Lightness and Junctions

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Abstract

The lightness of a test patch completely surrounded by an inducing field (the simultaneous contrast display) can be predicted by variants of Wallach's ratio rule. When a patch is surrounded by two or more regions with different luminances, a plausible extension of the ratio rule would predict that the effect of the surrounding regions should correlate with the length of the border they share with the test patch. However, as shown by the Wertheimer-Benary and White's effect, lightness of such patches can depart appreciably from these predictions. In this paper I argue that a fruitful approach toward the explanation of such effects is based on the analysis of junctions (such as T-junctions and X-junctions)
between regions. Several new displays and variations of old displays involving such junctions illustrate this approach. An alternative analysis of a lightness effect introduced by Adelson is provided, and the role of depth effects in achromatic perception is discussed. A number of limitations of the approach and possible ways to overcome them are discussed.

When the luminance of a single homogeneous patch of light on a homogeneous dark background is varied, its lightness*, or perceived achromatic color, changes with changes of luminance. The lightness of the patch changes also when its luminance is constant but the luminance of a neighboring region is varied. This is simultaneous lightness contrast, a classical example of contextual effects in lightness perception (see Heinemann, 1972; Whittle 1995a, b). One important aspect of this phenomenon is the degree to which the inducing field (the region whose luminance is varied) surrounds and contacts the test field (the region whose lightness is monitored). In the most thoroughly studied version of the effect the test field is completely surrounded and immediately bordered by the inducing field. As is well known, in such circumstances a test disk surrounded by a white annulus looks darker than when it is surrounded by a black annulus. The appearance of the test field over a medium to high luminance range can be predicted from the ratio of its luminance and the luminance of the inducing field (Wallach, 1948), or some related equations (Whittle, 1995a).

In another variant of the effect the inducing field does not completely surround the test field and is only in partial contact with it. For example, a square shaped test field is immediately bordered on one of its sides by an equally large square shaped inducing field (Diamond, 1955). On the basis of a comparison of the structure of studies using partial contact and surroundedness (Diamond, 1955; Horemann, 1963) with a number of experiments involving complete contact and surroundedness, Heinemann (1972) has concluded that the induction effects become more pronounced as the geometrical arrangement approaches one in which the test field is completely surrounded by the inducing field’ (p. 152).

* The distinction of lightness and brightness is not very important in display with homogeneous illumination or the absence of a salient illumination impression. Thus in most of the following it can be ignored and the terms can be used interchangeably. The exception in the discussion of Figure 8, where this distinction is crucial.

What is the appearance of a homogeneous patch when it is bordered by two or more neighboring homogeneous patches with different luminances? The ratio rule works best for instances of completely surrounded test fields, and is not immediately applicable in more complex cases, because more than one luminance ratio is involved. A plausible implication of Heinemann’s conclusion, which I will call the ‘border length hypothesis’, claims that the influence of the bordering regions should correlate with the length of the border they share with the test region. For example, a gray test field surrounded by more white than black should look darker than when it is surrounded by more black than white. The appearance of the test field in such studies might be predicted with a generalized ratio rule in the form of a weighted average, the weights being proportional to border lengths. This prediction has received qualitative support in a demonstration by Shapley (1986), which consists of a mondrian display that contains two patches of equal luminance. Both patches are surrounded by several other patches of different luminances, but one patch is mainly bordered by regions of higher luminances and the other mainly by regions of lower luminances; as expected, the first patch looks darker than the second patch.

However, in a number of cases the border length hypothesis makes wrong predictions. In this paper I will discuss some well known lightness perception phenomena, together with demonstrations of a number of new examples, that challenge it. I will argue that a fruitful strategy in the study of lightness percepts in such displays is to analyze the geometric and photometric structure of junctions (such as T-junctions and X-junctions) between regions. In the following I will apply this approach to several configurations, and will present an alternative account of an intriguing lightness effect by Adelson (1993).

