast illusion. The contrast of the half-ellipses fades away, but their polarities do not change. The lightness effect subsides gradually. Bottom display, left to right: the turning of the snake into the anti-snake. The polarities of the half-ellipses reverse, and their contrast fades away. As soon as polarities get switched (middle section), the lightness effect disappears.

but they continue to represent increments within the decremental (virtual) stripe and decrements within the incremental (virtual) stripe.

One may infer, then, that the original anti-snake fails to generate an illusion because the half-ellipses are still part of the framework within which the lightness of the diamonds is assessed, much as it happens in the articulated anti-snake. And if this is the case, one must conclude that frameworks are not necessarily well-defined, boundary-delimited parts of a scene. Further visual evidence for this idea will be found in section 8, where we will have to postulate frameworks whose periphery covers the nearest ends of luminance ramps, but not the whole ramps.

It may be interesting to add that, in the articulated anti-snake that emerges in the central section of the bottom panel, X-junctions are sign-preserving (exactly as in the snake), and two adjacent stripes of shadow and light come into view (exactly as in the snake). On either an atmospheric-boundaries or a lightness–shadow-invariance account, it seems that this should lead to a lightening of the bottom diamonds (relative to the top diamonds, and also relative to the bottom diamonds in the original anti-snake), since, this time, it is they that are covered by a dark medium. Yet, a matching experiment performed on a sample of seven subjects (see table 1) showed that the articulated anti-snake generates no illusion at all. The lightness difference between the top and bottom diamonds was significantly weaker than simultaneous contrast ($t_6 = 5.1$, $p = 0.002$), and indeed not different from zero (one-sample $t < 1$, ns).

These observations indicate that the lightness of a surface must be assessed relative to all the luminances that compose an articulated framework. The current version of the anchoring model can account quite smoothly for the darkening of the bottom diamonds in the snake as a consequence of the presence of the white half-ellipses, which, being the highest luminance, become the local anchor. The lightness of the diamonds would thus depend on their luminance ratio to such white, rather than to the light-grey of, say, the anti-snake. (The bottom diamonds in the snake are perceived as darker than the bottom diamonds in the anti-snake: $t_5 = 5.8$, $p = 0.002$.)

However, the model is incapable of explaining the lightening of the top diamonds caused by the dark half-ellipses, given that the diamonds themselves represent the highest luminance within the critical framework, and the introduction of darker regions will not alter their lightness assignment which is, locally, white in both snake and anti-snake. (The top diamonds in the snake are perceived as lighter than the top diamonds in the anti-snake: $t_5 = 4.2$, $p = 0.009$.) Note that, if anything, in the snake the top diamonds should look darker than in the anti-snake, on the grounds that what we may call configurational framework (ie the figure) contains a highest luminance (the white half-ellipses) absent in the anti-snake.

7 The double-brilliant illusion

Figure 8 depicts a further source of trouble for the anchoring theory. The two central diamonds are perfectly white, and serve as highest luminances in their local frameworks (the gradients that surround them). The diamonds should thus receive identical lightness assignments both globally and locally. Instead, the diamond that represents a larger increment relative to its immediate surround looks whiter than the diamond that represents a smaller increment. [For experimental data on simultaneous contrast with double increments, see Bressan and Actis-Grosso (2001).] Of course, anyone shopping for jewels would settle for the diamond on the right, which is less white but appears to emit or reflect suffused light. The non-overlapping of these two effects, a lightness illusion and a luminosity illusion, is clear evidence that luminosity and lightness are separable dimensions: luminosity is not a whiter white. On this topic, see also Zavagno and Caputo (2001).



Figure 8. The double-brilliant illusion. Both diamonds are white, and mounted on luminance-ramp settings. But the diamond sitting on the dark end of the ramp (left) looks whiter than the one sitting on the light end of the ramp (right).

The reason why the anchoring theory cannot handle the double-brilliant illusion is that the target regions represent luminance increments relative to their surrounds: in the current version of the theory, the region with the highest luminance has no lightness value other than white. I suggest that this problem be solved by resurrecting the surround-as-white rule originally advocated by Gilchrist and Bonato (1995), according to which white is assigned to the surround, and making it work side by side with the highest-luminance-as-white rule (Bressan, in preparation). If the lightness of a region is assessed on the basis of its luminance ratio not only to the highest luminance, but to the surround as well, and such surround is locally defined as white, regions on less luminant surrounds will appear lighter than regions on more luminant surrounds. (Only regions on actually white surrounds will not lighten at all.) Hence, the diamond on the left (whose immediate surround is black) will lighten more than the diamond on the right (whose immediate surround is light-grey). In terms I like a bit less, if the diamonds have the same luminance, but the one on the left has a larger luminance ratio with its surround, and the surrounds are both locally white, the target on the left must be lighter.

