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A gestalt account of lightness illusions

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Abstract. Illusions of lightness offer valuable clues to how lightness values are computed by the visual system. The traditional domain of lightness illusions must be expanded to include failures of constancy, as there is no distinction between these categories. Just as lightness is (relatively) constant in the face of changes in illumination level, so it is equally constant in the face of changes in background reflectance. Simultaneous lightness contrast, the most familiar lightness illusion, is fairly weak, and represents a failure of background-independent lightness constancy. It is argued that a combination of the highest-luminance rule of anchoring plus the Kardos idea of codetermination can account for most lightness illusions. Kardos suggested that the lightness value of a target surface is partly determined relative to the field of illumination (or framework) in which it is embedded, and partly relative to the neighboring field of illumination. Although Kardos did not apply his principle of codetermination to failures of background-independent constancy such as the simultaneous contrast illusion, this can be done rather easily by defining a framework as a perceptual group instead of identifying it strictly with an objective field of illumination.

Keywords: lightness, illusion, failures of constancy, simultaneous lightness contrast, reverse contrast, illumination, anchoring, codetermination

1 Introduction

The most familiar lightness illusion is called simultaneous lightness contrast, shown in figure 1. When two identical gray squares are placed on adjacent white and black backgrounds, the gray square on the black background appears lighter than the other square. Simultaneous contrast can also be called a brightness illusion. Lightness is perceived reflectance, while brightness is perceived luminance. Lightness is the more important term, as it refers to the our perception of the properties of an object or a surface. In recent decades many new lightness illusions have appeared. To what extent is it possible to find a common explanation for them?

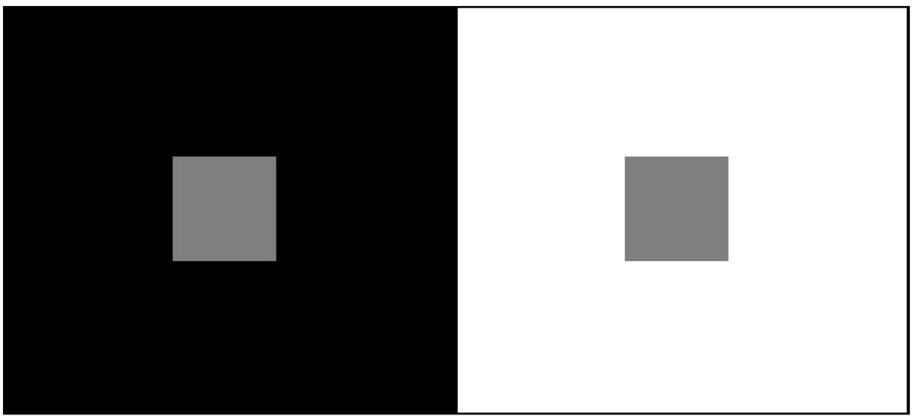

Figure 1. Simultaneous contrast illusion. Identical gray squares appear different when placed on black and white backgrounds.

2 Illusions as failures of constancy

Before we deal with explanation, we must expand our list of illusions by adding another category of perceptual phenomena that has historically been treated separately: failures of lightness constancy. Lightness constancy refers to the empirical fact that the perceived lightness of an object remains surprisingly constant despite a change in the illumination level. Constancy is rarely 100%; there is always some percentage of failure. For example, when the amount of light illuminating an object level is reduced by some percentage, the perceived reflectance of the object will not be reduced by the same percentage, but it might be reduced by one tenth as much as that. This is called a failure of constancy. But it is also a lightness illusion.

Failures of constancy must be included in our list of lightness illusions because failures of constancy satisfy the traditional concept of an illusion—namely, a discrepancy between the distal stimulus and the percept. Illusions and failures of constancy have been treated separately mainly for historical reasons. Of course, by tradition, failures of constancy, unlike illusions, involve adjacent regions of different illumination levels while illusions involve adjacent regions of different reflectance. But this distinction does not change the fact that in both classes of phenomena the percept diverges from the distal stimulus.

Unlike failures of constancy, illusions may seem surprising because targets of equal luminance appear different in lightness. In failures of constancy the targets that appear different in lightness also differ in luminance. However, this assumes that the input to lightness is luminance. Evidence from both stabilized retinal images (Yarbus, 1967) and physiology (Barlow & Levick, 1969; Cleland & Enroth-Cugell, 1970; Derrington & Lennie, 1982; Enroth-Cugell & Robson, 1966; Troy & Enroth-Cugell, 1993) suggests that it is luminance ratios that are encoded at the retina, not luminance per se. From this perspective it can be argued that failures of constancy are more surprising because the targets appear different in lightness even though they have equal luminance ratios. In illusions such as simultaneous contrast the targets have different luminance ratios and they appear different. But nevertheless, failures of constancy satisfy the traditional definition of illusion: a difference between distal stimulus and percept.

If a failure of constancy constitutes a lightness illusion, we can also say that the simultaneous contrast illusion constitutes a failure of constancy. To make this clear, we must explore the topic of constancy a bit more.