Challenges to the border length hypothesis

Figure 1 contains four gray squares with identical luminance values. As a standard example of simultaneous lightness contrast, square 1 (the leftmost square), with all white borders, looks darker than square 4 (the rightmost square), with all black borders. In contrast, squares 2 and 3 have two white and two black borders, all of equal length. Thus according to the border length hypothesis, the two squares should have the same lightness, but in fact square 2 looks darker than square 3. This is an example of White’s effect (Kingdom & Moulden, 1991; Moulden &
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A new variant of the Wertheimer-Benary effect is presented in Figure 2. The figure contains four triangles of the same size, shape and luminance, but in different orientations and positions with respect to the black-white background. Note that triangle 1 (the leftmost one) and triangle 2 (the second from left) have identical luminance relations at the borders: they both have a hypotenuse formed by a white border and two cathetes formed by black borders. Nevertheless, triangle 1 looks slightly darker than triangle 2. An analogous but converse relationship obtains for triangles 4 (rightmost) and 3 (second from right). Note also that triangles 1 and 3 have similar though not quite identical lightnesses, and the same is true for triangles 2 and 4; furthermore, the former look darker than the latter.

The geometric structure of displays standardly used to demonstrate White’s effect involve gray bars embedded in black and white square wave gratings. Such designs may have motivated some accounts of White’s effect which are based upon inhibitory interactions between neural mechanisms sensitive to particular spatial frequencies and orientations (Foley & McCourt, 1985; White, 1981; White & White, 1985). However, such models may be less well suited to account for displays that involve lightness phenomena clearly related or identical to White’s effect, but whose geometry significantly departs from the standard configurations. Two such examples are presented in Figure 3. The two displays are derived as geometrical transformations of the central portion of Figure 1, in which the original shapes and sizes are distorted but topological relations and luminances are preserved. Note that the lightnesses of the gray regions are similar to the lightnesses of the corre-
The importance of T-junctions

If in a display that contains only two homogeneous patches under equal illumination, set on identical homogeneous backgrounds, one patch looks darker or lighter than the other, then the reasonable cause of their perceptual difference must be a difference of luminances of their interiors. When two patches have identically luminant interiors and still look different, as is the case for squares 1 and 4 in Figure 1, the reason that one looks darker than the other is generally ascribed to the difference in the luminance relations at their borders. But why does square 2 look darker than square 3 when they have identical interiors and identical border relations? One class of otherwise diverse explanatory strategies is based on the fact that although the borders of the two squares are equivalent, their corners are not (Moulden & Kingdom, 1989a; Gilchrist et al., in preparation; Pessoa & Ross, 1995).

To describe what happens at corners, some terminology is needed. A T-junction, represented schematically in Figure 4a, is a meeting place of three regions, labelled X, Y and Z. T-junctions belong to the general class of 3-junctions, which are structures consisting of three branches that share a common origin and divide the local neighborhood into three regions, each two of which share an edge. The specificity of T-junctions is that two of the shared edges (the X/Z and the Y/Z edge) are collinear. I will call X-regions and Y-regions collinear regions, and Z-regions flanking regions.

T-junctions, as discussed here, are geophotometric notions, that is, in addition to having geometric, or spatial structure (branches and regions), they also have photometric, or color structure (region luminances). In most cases that I will study, there is one collinear region, labelled X in Figure 4a, which is gray. Furthermore, either Y is white and Z is black (call this the collinear-white / flanking-black structure), or the other way around (the collinear-black / flanking-white structure). This is in accord with the finding of Špehar, Gilchrist & Arend (1995) that White's effect is only present if the luminance of the X-region falls between the luminances of the Y-region and the Z-region.

The difference between squares 2 and 3 in Figure 1 can now be described in the following way: for square 2, all four corners exhibit the collinear-white / flanking-black structure, whereas for square 3 all four corners exhibit the collinear-black / flanking-white structure. In Figure 2, the T-junctions of triangles 1 and 3 have the first type of structure, whereas the T-junctions of triangles 2 and 4 have the second type of structure. In Figure 3, the distorted versions of Figure 1 have conserved its T-junction structures, so that the corresponding gray regions have the same structure as in Figure 1.

