

Influence of target size and luminance on the White–Todorović effect

Burak Güçlü^{a,b,c,*}, Bart Farell^{a,b}

^a Institute for Sensory Research, 621 Skytop Road, Syracuse, NY 13244-5290, USA

^b Department of Bioengineering and Neuroscience, Syracuse University, Syracuse, NY 13244, USA

^c Biomedical Engineering Institute, Boğaziçi University, Bebek, İstanbul 34342, Turkey

Received 1 April 2004; received in revised form 16 September 2004

Abstract

Variants of a lightness effect described by [Todorović's, D. (1997). Lightness and junctions. *Perception*, 26, 379] were studied to quantify the failure of lightness constancy as a function of target luminance and target size. Todorović's effect is similar to White's effect. Simultaneous lightness contrast appears to operate selectively between stimuli belonging to the same perceptual group, and not between stimuli of equal proximity belonging to different perceptual groups. We found that mid-gray targets grouped with a white contextual stimulus were matched on average to a darker-than-veridical gray. Those grouped with a black contextual stimulus were matched on average veridically. This is consistent with 'anchoring' effects observed in simple two-stimulus displays. However, target luminance had an effect that was not captured by mid-level target luminance data or data averaged across target luminances. For both white and black contextual stimuli, light-gray targets were matched to a darker-than-veridical gray and the direction of this error shifted toward the lighter-than-veridical direction as the luminance of the target was lowered. The result was a constant difference between the perceived lightnesses of targets presented with white and black contextual stimuli. Target size had no effect on perceived lightness. These data imply that the Todorović–White effect can be characterized as lightness assimilation rather than as lightness contrast. By accounting for compression as well as the Todorović–White effect, assimilation is the more general explanation.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Simultaneous contrast; Lightness constancy; T-junction; Anchoring; ODOG filter; Assimilation; Compression; Contrast normalization

1. Introduction

In the classical demonstration of the simultaneous lightness contrast (SLC), a gray test figure is perceived as lighter when placed on a black background than when placed on a white background. This effect is commonly attributed to a low-level lateral inhibitory process which induces contrast enhancement at the edges of regions varying in lightness (Palmer, 1999). However, SLC also has a more global component, for the effect can extend

far from the edges and usually shifts the perceived lightness of the entire figure. Other explanations of the SLC include unconscious inference, which attributes the effect to an erroneous evaluation of the illumination, Gestalt theory, which uses the concept of perceptual belongingness (Agostini & Galmonte, 2002; Agostini & Proffitt, 1993), and spatial filtering with an incomplete set of basis functions (Blakeslee & McCourt, 1999, 2004).

SLC is a serious violation of lightness constancy, but its magnitude is predictable, at least in simple stimulus configurations, based on the ratio of the test-field luminance to the luminance of the background (Wallach, 1948). When the background is complex; that is, not forming a uniform lightness level, the perceived lightness of the test figure may depend on factors that cannot be

* Corresponding author. Address: Biomedical Engineering Institute, Bogazici University, Bebek, Istanbul 34342, Turkey. Tel.: +90 212 3596413; fax: +90 212 2575030.

E-mail address: burak.guclu@boun.edu.tr (B. Güçlü).

reduced to a ratio rule. White's (1979) effect is a well-known instance of simultaneous contrast that cannot be explained by luminance ratios.

In White's effect (1979), gray bars replace segments of a square-wave grating. Gray bars placed in the white phases appear darker than the gray bars placed in the black phases. This result is the opposite of what would be expected from a theory based on local inhibitory effects; an elongated gray bar placed in the white phase is surrounded much more by dark regions of the grating than by white regions, yet it appears darker than its counterpart placed in the black phase. Moulden and Kingdom (1989) studied the effects of the heights and widths of flanking and coaxial grating bars on the lightness of the gray test bars and found that two loci are critical for the effect and drive apparently separate processes: a local process predominantly operating at the corners outside the test bars and a spatially more extensive process operating on the inducing bars of the grating. The specific shapes of the test figures and inducers are not of general importance for production of the effect; for example, the stimuli need not be parallel or rectilinear (Todorović, 1997).

Superficially, White's effect seems to be based on depth cues that induce belongingness between the gray test bars and the inducing bars into which they are inserted. It has been shown using other stimulus configurations that coplanarity, independent of retinal adjacency, can greatly affect perceived lightness (Gilchrist, 1977). Hence, if white and black phases of a square-wave grating are seen in a foreground/background relation and therefore as non-coplanar, then gray bars associated with white bars would be expected to be perceived as darker than gray bars associated with black bars, a selective SLC effect. However, Zaidi, Spehar, and Shy (1997), using three-dimensional configurations of a simple version of White's effect, showed that the effect can persist when coplanarity, and the perceptual belongingness that goes with it, are removed.