2.1 *Two kinds of constancy*

Today, those who study lightness understand that we must talk about two fundamental types of lightness constancy. The traditional, familiar type is called illumination-independent constancy. The more recently recognized type is called background-independent constancy (Arend, 1994; Gilchrist, 2006). For most of the nearly 150-year history of lightness research, the term lightness constancy referred to first of these, the relative constancy of surface lightness despite changes in the illumination level. In 1948 Wallach pointed out that there is a very simple solution to this kind of constancy; the lightness of a surface is based simply on the luminance ratio between the surface and its immediate background. Wallach noted that, when the illumination level changes, this ratio does not change, and this, he suggested, explains constancy.

The recognition that lightness is also largely independent of background luminance came to be recognized only in the latter half of the 20th century (Arend & Spehar, 1993; Brenner & Cornelissen, 1991; Gilchrist, 1988; Gilchrist, Delman, & Jacobsen, 1983; Whittle & Challands, 1969). Whittle (1994, page 128) has given a compelling description of this kind of constancy:

> "An object moved over different backgrounds does not seem to change much in lightness. To get a good look at a sample of cloth, you may pick it up and take it to a good light, but you don't worry about what background is behind it. It's as though

> the background doesn't matter. It is not that there is no simultaneous contrast effect, if you look for it; just that it is amazingly small. If brightness were always contrast brightness such objects would flash on and off all the time as they changed from being increments to decrements. They do not."

The lightness of an object remains roughly constant as the object is viewed against different backgrounds. This challenge to constancy is just as important as the challenge posed by changes in illumination level, but it cannot be explained by Wallach's ratio theory. Indeed, ratio theory explicitly predicts that the lightness of the object will change when viewed against different backgrounds. But, you might respond, everyone knows that lightness *does* change when the background changes. Is that not exactly what simultaneous lightness shows?

2.2 *Two kinds of constancy failures*

Fair enough. But the simultaneous contrast illusion is relatively weak. For two targets of the same luminance, black and white backgrounds produce only one sixth as much perceived lightness difference as do backgrounds that are equally different in luminance when that difference is seen as a difference in illumination. Thus, the simultaneous contrast illusion should be called a failure of background-independent constancy. The same pattern applies to both failures of illumination-independent constancy and failures of background-independent constancy. A gray object does look darker gray when placed in a shadow, but typically its reduction in perceived lightness is only about 10% of the amount by which its luminance is reduced. Likewise, when a gray square is moved from a black background to a white background, the reduction in its lightness is only about 10% of the amount its lightness should be reduced according to ratio theory (Gilchrist, 1988; McCann, 1987).

For example, in the standard case of two gray squares on adjacent black and white backgrounds, the local luminance ratios of these two squares differ just as much as the local luminance ratios of a white square and a black square standing on a common middle gray background. That is, a white square on a middle gray background has the same local ratio as the gray square on the black background in the simultaneous contrast illusion, and a black square on a middle gray background has the same local ratio as the gray square on the white background. Obviously in the case of simultaneous contrast, the two squares look nowhere near as different as white and black. It is more like 10% of that difference. Thus in the case of simultaneous contrast we have a 10% failure of background-independent constancy, and a 90% success, just as with illumination-independent constancy we find roughly a 10% failure and 90% success, given a change of illumination commensurate with the change in luminance from white background to black background.

These percentages refer to the location of subject matches along a log scale running between two poles: luminance matching and ratio matching. For simultaneous contrast, 100% success means luminance matching while 0% success means ratio matching. For failures of constancy these are reversed; 100% success means ratio matching while 0% success means luminance matching, consistent with the traditional Brunswik (1929) or Thouless (1931) constancy measures.

3 Components of an explanation

Finding an explanation that can be applied to the entire range of lightness illusions presents a challenge, even more so now that we have expanded our collection of lightness illusions to include what have usually been called failures of constancy. Nevertheless, I believe that a combination of the highest luminance rule of anchoring (Li & Gilchrist, 1999) and the principle of codetermination proposed by Kardos (1934) can come close. First, a brief summary of these components.

3.1 *Highest luminance rule*

It is widely recognized that lightness depends strongly on relative luminance, as Wallach had suggested. But relative luminance, per se, is not sufficient to generate specific lightness values. For that, an anchoring rule is needed. An anchoring rule states a relationship between some value of relative luminance and a value on the scale of perceived lightness. Two candidate rules have been suggested. The highest luminance rule, which was suggested by Wallach (1976) and by Land and McCann (1971), states that the highest luminance within the scene (or more likely, within a field of illumination) will appear white and serve as the standard for darker values. The average luminance rule, central to Helson's (1964) adaptation-level theory and equivalent to the gray world assumption (Buchsbaum, 1980; Hurlbert & Poggio, 1988), says that the average luminance within a scene will appear middle gray and serve as the standard to which lighter and darker regions are compared.