The reason that White's effect and simultaneous lightness contrast are displayed together in Figure 1 is to point out the fact that squares 1 and 2 have very similar lightness values, and that the same is true for squares 3 and 4. It is as if the lightness of square 2 is not much affected by its top and bottom black neighboring regions, despite their prominent presence, but that square 2 rather 'contrasts' mainly with its

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*Figure 4. The structure of junctions. (a) The schema of a T-junction, involving three regions (X, Y, and Z), separated by three branches. As defined in the text, with respect to the X-region, the Y-region is collinear, and the Z-region is flanking. (b) The structure of all junctions in the second pair of patches in Figure 5 and at two places in the fourth pair patches. (c) The structure of all junctions in the fifth pair of patches in Figure 5 and at two other places in the fourth pair patches. (d) The schema of an X-junction, involving four regions (Y, Z, U, and V), separated by four branches. With respect to the Y-region, the Z-region is collinear, but the V-region is not.*

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The term 'flanking' is used in similar analysis by Moulden & Kingdom (1989a). I prefer 'collinear' to their 'coaxial', because the former term is applicable in Figures 2, 3 and 5, where the notion of an 'axis' is less appropriate.
white neighbors, and therefore looks like square 1; an analogous converse account applies for square 3. A similar description can be provided for Figures 2 and 3.

How can we predict the relative lightnesses of patches in Figures 1, 2 and 3? The preceding analyses can be summarized by the following qualitative \textit{T-junction rule}: the lightness of patches that share edges with several other regions and whose corners involve T-junctions is predominantly dependent on the luminance of collinear regions. The direction of the dependence is the same as in simultaneous lightness contrast, that is, a gray patch collinear with \textit{white} regions will look darker than a gray patch collinear with \textit{black} regions.

An inspection of Figures 1, 2 and 3 reveals that, in contrast to the border length hypothesis and the grating inhibition account, this rule covers all presented cases. One reason that the lightness difference may be more salient for the gray regions in Figure 1 and 3 than for those in Figure 2 could be that T-junctions constitute all four corners of the gray regions in Figures 1 and 3, but only two corners of the triangles in Figure 2. In the following it will be shown how the above rule can be applied to some novel configurations and extended to general 3-junctions and some 4-junctions. The limitations of this approach will be discussed in the last section.

\textbf{A novel lightness effect}

A related, but somewhat differently structured lightness effect is presented in Figure 5. This display has two rows containing five gray patches of different shapes and sizes but identical luminance. The bottom portion of the figure is derived from the top portion by painting the white regions black and black regions white, but conserving the luminance of the gray regions. Thus each top gray patch has a counterpart bottom patch with equal luminance but opposite surround. The first pair of patches (the two leftmost gray squares) depict another instance of simultaneous lightness contrast, presented in this figure for comparison purposes.

The second pair of patches (the two gray regions second from left) can be described as gray \textit{crosses} centered among black or white squares, or, geometrically less correct but perceptually more salient, as gray \textit{squares} partially overlapped by white or by black squares*. Note

![Figure 5. New lightness effect.](attachment://figure5.png)

* A size illusion can be noticed by comparing the perceived sizes of gray patches of the first and second pair. The grey regions of the second pair, perceived as overlapped squares, look \textit{smaller} than the squares of the first pair, although, as squares, they would have the same objective size. Related illusions were studied by Kanizsa (1979, chapter 11).
that the total lengths of the black borders and the white borders in the top and bottom gray patches are identical. Said more precisely but somewhat cumbersomely, the top patch has both white borders (four rectilinear edges) and black borders (four corners that consist of two edges forming a right angle); the length of each white border is equal to the length of each black border (the sum of the lengths of the two black edges), and thus the total length of all white borders is equal to the total length of all black borders. Analogous but converse relations obtain for the bottom gray patch. In sum, both the top and the bottom gray patch are bordered by equal extents of white and black. Thus with respect to both interior luminances and border luminance relations, the two patches are identical. Nevertheless, and this is the effect of interest here, the top patch looks darker than the bottom patch.