White's effect is commonly interpreted in terms of T-junctions. Several different approaches exist for applying a T-junction analysis (e.g. see Anderson, 2001; Grossberg, 2001; Todorović, 1997; Zaidi et al., 1997). Ross and Pessoa (2000) presented a computational model with selective integration of luminance after the image is separated into different regions using T-junction information. Similarly, Kelly and Grossberg (2000) incorporate T-junction sensitivity into their model by using the interaction of long-range bipole cells and short-range competing hypercomplex cells. In Todorović's (1997) terms, at a T-junction only the collinear regions—those on either side of the stem of the T—are associated and the interaction between them is in the direction of SLC. This paradigm is applicable to both White's effect and the related lightness effect given by Todorović (1997). On the other hand, the top of the T-junction is

important in Anderson's (2003) scission theory, which is based on the decomposition of the visual pattern into multiple layers. The black/white bars are interpreted to be underlying surfaces behind the gray target surface. This phenomenal transparency dictates that the targets in the black bars look lighter, because some of the darkness is attributed to the underlying black background. Similarly, some of the lightness is attributed to the white background and this reduces the lightness of the gray target when it is placed in a white bar.

The models mentioned so far may be classified into low-level filtering (e.g. Blakeslee & McCourt, 1999, 2004; Kelly & Grossberg, 2000), mid-level surface (e.g. Anderson, 2003), and Gestalt (e.g. Gilchrist, 1977) approaches. Although these models have been fairly successful for explaining White's effect, their qualitative and quantitative accountings of lightness effects in more complicated displays is currently uncertain. We examined lightness effects in three versions of a stimulus introduced by Todorović. These stimuli differ in their amenability to T-junction analyses and in the spatial-frequency and orientation content of the target region. The lightness effect of Todorović (1997), slightly modified by Palmer (1999) to include (amodal) circular test figures instead of squares, is shown in Fig. 1. In Fig. 1a, the gray circle appears to be lying on a black background and to be partially occluded by white squares. In Fig. 1b, the circle, which has the same lightness level as in Fig. 1a, appears to be lying on a white background and to be occluded by black squares. Both circles have the same luminance level. According to a simultaneous contrast theory, the apparent brightnesses should have been reversed, because the circle in Fig. 1a is surrounded more by white regions than the circle in Fig. 1b. Instead, the direction of the contrast effect is in the opposite direction; the circle in Fig. 1b appears darker than the circle in Fig. 1a, the same direction as seen in White's effect.

It is tempting to state that the amodal circles are associated with the background and SLC operates to gene-

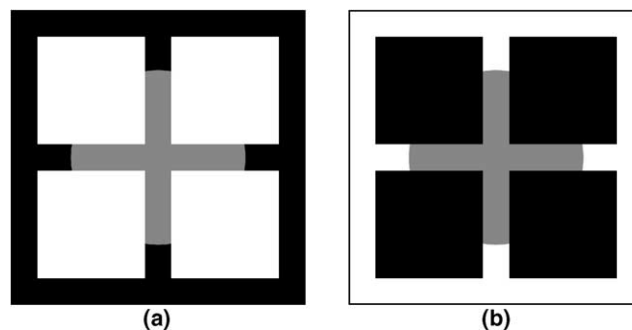


Fig. 1. Todorović (1997) lightness effect (slightly modified by Palmer (1999)). The amodal gray circles have the same lightness levels, but the circle in (b) is perceived darker than the circle in (a). This illusion is similar to White's (1979) effect.

rate the perceived contrast with respect to this background, but as previously noted, depth-defined belongingness is not a reliable factor (Zaidi et al., 1997). According to a T-junction analysis, at the junctions where the black, white and gray surfaces come together, the gray and black regions are collinear in Fig. 1a and the gray and white regions are collinear in Fig. 1b. Within these collinear associations, the inhibition by the regions surrounding the gray areas produces the contrast effect. This explanation does not require the amodal completion of the circle. Still, the necessity of T-junctions and grouping concepts to explanations of the White and Todorović effects is controversial. Blakeslee and McCourt (1999) have examined the output of an array of oriented filters tuned to different spatial scales and found that a variety of lightness effects, including the White and Todorović effects, could be simulated qualitatively without explicit regard to T-junctions or to considerations of perceptual grouping. Yet Blakeslee and McCourt's filters do not predict the lightness of the target in a Todorović display when the outer edges of the target cross are coplanar with the outer edges of the squares. Models based on T-junctions, however, do predict the perceived lightness of the target in this case (Blakeslee & McCourt, 1999). These oriented filters also do not capture the lightness assimilation found in the bull's-eye displays of Bindman and Chubb (2004); nor do T-junctions explain this effect (there are none), nor does grouping.