Li and I (Li & Gilchrist, 1999) pitted these two rules against each other. The concept was to present an observer with two adjacent surfaces of different luminance that fill the entire visual field. Under these conditions the visual system would be presented with only relative luminance. The specific shades of gray perceived by the observer would reveal the visual system's implicit anchoring rule. To this end we placed the observer's head inside a large, diffusely illuminated, opaque hemisphere. Half of the interior of the hemisphere was painted black, and the other half was painted middle gray. According to the average luminance rule, the two halves should appear light gray and dark gray, symmetrically distant from middle gray, with no white or black appearing. However, every subject perceived the gray half as white and the black half as middle gray, providing unequivocal support for the highest luminance rule.

3.2 *Codetermination*

Kardos (1934), the brilliant but neglected gestalt theorist, was perhaps the first to propose a theory of (illumination-dependent) failures of lightness constancy. Katz (1935), who did much of the pioneering research in lightness, showed that lightness must be computed using separate standards in separate fields of illumination. Gestaltists like Koffka (1935) and Gelb (1929) regarded separate fields of illumination as frames of reference for lightness computation, a framework being a region of the retinal image that is perceived as having a single, common level of illumination. Kardos went beyond the framework idea to argue that lightness is not computed exclusively within such frameworks, but there is always some cross-talk between frameworks. He called this cross-talk codetermination, suggesting that the lightness of a given surface is determined not only by its relationship to the field of illumination in which it is embedded, which he called the relevant field, but also to some extent by the neighboring, or surrounding, field of illumination, which he called the foreign field.

This explains why an object appears to have a slightly darker reflectance when it is placed within a shadow. Without codetermination (that is, without the influence of the foreign framework), object lightness would be seen veridically; that is, the match selected by a subject would have the same reflectance as the object. But relative to the field of illumination outside the shadow, the target is a darker gray; and even if this relationship is given a weight of only 10%, it predicts that the target will be seen as somewhat darker than otherwise.

In anchoring terms, the lightness of a given target is anchored partially by the highest luminance in its relevant framework and partially by the highest luminance in the foreign framework. In general, anchoring within the relevant framework produces constancy while anchoring to the foreign framework produces failures of constancy. Keep this heuristic in mind in the analysis that follows.

Empirical results indicated that, within each framework, lightness is computed by assigning the value of white to the highest luminance (Li & Gilchrist, 1999), which serves as the anchor, and then computing the lightness of darker surfaces in proportion to their luminance relative to the anchor. Thus, for example, if the luminance of a given surface is half of the luminance of the anchor, its computed reflectance (45%) will be half that of white (90%). The formula is simply $R = (T/H)0.9$, where R is perceived reflectance, T is target luminance, H is the highest luminance, and 0.9 is the reflectance of white.

3.3 *Weighting*

Katz (1935) presented observers with adjacent fields of illumination and shadow, as shown in figure 2. Each field contained a gray disk, actually a spinning color wheel adjustable for gray shade. The disk in one field would be set to a fixed gray shade, and the observer was asked to adjust the other disk until the two disks appeared equal in surface lightness.

Katz, working with his student Burzlaff (1931), found that the degree of constancy depends on two main factors: (1) the size of the fields and (2) the degree of articulation of the fields. Articulation level was operationally defined as the number of distinct surfaces within a field. Ironically, Katz never integrated these empirical findings into his theory of lightness constancy, which was scarcely different from Helmholtz's (1866/1924) proposal that the level of illumination is taken into account. But it is the Kardos concept of codetermination that really makes sense out of Katz's findings. The larger the relevant field of illumination and the greater its degree of articulation, the more weight it has in the codetermination compromise, and thus the higher the degree of constancy (ie the smaller the failures).

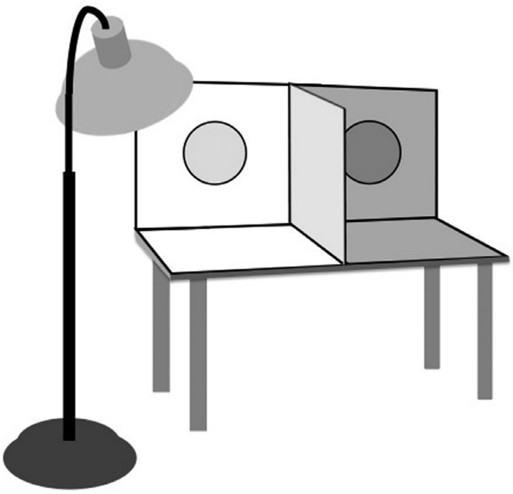

Figure 2. Arrangement used by Katz (1935) to study lightness constancy.

Thus, the Kardos principle of codetermination (and specifically the influence of the foreign field of illumination) explains the failure of constancy (which I am calling an illusion) under a change of illumination. And the Katz–Burzlaff finding that the size of the failure of constancy is inversely proportional to the degree of articulation can be understood by assuming that the articulation level within a framework modulates the influence of that framework in the codetermination process.