In the third pair of top and bottom patches the gray portions are enlarged. The total length of the black border of the top cross is three times larger than the total length of the white border, whereas the opposite is the case for the bottom cross. Thus, (as in White's effect with elongated gray bars) according to the border length hypothesis the top patch should look lighter than the bottom patch, but it actually looks darker. The remarkable fact is that the three discussed top patches (the square, the small cross and the large cross) all have rather similar lightness levels, and the same is true for the three corresponding bottom patches; furthermore, the former look darker than the latter. Thus neither the presence of the overlapping squares nor the lengths of the borders appear to have much influence on the lightness levels in these examples. However, the lightness relations are in accord with the T-junction rule. Eight corners of the crosses involve T-junctions. In top patches they are all of the collinear-white / flanking-black type, and thus these patches are correctly predicted to look darker than the corresponding bottom patches, whose T-junctions are all of the collinear-black / flanking-white type.

The patches in the fourth pair are derived from patches in the second pair by changing the overlap relations between the gray figures and the surrounding figures in two places. In the patches of the fifth pair the remaining two overlap relations are also switched. Note that these overlap exchanges have changed neither the border lengths nor the luminance relations: in all four gray patches of the fourth and fifth pair the total lengths of the black borders and the white borders are equal, just as in the patches in the second pair. However, the T-junction structures are radically changed. There are two types of T-junctions. The junctions of the first type, corresponding to all corners in the second pair and to two corners in the fourth pair patches, are depicted in Figure 4b. The junctions of the second type, corresponding to the other two corners in the fourth pair patches and to all corners in the fifth pair patches, are depicted in Figure 4c. Note that for T-junctions in Figure 4b the gray region is in the collinear position, as in the T-junction in Figure 4a. In contrast, for T-junctions in Figure 4c the gray region is in the flanking position. For such gray regions the above T-junction rule does not apply, as it only deals with lightnesses of collinear regions. Perceptually, the lightness difference between top and bottom patches of the fourth pair is elusive, and the top and bottom patch of the fifth pair appear more or less equal.

What is the relation between the lightness phenomena exhibited in the second and third pairs of patches in Figure 5, and White's effect and Wertheimer-Beany effect? In terms of local junction structure they are all very similar, and this fact is another corroboration of the T-junction rule. On the other hand, in terms of more global geometric aspects the displays are different. In particular, the new display involves perceived depth stratification, in that the gray regions are easily perceived as located behind the overlying black or white squares. This aspect of the percept is clearly due to the fact that T-junctions may act as depth cues, such that the Z-region is perceived as in front of the X-region and the Y-region (see Figure 4a). Such an interpretation is provided consistently at all T-junctions of the second and third pairs of patches. In contrast, perceived depth stratification is less apparent in the variations of the White and Wertheimer-Beany displays. The reason may be that the T-junction generated depth cues in these displays are in fact contradictory. For example, consider the middle horizontal line in Figure 1. Its parts are the top edge of square 2, the bottom edge of square 3, and the common edge of a white stripe and a black stripe. Note that the structures of the two top T-junctions of square 2, interpreted as depth cues, would indicate that the black stripe, which here takes the role of the Z-region, is in front of the white stripe (and square 2); in contrast, the structures of the two bottom T-junctions of square 3 would indicate that the white stripe, which is here the Z-region, is in front of the black stripe. A similar analysis applies for Figures 2 and 3. Such contradictory cues may induce the perceived flatness of these displays.

In spite of this difference in perceived depth characteristics, the lightness effects in the new display and in the Wertheimer-Beany and White's displays are analogous and can all be accounted for with the T-junction rule. Note that White's effect does depend on manipulations of
stereoscopic depth (Špehar, Gilchrist, & Arend, 1995; Taya, Ehrenstein, & Cavonius, 1995). However, the preceding analysis suggests that in the non-stereoscopic displays presented here, it is not the depth-inducing aspect of the T-junctions that is responsible for the lightness effects. The role of depth will be discussed further in the analysis of Figure 8 below.

Junction angles

As noted, a T-junction is a 3-junction with two collinear branches. However, in general 3-junctions no two branches need to be collinear. Not much is known about the effect of the size of the angle between branches on lightness in such displays. One type of such effect is demonstrated in Figure 6. It contains 5 displays, the first and last of which are standard White’s effect configurations, except that the two equiluminant gray squares have a common corner. This corner thus exhibits an X-junction, a coming together of four regions; the role of X-junctions will be studied further in Figure 7. Note that the top left square is lighter than the bottom right square in the first display, but that their lightness relation is reversed in the last display, in accord with the difference in orientation of the background stripes and the corresponding difference of T-junction structures.