8 The Christmas-tree illusion

To construct this figure, I took a pyramid-shaped section of the impossible-lighting wall-of-blocks depicted in figure 4, and since it reminded me of a Christmas tree I laid square-shaped candles on its branches (figure 9). When one does this, the rows of candles sitting on the apparently lighter branches lighten up.

This illusion could be viewed as a sort of second-order contrast effect, but what the small squares are affected by is clearly neither the physical nor the perceived grey shade of the diamonds they sit on. In the first case, since identical squares are standing on identical surrounds, there would be no illusion at all. In the second, since squares on lighter-looking surrounds should if anything darken (and we leave aside, again, the problem of lightnesses affecting lightnesses), the illusion would go in the opposite direction.

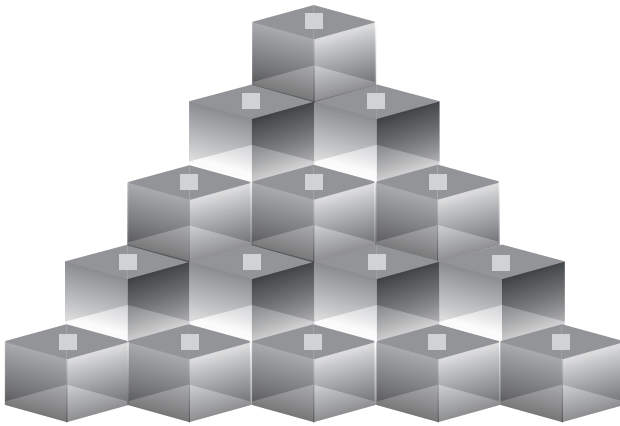


Figure 9. The Christmas-tree illusion. The tops of all blocks are the same shade of grey; the small squares on them are all identical. Those on the perceptually lighter tops appear lighter.

In the anchoring theory, the final lightness of a given surface is a weighted average of the values computed for that surface within each framework. This notion is nicely illustrated by the Christmas-tree illusion. Why do some candles lighten up? Locally, there can be no illusion here: the luminance ratios between the candles and the tops of the branches (local surround) are identical. Globally, there can be no illusion either: the luminance ratios between the candles and the white background are, again, identical. Yet, the lightness of each candle is also assessed in relationship to a middle-level framework that includes the four regions (two above and two below) adjacent to the tops of the branches. These regions consist of the dark ends of four luminance ramps in the case of the candles that lighten up, and of the light ends of four luminance ramps in the case of the candles that do not. In this framework, the former candles represent the highest luminance, and are thus assigned a value of white; the latter candles do not represent the highest luminance, and are thus assigned a value of light-grey (compared to the local highest luminance, ie the light end of the gradient).

Incidentally, the illusion also obtains when the candles are perfectly white (and hence represent the highest luminance in all frameworks they belong to). This provides circumstantial evidence that some kind of surround-as-white rule may have to be extended to regions that are not adjacent to the target, provided they still group with it (Bressan, in preparation). But the outcome of such apparent complexities, as it will be argued in the next and final section, is simplicity itself.

9 Keeping it simple

When it comes to explaining lightness illusions, a slightly modified version of the anchoring theory performs considerably well, and indeed better than any other scheme. It seems only fair to remark, though, that if the standard intrinsic-image approach evidently fails with these figures, an edge-classification-independent version of it may not. In essence, every lightness illusion (starting from old simple simultaneous contrast) consists in the comparison between a region that might be regarded as more illuminated and a region that might be regarded as less illuminated. What the new figures presented in this paper challenge, however, is the importance of edge interpretation, a central concept in the intrinsic-image doctrine.

The question of why junctions appear to be crucial in lightness estimation may have a simple answer. All junctions share a single feature, the one that is left when we remove the stem of the T, one stroke of the X, the angled arms of the Y and Ψ (that is, when we destroy the junctions): a straight piece of contour. This contour is present in all our figures before and after the splitting, shrinking, and shifting, and what it does is segregate the regions lying on its two sides, and dictate separate lightness assessments. As it happens, the presence of junctions is neither necessary (think of the shrunken criss-cross figure or the dungeon display, not to mention, of course, traditional simultaneous lightness contrast), nor sufficient, as shown by the collapse of the illusion in the passage from the snake to the articulated anti-snake (identical X-junctions), or by the dissolution or reversal of White's effect for certain luminance combinations (identical T-junctions; see Spehar et al 1995). Of course, one could claim that when we change the luminances of the regions meeting at the junctions we are changing the junctions themselves, and that therefore junctions matter. Yet, the explanatory power of the concept of junctions is founded on purely geometrical considerations, such as the idea that contrast occurs predominantly between the regions that share the stem, rather than the top, of the T (Todorović 1997), or that, since regions at the top are automatically interpreted as occluding or distant surfaces, contrast coming from them is inhibited (Zaidi et al 1997). It is unclear how and why such rules should only hold for certain photometric structures of junctions and not for others.