4 Application to illumination-dependent failures

This combination of codetermination and highest luminance anchoring also provides an explanation of most additional aspects of the pattern of constancy failures, including the following:
(1) It explains why the deviations from constancy are greater (in absolute terms, not relative) when the difference in illumination is greater, because then, relative to the foreign field, a target surface in shadow becomes even darker gray and a target surface in bright illumination becomes even lighter gray.

(2) It explains why the deviations from constancy (even in relative terms) are not equal for all shades of gray. Empirical results (Ivory & Gilchrist, 2010) show that, in a shadow, light grays are darkened more than dark grays. This is because, for a light gray target, the gap between its value relative to the relevant framework and its value relative to the foreign framework is greater than the gap for a dark gray target. Likewise, for analogous reasons, in a spotlight, lightness values rise, but dark grays are lightened more than light grays (Cataliotti & Gilchrist, 1995).
(3) It explains why, with adjacent fields of light and shadow, the degree of illumination-independent constancy is higher when both backgrounds are light gray than when both backgrounds are dark gray, as reported by Kardos (1934), Helson (1943), Leibowitz, Myers, and Chinetti (1955), and Hano (1955). This stems from the asymmetry inherent in the highest luminance rule. The darker the backgrounds, the more likely each target is to be the highest luminance in its relevant framework and be assigned a value of white. Keep in mind that constancy tends to come from anchoring in the relevant framework while failures of constancy come from anchoring in the foreign framework. As long as both targets are the highest luminance in their relevant frameworks, regardless of what those luminances are, the two targets will have the same lightness value (white) in those relevant frameworks. If the two targets have equal luminance values and are seen as equal in lightness, this is defined as zero constancy.

Strictly speaking, this implies that the crucial factor is not so much the darkness of the backgrounds, but whether or not each target is an increment (and thus the highest luminance) relative to its background. Thus, we would expect that decremental targets on dark backgrounds would produce better constancy than incremental targets on relatively light backgrounds. In fact, Kozaki (1963, 1965) has shown exactly this result.

Consistent with Katz's (1935) early findings, a wide range of more recent studies has shown that the size of illumination-dependent failures of constancy is inversely related to the degree of articulation within the relevant framework (Adelson & Pentland, 1996; Arend & Goldstein, 1987; Burzlaff, 1931; Henneman, 1935; Kardos, 1934; Katona, 1929; Kozaki, 1963; Schirillo & Arend, 1995; Wishart, Frisby, & Buckely, 1997). Although most theories of lightness and brightness offer no account of this powerful effect of articulation level, it fits comfortably with the concept of codetermination, with its graded balance of relevant and foreign influences, and the provision that the weight given to a given framework is strongly determined by its degree of articulation.

5 Kardos's treatment of simultaneous contrast

Kardos never applied his codetermination principle to simultaneous contrast. Kardos (1934) attributed this contrast illusion to what he called faulty performance:

> "in all typical contrast situations there exists some unfavorable aspect in the stimulus configuration, so that the above system must go wrong in its performance, which has to lead to 'illusions' concerning object colors" (page 178).

However, he did not link this faulty performance in simultaneous contrast—that is, background-dependent failures of constancy—with the faulty performance represented by illumination-dependent failures of constancy. In his discussion of faulty performance in simultaneous contrast (Kardos, 1934) he claims that (illumination-independent) lightness constancy "certainly does not involve such a faulty performance" (page 82). Yet he himself documented the faulty performance in constancy, referring to the "imperfection of the organization into specially illuminated fields" (page 178).

In fact, it is not too difficult to extend the Kardos notion of codetermination to cover simultaneous contrast. To do so requires a shift in the concept of framework. The two halves of the simultaneous contrast pattern must be treated as frameworks even though they are not experienced as fields of illumination.

5.1 *Frameworks*

The term framework refers to the gestalt concept of the frame of reference. This concept is most intuitive in motion perception. Motion is always perceived in relation to a frame of reference. If a bag falls off the luggage rack on a train, we perceive it to fall vertically. Yet, in relation to the environment outside the train, it falls obliquely. The value of this concept is not confined to perception; it plays an essential role in physics, as has been amply demonstrated in the thinking of Einstein involving elevators and trains. In motion perception the concept of frame of reference has been exploited most prominently by Koffka (1935) and by Duncker (1950). But for Koffka and Kardos the concept is essential for understanding lightness as well, arguing that Katz's 'fields of illumination' serve as frames of reference in computing lightness values.

Even for Kardos, the concept of framework, or field, is not synonymous with a field of illumination. Kardos himself recognized that a region of the visual field does not function as a frame of reference merely because it objectively is a field of illumination: "The objective partition of the whole field into such regions cannot be the immediate cause of the parallel phenomenal organization" (1934, page 56). The partition of some region of the visual field into a framework must be determined by certain 'cues' or grouping factors. But inevitably some of those cues will appear even in the absence of a region of illumination. In such cases those cues will function in the same way, and produce framework effects, though possibly much weaker effects.