The middle three displays depict discrete stages from a continuous transformation of the first display into the last in which the gray squares remain identical but their background gradually changes from horizontal into vertical stripes. This transformation essentially involves changes of the angles at the 3-junctions: in the course of the transformation collinear regions of the squares become flanking, and vice versa. Concomitantly, the lightness difference of the squares diminishes, disappears, and then reverses. This figure suggests an extension of the T-junction rule to general 3-junctions: the influence of a neighboring region on the lightness of a gray patch diminishes in proportion to its departure from collinearity.

X-junction effect

Lightness effects in displays involving junctions with more than three branches have rarely been explicitly studied. Moulden & Kingdom (1989b) and Zaidi (1990) have used displays with X-junctions, that is, structures with two pairs of collinear mutually perpendicular branches. In contrast, the two top displays in Figure 7 involve 4-junctions in which only two branches are collinear; for simplicity, such 4-junctions will here also be called X-junctions. All gray regions in the two displays have equal luminances. The central gray patches share two edges with white regions and two edges with black regions. The top right display is derived from the top left display by painting white regions black and black regions white. All corners of the central gray patches are constituted as X-junctions. The scheme in Figure 4d depicts such an X-junction (as exemplified by the lower left corner of the central gray patches), and the corresponding four regions, Y, Z, U, and V. The lightness of the gray region labelled Y is of interest here. Note that the branch constituting the Y/V edge is collinear with the branch constituting the Z/U edge. In accord with the terminology used for T-junctions, region Y is collinear with region Z, but not with region V. The perceptual effect that is of interest here is the following: the central gray patch in the top left display looks lighter than its counterpart in the top right display.
An account of this lightness effect involving X-junctions can be phrased as an X-junction rule, which is very similar to the above T-junction rule: the lightness of a gray patch is predominantly affected by the luminance of its collinear neighbors, and the direction of the effect is as in simultaneous lightness contrast. Thus, in the top left display the collinear neighbors of the central gray patch are black, and it accordingly looks lighter than the central patch in the top right display, whose collinear neighbors are white.

The relation of the X-junction effect and White’s effect is illustrated with two bottom displays in Figure 7. These figures are derived from the corresponding top displays by painting their first and third row uniformly with the color of the rectangles bordering the central gray patches at top and bottom. This manipulation has transformed X-junctions into T-junctions, and has transmuted the X-junction displays into a variant of White’s effect in which the gray patch in the bottom left display is lighter than in the bottom right display, a lightness difference in the same direction as between the central gray patches in the top displays.

The corrugated mondrians

The two top displays in Figure 8 are based on Adelson (1993). They are built up from the same 5x5 matrix of various grey-levelled regions in the same neighborhood relations, but with different shapes, so that the overall geometry of the figures is different. The parts of interest are the third region in the second row (I will refer to it as ‘the top patch’) and the third region in the fourth row (‘the bottom patch’). The two patches have the same luminance, but the top patch looks clearly darker than the bottom patch in the top left display, and much less so in the top right display. The reason for this difference cannot lie in the luminance relations across the borders of these patches, because these relations are identical in the two displays.