It has been suggested (Gilchrist et al 1999) that we do analyse junctions for purposes of lightness assessment, but use them solely to delimit the context within which lightness is computed (that is, as grouping cues, or means of defining frameworks), rather than as a way of telling reflectance and illumination edges apart. Indeed, the failure of the illusion to subside, even minimally, in figures such as the shrunken criss-cross (as compared to its whole, Ψ -junction-equipped variant), or the split-spiral (as compared to its unsplit, X-junction-equipped variant), is in harmony with this view. Note that in these figures such junctions are not used for grouping purposes. In the split-spiral figure, for example, the two half-fields segregate perfectly well on the basis of (achromatic) similarity, and each half-spiral is grouped with its own half-field on the basis of adjacency and surroundedness.

T-junctions (and X-junctions as combinations of T-junctions) signal one of the possible embodiments of the principle of good continuation (two aligned regions, one on either side of the stem) and hence represent a fine grouping cue, but whether this grants them a prominent place in lightness computation is a different matter. I have argued that, in the snake family, the internal half-ellipses affect the lightness of the diamonds by grouping (via good continuation) with the stripe they sit on. Now, it stands to reason that this framework should be stronger (or at least equally strong) in the horizontally shifted snake, where half-ellipses and stripe share the stems of T-junctions, than in the original snake, where the ambiguity of X-junctions permits the half-ellipses to participate in two separate frameworks, one including the stripe and one excluding it. Yet, in the horizontally shifted snake the lightness illusion is, however

slightly, significantly smaller than in the original one ($t_5 = 4.36$, $p = 0.007$). Granted that the illusion is originated in the local framework that contains stripe and half-ellipses, in the display where from the standpoint of junctions and subjective belongingness this framework appears better insulated the illusion is weaker.

This paradox will not be solved here; yet, if X-junctions have an edge over T-junctions in generating lightness illusions in displays such as these, it must be because, beside connecting the elements of a lightness framework, they also bind together sections of objects that fall partly inside and partly outside it. This goes counter to the idea that, in complex images, junctions affect lightness by strengthening the segregation of the crucial framework relative to the other frameworks. If segregation is a helpful concept here, it has little to share with segregation as typically established by junctions in familiar perceptual groups.

The superiority of X-junctions over T-junctions in these figures is, admittedly, reminiscent of atmospheric boundaries. But this bell only rings till the snake starts sloughing its skin. In the articulated anti-snake, X-junctions signal different atmospheres to the visual system, but the diamonds sitting in the light do not darken, nor do those sitting in the shade lighten. And in the final metamorphosis the articulated anti-snake loses all its X-junctions, but the lightness relationship between the top and bottom diamonds remains the same.

Junctions, then, cannot be the real issue: they may occasionally consort with the real issue, which is a special type of grouping. The volatile nature of such association suggests that the rules of grouping for lightness be sought less in the domain of junctions and more out of it. Partly, in its vicinities (contours across which the direction of contrast remains constant, for example, may establish more effective lightness boundaries than contours across which luminance polarities reverse). Mostly, someplace else entirely. The superiority of gradients in wall-of-blocks figures indicates that luminance ramps make better lightness boundaries than sharp edges. Reverse-contrast effects (such as the dungeon illusion) demonstrate that grouping need not be driven by boundaries. They show that a framework may link together disjoint elements in a scene, and that alternative frameworks may separately and simultaneously operate on different figural planes, with weights that depend on which plane the target appears to lie at.

Lightness illusions might be a result of the need to discount the illuminant: a reasonable stance, if one looks at things in evolutionary terms. But even if they are, what all our evidence seems to converge on suggesting is that, functionally, the illuminant must be defined in a truly plain, unadorned, rudimentary way. The bare necessities of life include being quick at assessing a patch in a dark region as lighter than a same-luminance patch in a light region. A device that does this will on average be successful when coping with the real world. Whether the landscape also offers especially revealing junctions, an impression of transparency, a sense of reduced illumination matters little. If this is the case, the notion of having to decompose a scene into intrinsic images in order to be able to assess lightness is overkill, and the relative simplicity of anchoring represents a very good bet.

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