The simultaneous lightness pattern contains two obvious frameworks: the black background surrounding one gray square and the white background surrounding the other. Objectively, these are not two fields of illumination; nor are they perceived as differing in illumination. But they share certain features with fields of illumination. For example, the black background has a border that has a consistent sign along its entire length, something that is also true of a shadow. If one assumes that the two halves of the simultaneous contrast illusion function as weak frames of reference, one can account for the illusion using the Kardos codetermination idea.

5.2 *Relevant/foreign versus local/global*

The codetermination approach to simultaneous contrast is already incorporated within anchoring theory (Gilchrist, 2006; Gilchrist et al, 1999), except that the Kardos concepts of relevant and foreign have been replaced by the closely related concepts of local and global. While relevant and foreign frameworks are typically coequal and adjacent (like France and Switzerland), local and global frameworks are hierarchical (like France and Europe), with the local framework embedded within the global. It appears that the contrast illusion can be explained using either construction, and presumably further research will sort out which is most correct. For present purposes, however, we will analyze lightness illusions in local/global terms.

6 Application to background-dependent failures

In the simultaneous contrast display the two local frameworks are obvious. The global framework includes both of these and, depending on the larger context, might include the desk on which the pattern rests and/or other elements of the environment. But for simplicity we will begin by defining the global framework merely as the whole contrast pattern itself.

To derive predicted values in the contrast display, we need to (1) compute all the values within the local frameworks, (2) compute the global values for the same surfaces, and then (3) take a weighted average. The weights depend mainly on the articulation (number of distinct patches) within a framework.

6.1 *Scale normalization.*
One additional factor needs to be mentioned, and it concerns the relationship between the range of luminances within a framework and the range of perceived lightness values. Empirical results reveal a tendency for the perceived range to approximate the range between white and black (30:1, because white reflects roughly 90% and black roughly 3%). Thus if a framework contains a luminance range greater than 30 : 1, the range of lightness values will be somewhat compressed relative to the luminance range. And when the luminance range within a framework is less than 30 : 1, the perceived range will expand.

Now let us apply these ideas to the simultaneous contrast illusion. In the global framework both gray squares are assigned the same value of middle gray. The illusion comes from their differing local values. The gray square on the black background, being the highest luminance in its framework, gets a local value of white. This tells us that its perceived value must lie somewhere between white (local value) and middle gray (global value), depending on the weighting function. Because the global framework has twice as many elements (and many more if the larger surround is included) it gets more weight than the local framework. Thus the square should appear closer to middle gray than to white. Thus the illusion is attributed primarily to the lightening of this square due to its local value of white. A strikingly similar explanation for the simultaneous contrast illusion was given by McCann (1987).

For the square on the white background, its local value is similar to its global value except that scale normalization in the local framework would darken it slightly. (The luminance range within its framework is about 5:1, so some expansion will occur, expressed as a movement away from the anchor.) This kind of explanation is qualitatively different from the traditional account of simultaneous contrast in terms of lateral inhibition. The key features of this approach are (1) perceptual grouping, (2) anchoring, and (3) codetermination.

7 Role of perceptual grouping in simultaneous contrast
According to the traditional account of simultaneous lightness contrast, the background of each target square exerts its effect through lateral inhibition occurring at the target–background border. However, according to the gestalt model proposed here, each target square is perceptually grouped with its immediate surround. That is, the important factor is not that the target and its background share a border, but rather that they appear to belong together. These two claims may seem similar, but they can be distinguished.

The first demonstration that belongingness is more important than adjacency can be seen in figure 3, which shows the Benary effect studied by Benary (1924) and his mentor, Wertheimer.

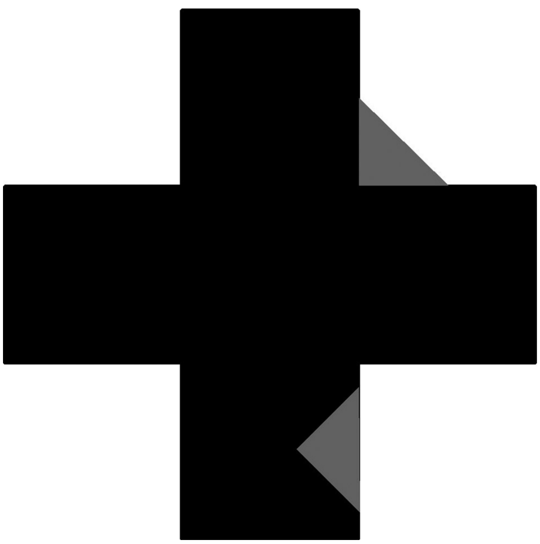

Figure 3. The Benary effect. The two triangles are identical and have identical adjacent luminances, yet they appear different.

In this example the lower gray triangle appears slightly lighter than the upper triangle, even though the two gray triangles not only have equal luminance, but in fact they have identical local neighbors. Both triangles border white along the hypotenuse and black along the two other sides. Obviously, the lower triangle appears to belong to the black cross while the upper one appears to belong to the white background. This illusion, though weak (Gilchrist, 1988; Mikesell & Bentley, 1930), already suggested that the contrast illusion has to do with perceptual grouping.