Adelson’s explanation of the lightness difference between the two patches in the top left display is that the figure ‘is seen as a 3D object with different amounts of illumination falling on the different planes. Under this interpretation, [the top patch] is a dark grey patch that is brightly lit, whereas [the bottom patch] is a light grey patch that is dimly lit. The fact that the brightness is changed suggests ... that the inferred reflectance influences the brightness estimate’. In contrast, in Figure 8b ‘the two patches are perceived as lying in the same plane with the same illumination; thus their inferred reflectances will be the same. The small residual brightness illusion might be attributed to low-level processes’ (Adelson, 1993, p. 2044). In a similar vein, Albright (1994) explains the effect in the top left display as due to the fact that the contrast between the top patch and the neighboring regions in the second row ‘is not preserved between the corresponding surfaces of the [fourth row]; it is, in fact, reversed. Since the probable shadow cannot account for such a contrast reversal, it is likely that [the top patch] has a lower surface reflectance that its counterpart [the bottom patch]. Hence [the top patch] is perceived as dimmer.’ (Albright, 1994, p. 176). In the following I will argue that this type of explanation fails to account for lightnesses in two related displays, and that the above X-junction rule offers an alternative account.
The bottom left display in Figure 8 is derived from the original figure (top left display) by changing the orientations of the parallelograms in row 4 and by bodily moving row 5 to the left to restore continuity. This manipulation has left the neighborhood relations and the luminance values unchanged, but the surface has acquired a different geometrical structure and looks like a staircase. In particular, in contrast to the original figure, rows 2 and 4 in this figure are perceived as lying in parallel planes. Thus the top patch and the bottom patch should receive the same illumination and, since they have the same luminance, according to the proposed explanation, their lightness difference should vanish, or at least decrease to the same level as in the top right display. Nevertheless, the lightnesses of the two patches in fact appear virtually the same as in the original figure.

In a counterargument, one could claim that row 4 in the bottom left display is perceived to lie in a shadow, or to be overlaid by a dark filter, and that therefore the bottom patch is still seen as dimly lit but bright. However, such a proposal would appear to be less elegant and more ad hoc than the original idea in which the difference in illumination between rows 2 and 4 follows naturally from geometry. Furthermore, one would need to explain why this shadow-or-filter account does not apply to the top right display, in which the bottom patch may also be seen to belong to a darker stripe.

Another problem for this theory is provided by the bottom right display. The difference from the original figure is that two white lines are added to flank the bottom patch. Note that a sense of the reduced illumination of the fourth row remains, but that the lightness difference between the top and the bottom patch is greatly decreased. This effect can be accounted by ‘lower level’ processes, due to which the high luminance flanks darken the gray parallelogram between them. In sum, compared to the original display, the lightness effect is changed in the bottom right display, although the phenomenal sense of illumination as well as the geometry of the original figure is preserved, whereas it is preserved in the bottom left display, although the geometry and the corresponding angle of illumination are changed. Thus although one may agree with the phenomenological description of perceived illumination differences or the perceived presence of filters or shadows, the notion that such percepts induce the observed lightness differences between the two patches is doubtful.

The effects in Figure 8 are consistent with the X-junction rule. Note that both the top and the bottom patch in the original figure are
collinear with their horizontal neighbors. These neighboring regions have a higher luminance in the case of the top patch and a lower luminance in the case of the bottom patch, and thus, according to the rule, the bottom patch should look lighter, as it does. Furthermore, note that the transformation that has converted the original figure into the bottom left display has changed the perceived global 3-D geometry, but has conserved the collinearity relationships between its elements, so that, in terms of X-junctions, the same analysis applies as for the original figure, and the same perceptual outcome is evident. In contrast, the transformation that has converted the original figure into the top right display has not only changed the 3-D geometry but also the collinearity relationships: here the two corresponding patches are collinear with their vertical neighbors. All these neighboring regions have the same luminance, and thus the X-junction rule predicts no lightness difference between the two patches. The fact that a small difference does persist is consistent with the idea that lightness is predominantly but not exclusively affected by collinear regions, and that flanking regions may induce a residual effect.