White's (1979, 1981) illusion, seen in figure 4, is much stronger, even stronger than simultaneous contrast (Gilchrist, 1988; McCann, 1987; White, 1981), despite the fact that any traditional contrast effect based on neighboring regions adjacent to the target bars should go against the illusion. But, just as in the Benary illusion, the bars that appear darker are those that appear to belong to the white background, while the bars that appear lighter appear to belong to the black stripes. The Todorović (1997) illusion seen in figure 5 shows the same effect as White's illusion, but here the asymmetry between the degree of contact with white and black neighbors is pushed to an extreme. In these three illusions the key grouping factor appears to be the T-junction, which seems to group together the regions that meet at the stem of the T, but to segregate the region above the top edge of the T from those below it.

Figure 4. White's illusion shows that perceived belongingness is more important than adjacent luminance. The gray bars are all identical.

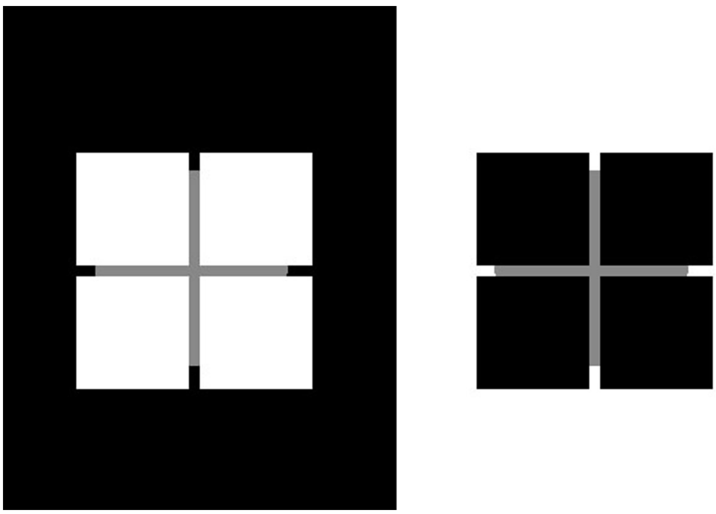

Figure 5. The Todorović illusion is a more extreme version of White's illusion. The gray region bordered mostly by white appears lighter than the identical region bordered mostly by black.

Finally, the importance of target–background belongingness over target–background adjacency becomes complete in a class of illusions called reverse contrast illusions. Figure 6 shows one example, Bressan's (2001) dungeon illusion. The gray square that shares its entire border with black appears darker, not lighter, than the square that shares its entire border with white. The reason for this counterintuitive outcome is obvious in light of our previous discussion. A perceptual group has been created to which the gray square belongs due to similarity and proximity. This and other reverse contrast illusions (Agostini & Galmonte, 2002; Gilchrist, 2006) show that what is important about the so-called inducing region is not that it shares a border with the target but that it is perceptually grouped with the target.

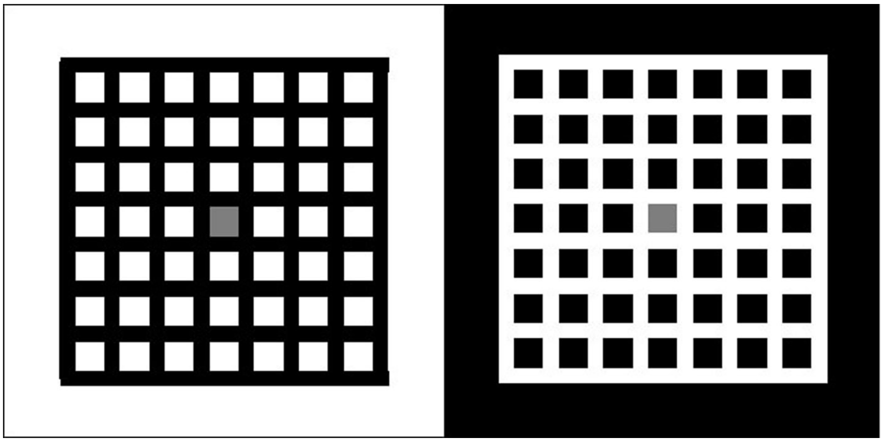

Figure 6. In Bressan's (2001) dungeon illusion the square totally surrounded by black appears darker than the identical square surrounded by white.

Economou and I carried out a series of experiments using his version of reverse contrast (figure 7) in which we varied the strength of different grouping factors to see how this would affect target lightness (see Gilchrist, 2006, pages 323–324). We varied (1) the good continuation of the end points of the flanking bars, (2) the proximity of the target and flanking bars, (3) the shape similarity of the target to the flanking bars, (4) the orientation similarity of the target and flanking bars, and (5) the number of flanking bars (articulation). In each case we found that

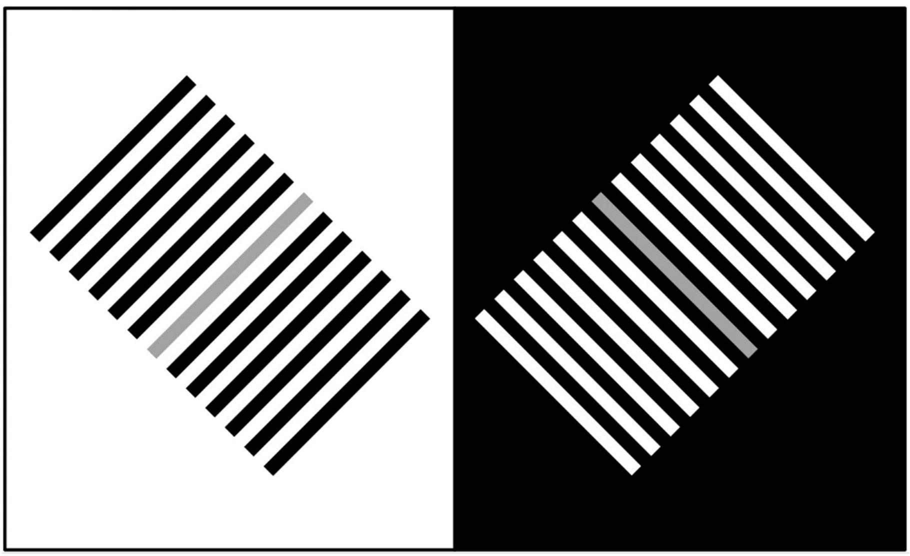

Figure 7. Reverse contrast illusion created by Economou.

degrading the grouping factors on which the perceived group of bars is based systematically weakens the reverse contrast illusion. In a separate line of research we used a stereoscope to determine in which of three depth planes each component (the target bars, the flanking bars, and the black and white backgrounds) appears. Consistent with the grouping approach, we found the strongest illusion when the target bars and flanking bars appeared in the same plane but the black and white backgrounds appeared in a deeper depth plane. We found no reverse contrast (but no contrast either) when the target bars appeared in the same plane as the black and white backgrounds while the flanking bars appeared in a nearer depth plane.

Coren (1969) performed analogous experiments using the Benary effect. He used stereopsis to cause each of the gray triangles to appear either in the same plane as the black cross and white surround or in a nearer plane. This manipulation of depth modulated the Benary effect in a manner that was consistent with the grouping interpretation of simultaneous contrast. These results due to grouping by coplanarity are consistent with my earlier experiments that used grouping by coplanarity to produce even larger lightness differences (Gilchrist, 1977, 1980).

Many recent publications have shown that the strength of the simultaneous contrast illusion can be modulated by manipulating grouping factors. Laurinen, Olzak, and Peromaa (1997) showed that simultaneous contrast can be strengthened or weakened using the spatial frequency of a texture overlaid on each of the four regions to perceptually group or ungroup them. They showed that the illusion is weakened when the two target squares share a common texture and the backgrounds share a common (but different) texture. I have shown (Gilchrist, 2006, figure 10.4) that the contrast illusion is strengthened when each target shares the same texture as its own background, but the texture of one target–background pair is different from that of the other target–background pair. Bonato, Cataliotti, Manente, and Delnero (2003) have also both weakened and strengthened the simultaneous contrast illusion using texture as a grouping principle. Olkkonen, Saarela, Peromaa, and Laurinen (2002) have demonstrated a weakening of the illusion when the targets share a common hue and the backgrounds share a common, but different, hue.

A number of studies (Agostini & Bruno, 1996; Arend & Spehar, 1993; Bressan & Actis-Grosso, 2001; Diamond, 1953; Gilchrist, 1988; Heinemann, 1955; Jacobsen & Gilchrist, 1988; Schirillo & Shevell, 1997) have reported that little or no contrast effect occurs when both target squares are increments (higher luminance) relative to their respective backgrounds. This follows directly from the asymmetry to the highest luminance rule. According to the codetermination account presented here, the contrast illusion stems from the weak (and inappropriate) effect of local anchoring. When both targets are increments, each, being the highest luminance, is treated as white within its local framework. Thus no illusion would be expected. The logic here closely parallels the analysis presented above for why illumination-independent constancy is weaker when both targets are increments.

Several studies (Adelson, 2000; Bressan, 2001; Gilchrist, 2006) have shown that the simultaneous contrast illusion is strengthened when the homogeneous black and white backgrounds are replaced by articulated Mondrian-type backgrounds, even when this lowers the average luminance of the white background and raises the average luminance of the black background (Gilchrist et al., 1999). Consistent with the analysis presented here, this increases the weight of the local frameworks, which are held to be responsible for the illusion.

8 Framework versus perceptual group

Perhaps the concept of frame of reference is too rigid, and might better be replaced by the notion of a perceptual group. Koffka certainly seems to use the two notions in a similar way. Treating a field of illumination as a perceptual group has at least one advantage over treating it as a frame of reference—namely, that it conveys a more graded concept, as opposed to all or none. A perceptual group can be stronger or weaker, and this fits the codetermination idea in which the lightness of a target surface comes from a weighted average of its value in its relevant framework and its value relative to the global (or foreign) framework.