The preceding analysis suggests that the lightness effects in Figure 8 can be accounted for without invoking perceived illumination and 3-D structure. However, it does not follow that these factors are irrelevant for lightness perception in general. In fact, depth effects on lightness were demonstrated in a number of experiments (Beck, 1965; Flock & Friedberg, 1970; Gilchrist, 1977, 1980; Gogel & Marshon, 1969, 1970; Hochberg & Beck, 1954; Marshon 1972; Schirillo, Reeves, & Arend, 1990; Wolff, 1933), although other studies failed to register them (Dalby, Saillant, & Wooten, 1995; Epstein, 1961; Gibbs & Lawson, 1974; Gilchrist, 1980; Julesz, 1971; Rubin, 1934). The reasons for these discrepancies are not quite clear (for some discussions see Dalby, Saillant, & Wooten 1995, Gilchrist, 1980, and Gogel & Marshon, 1977). Gilchrist (1980) noted that one condition to obtain strong depth-related lightness effects is that the luminance range of the display significantly exceeds the 1:3 ratio, which is approximately the range of reflectances of objects in everyday environments. Except for atypical cases such as fluorescence, this luminance range can only be exceeded when the scene contains multiple light sources, shadows, or strong gradients of illumination. In displays such as those in Figure 8, observed under homogeneous illumination, such is not the case. Furthermore, in studies that obtained depth effects on lightness, the perceived 3-D organization was mainly induced by monocular or binocular depth cues from real 3-D scenes or by stereoscopic presentations, whereas the displays in Figure 8 are neither in real 3-D nor involve stereoscopy, but invoke depth purely through geometric organization.

According to Adelson (1993), the difference between the two patches in the original display is that although they have the same luminance, one looks as a dark gray patch brightly lit whereas the other looks as a light gray patch dimly lit. Now, conditions can be arranged in which a black surface receives higher illumination than a white surface (due to a spotlight or differential orientation toward the light source), such that their luminances are equal. In relatively articulated scenes and with favorable viewing conditions (such as non-restricted overview of the scene, binocular observation, near viewing distance etc.), subjects can distinguish the two surfaces, and correctly perceive one as highly illuminated black and the other as poorly illuminated white, although they may also note that there is an additional perceptual aspect (correlated with luminance) in which the surfaces are very similar (Gelb, 1929, 1932; Gilchrist, 1979, 1980; Katz, 1935; Hering, 1920/1964; Schirillo & Arend, 1995). Such percepts involve a phenomenological separation of perceived reflectance (lightness), perceived illumination, and perceived luminance (brightness); that is, the same surface may simultaneously exhibit values on three different achromatic perceptual dimensions. Acknowledgement of this perceptual multidimensionality is indeed crucial for clarification of lightness perception problems. Computer-generated displays can be constructed in such a way that the same patch can be judged both with respect to its brightness and to its lightness, with relatively different outcomes (Arend & Goldstein, 1987; Arend & Špehar, 1993a,b). However, in my judgement, a clear separation of these attributes is not perceptually salient in displays in Figure 8. Adelson (1993) notes the importance of the lightness-brightness distinction, but although the interpretation of the results is formulated in terms of lightness (it invokes the difference between a light gray patch dimly lit and a dark gray patch brightly lit), his subjects were only asked to match the brightnesses of the patches. In sum, as suggested by the preceding arguments, the factors that play a role in genuine 3-D scenes under differential illumination may not readily transfer to percepts induced by flat homogeneously illuminated displays, and the role of more complex 'lower level' structural factors, such as T-junctions and X-junctions, must be controlled for and taken into account.
Limitations

The junction-based account has a number of limitations. For example, it has been checked only for a limited number of different displays. Adelson (1993) has presented a lightness illusion using ‘wall-of-blocks’ patterns involving four lightness levels, 3-junctions, 6-junctions, and two different types of 4-junctions. The present account should be extended to handle such rather complex displays. Also, the current version of the account is qualitative and relative, as it only predicts ordinal lightness relations between regions. One way to quantify it would be an extended ratio rule involving large weights correlating with junction angles and small weights correlating with border lengths.

Another limitation of the junction-based account is that, similar to the ratio rule, the account is an input-output regularity and is silent about the underlying mechanisms. One strategy for the study of such mechanisms is to simulate the structure of neural activations induced by various types of junctions. One type of such analysis was performed by Moulden & Kingdom (1989a), who present the results of convolutions of elementary White’s effect stimuli with difference-of-gaussians kernels. The resulting displays indicate a structural difference of the effects of two types of T-junctions on a field of simulated neurons with concentric antagonistic receptive fields. Another example is work by Pessoa & Ross (1996), an extension of the Grossberg & Todorović (1988) brightness model. They present a neural network simulation involving a number of different interacting processing levels, that involve inhibitory interactions between boundary contour mechanisms, and neural structures that act as T-junction detectors and depth cues. On the other hand, Gilchrist et al. (in preparation) have shown how an approach based in part on the gestalt concept of perceived belongingness can account for a wide variety lightness phenomena. An inspection of the figures presented here indicates that junction structure is indeed a powerful determinant of perceived belongingness of collinear regions, and conversely, the non-belongingness of non-collinear regions. Furthermore, the gray patches that are perceived to belong to white regions look darker than patches perceived to belong to black regions. Note that many factors other than T-junctions may also determine perceived belongingness and lightness (Agostini & Proffitt, 1993; Gilchrist et al., in preparation).

A major problem with the junction account, as formulated above, is that small displacements of display regions can lead to drastic changes in terms of junction structures, but may not induce similarly drastic changes of lightness. For example, suppose that square 2 in Figure 1 is displaced vertically upwards, and that the displacement distance is equal to 10% of the length of its side. Ten successive displacements of this type would transport the square to a position equivalent to the position of square 3. As White & White (1985) have shown in a study of essentially this form, in such a transformation the lightness of the square would increase gradually from its initial darker value to the lighter value of square 3. In contrast, the junction structure changes quite abruptly already with the first displacement, and remains the same until the penultimate displacement, when it changes again. White & White (1985) see this outcome as a serious difficulty for approaches based on local analyses, such as T-junctions.

![Figure 9. Transformations of T-junctions. (a,b,c) Three positions of a square on a grating. See text for details. (d,e,f) Local structures at the corners of the squares in a, b, and c.](image)

I do not regard their finding as a proof that the junction account is invalid, but rather that it must be augmented with additional considerations. Some essential aspects of their stimuli are represented in Figure 9. The initial position of the square, as well as its positions after the first and fifth displacement step, are schematically depicted in Figures 9a, b, and c. The corresponding junction structures at the top and bottom left corners are depicted in Figures 9d, e, and f. A classification of Figures 9a, b, and c purely in terms of junctions would assign Figures 9b and 9c into the same category, and Figure 9a into a different category. However, such a classification would clearly fail to capture an aspect in which Figures 9a and 9b are similar to each other, and different from Figure 9c. For example, the square in Figure 9b is nearer to its position in Figure 9a than in Figure 9c. Similarly, the local structures in Figure 9e can be regarded as more similar to those in Figure 9d than in Figure 9f, for example in the sense that blurred versions of Figure 9d and 9e would be hard to distinguish, but both would be much more clearly distinct from the blurred version of Figure 9f.

The relevance of these considerations may be appreciated in relation to the accounts of the White illusion based on T-junctions. For example, consider the Moulden & Kingdom (1989a) approach, which stresses the distributions of activation induced in sheets of neurons with concentric opponent receptive fields. One would expect that the activation distribution induced by the geophotometric structures in Figure 9e would be more similar to the distribution induced by structures in Figure 9d than by structures in Figure 9f. Similarly, a more general version of Pessoa & Ross (1995) T-junction detectors should react more similarly to structures in Figures 9d and 9e than to structures in Figure 9f. Finally, within the belongingness approach of Gilchrist et al. (in preparation), it can be argued that whereas the square in Figure 9a clearly belongs to the white stripe, the square in Figure 9b is also perceived to belong to it, but to a somewhat smaller extent, in distinction to the square in Figure 9c. In fact, although these three approaches are clearly opposed to each other in many aspects, on a more general level they may to some extent be complementary: a certain activation structure of concentric opponent neurons might be equivalent to a T-junction detector, which may be one determinant of belongingness.

The usefulness of the junction analysis is that it directs our attention to some particularly simple and salient local stimulus configurations. The structure of lightness effects generated with such prototypical displays may guide our attempts to understand the phenomena induced by more complex and messier stimuli. In spite of limitations, the junction analysis provides a simple account of the few relevant previously described phenomena as well as of some novel configurations presented here. It is also shown to be superior in terms of empirical adequacy and breadth of application to some alternative accounts. Furthermore, it is demonstrated here that the relation of roles of junctions and depth in achromatic color perception needs careful consideration. In sum, the analysis of junctions appears to provide useful constraints for broader theories of lightness perception.

References