A critical question, of course, concerns how frameworks are identified by the visual system. To a first approximation, this can be described in terms of two complementary processes: grouping and segregation. Most of the gestalt grouping principles have already been shown to create lightness illusions (Gilchrist, 2006, pages 319–324). I would add T-junctions as a grouping principle, with grouping between the two sectors meeting at the stem of the T and segregation between the sector above the crossbar and the two sectors below it. In terms of segregation, I concur with Kardos in identifying two main factors: penumbrae (blurred edges) and depth boundaries (corners and occlusion edges).

8.1 *Two kinds of grouping*

It must be emphasized that the concept of perceptual grouping used here is different from the traditional notion. Starting with the classic Wertheimer (1912) paper on grouping principles, the concept of perceptual grouping has been applied to the problem of object segmentation. This is a problem that was recognized by only the gestalt theorists, and it is more fundamental even than the problem of perceptual constancy, because the notion of perceptual constancy already assumes the visual segmentation of objects.

Because we effortlessly perceive a world of objects, it is easy to overlook the fact that the retinal image, per se, does not contain any objects. It is an undifferentiated array of color patches. Some adjacent color patches are parts of a single object while other adjacent patches are not. Sorting all this out presents a profound challenge to the visual system, and this is why Wertheimer proposed the grouping principles.

However, in the context of lightness computation, perceptual grouping refers to the grouping of retinal patches that represent surfaces sharing a common level of illumination. Helmholtz argued that lightness computation requires an estimate of the illumination level. Although this sounds plausible, Helmholtz, despite hand-waving, was not able to specify how this might be done; nor have any of his followers. But the visual system does not need to know the amount of illumination. It needs to know only which surfaces are getting the *same* illumination (Gilchrist, 2006). Knowing that allows a rather simple computation of lightness values within each perceptual group—namely, assign white to the highest luminance and scale the darker surfaces in relation to that. Then, once codetermination has been factored in, lightness values can be predicted. Empirical work shows that this mid-level approach actually fits the data better than an approach based on an estimate of the illumination level, assuming such an estimate is even possible.

To oversimplify slightly, the traditional kind of perceptual grouping can be called grouping by common reflectance, while this new kind of grouping can be called grouping by common illumination. These are intimately related, and indeed complementary. When a shadowed half of an object is grouped with its illuminated half, this already implies that the boundary cutting across the object is an illumination boundary, or, in present terms, a framework boundary.

The problem of segregating the retinal image into functional frameworks representing regions of common illumination presents a serious challenge for theory. However, the Helmholtzian approach faces the same challenge. In addition to the daunting question of how the illumination level is estimated within a region of illumination, that approach must also be able to segment that part of the retinal image to which the illumination estimate applies.

A review of the various theories of lightness and brightness lies beyond the scope of this paper (for that, see Gilchrist, 2006), but a few points can be made. Bressan's (2006) double-anchoring theory aside, no other theory even claims to explain both of the broad classes of lightness error described here: lightness illusions and failures of illumination-independent constancy. None of them can account for all three features of illumination-dependent constancy failures listed earlier, and most theories cannot account for any of the three features. As for failures of background-independent constancy (ie lightness illusions), the performance of most other theories, including the many brightness models, is spotty. Few if any can account for the absence of simultaneous contrast effects when both targets are increments. Few can account for reverse-contrast illusions. None of the brightness models can account for illusions caused by effects of depth on lightness.

It is fair to say that the gestalt approach presented here is not yet as well operationalized quantitatively as some of the brightness models. But how valuable is operationalization if the model exhibits huge qualitative failures? Obviously, one would like a theory that is both highly operationalized and one that accounts for a wide range of data. But how should these two goals be prioritized? We have seen two alternative approaches. In general, brightness models have sought to maintain a high degree of mathematical rigor from the outside. Such an approach can typically be applied to only a narrow range of data, at least initially. Then an attempt is made to extend the range of application, while maintaining the rigor of the model. In my view, this approach has not been successful. The approach I have outlined takes a different tack. It begins with an attempt to broadly characterized a wide range of data, initially in more qualitative terms. Then the attempt is to develop the model in the direction of greater rigor. I believe this second approach will be more successful.

9 Conclusion

As this tour of lightness illusions has revealed, the concept of codetermination can go far in providing a unified account, especially when combined with the concepts of anchoring to the highest luminance and frameworks, or perceptual groups. This approach comes close to a unified account of both failures of constancy and illusions, or, as defined here, illumination-dependent errors and background-dependent errors. To explain illumination-dependent errors, we have relied on the Kardos concepts of relevant and foreign frameworks, whereas to explain background-dependent errors (like simultaneous contrast), we have invoked the concepts of local and global frameworks as found in anchoring theory. It is likely that a single rubric can be found that can be applied to both classes of illusion, but that will await the results of ongoing work.

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