The White–Todorović effect is opposite in direction from the standard SLC effect. Because both white and black inducing stimuli are present, it is a simple matter

to view the effect as basically the same as SLC but selective—induced by one but not the other of the white and black stimuli. This, in essence, is what theories of belongingness do. If the White–Todorović effect is a species of simultaneous contrast, then it should respond to the same variables as do other forms of simultaneous contrast. Even if the White–Todorović effect does respond to the same variables as SLC, however, it may do so differently. Some hint that this is the case can be seen in the effects of target luminance. Spehar, Clifford, and Agostini (2002) recently showed that if the target figure is either lighter or darker than both inducing stripes, White's effect is reversed. Moreover, the lightness perceived in this reversed state changes with the border length between target and inducer, whereas in White's effect border length has no influence on apparent target lightness (Spehar et al., 2002).

In this study we examined the effects of target luminance and size on perceived brightness in a Todorović-like stimulus. We varied target luminance within the range bounded by the black and white inducing stimuli, so as not to reverse White's effect, as observed by Spehar et al. (2002). We varied target size in order to control for the integrated luminance of the target stimulus and the border length between target and inducer regions. We carried out these measurements of effects of target luminance and size on three stimulus configurations that varied the spatial relationship and junctions between the target pattern and the stimulus context in which it appeared.

Both relative luminance and relative size affect perceived brightness in standard SLC displays, as does

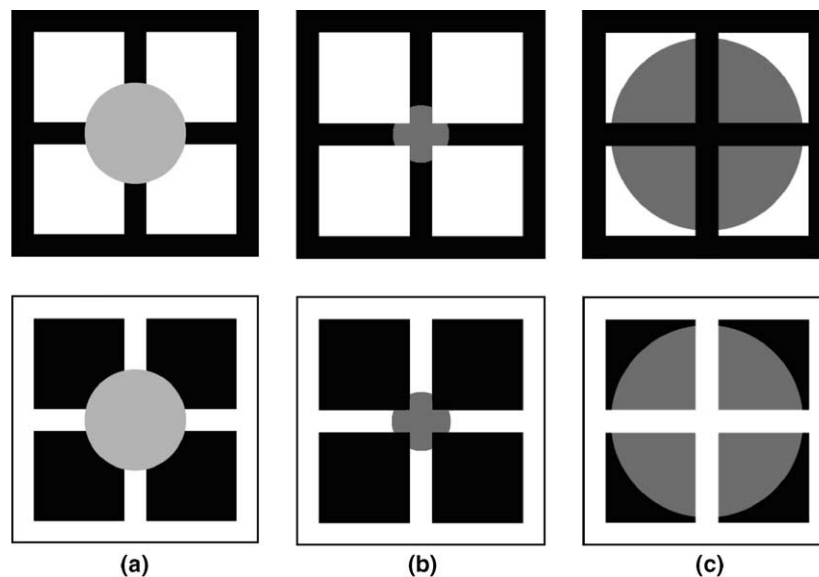


Fig. 2. Variants of Todorović's effect in three contexts. In each context, the gray circles have the same lightness levels, (a) Context A has the target circle unoccluded. No appreciable contrast effect is seen, (b) Context B has the target circle occluded by the squares. The circle with the white frame arrangement is perceived darker than the circle with the black frame arrangement, (c) Context C has the target circle occluded by the frame. The circle with the white frame arrangement is perceived lighter than the circle with the black frame arrangement.

the interaction of these variables, and our stimuli will permit us to examine whether similar effects occur as well in White–Todorović configurations. Gilchrist et al. (1999) have summarized much of the literature on the influence of luminance in terms of an anchoring effect in which the brightness of the darker of two surfaces varies directly with the luminance of the brighter surface. The brighter surface serves as the ‘anchor’, scaling the brightness of the darker surface. Size matters for the anchoring effect, which is altered when the area of the darker surface exceeds that of the lighter surface. If T-junctions segregate the figure into surfaces that form perceptual groups which interact through simultaneous contrast and those that do not form such groups, then these anchoring and area effects should appear in White–Todorović patterns, too.

The three contextual arrangements of a Todorović-like stimulus that we use present very different visible portions of the target circle (Fig. 2). In Context A, the target circle is not occluded by any other stimulus and is completely visible. Context B is identical to the arrangement shown in Fig. 1 where the amodal circle is occluded by the squares. Context C has the amodal circle occluded by a cross, which may seem as a frame separating transparent squares.

In two of the arrangements (Contexts B and C) the visible portions of the target are spatially complementary and among all three arrangements the spatial-frequency and orientation content of the visible portions differ. The spatially complementary targets are both predicted to show contrast effects based on their T-junctions, whereas the other target (Context A) is predicted to show no such effect. We will also examine simulated responses to these three patterns generated by a filtering theory in which T-junctions play no role but spatial configuration and scale do (Blakeslee & McCourt, 1999, 2004). Our results show the operation of two effects, the White–Todorović effect and lightness compression effect, the latter of which suggests that the former may result from lightness assimilation rather than lightness contrast.

2. Methods

2.1. Apparatus and stimuli

Twenty-one standard gray scale cards with edges measuring 4.6 cm × 4.6 cm were prepared using the computer-graphics program CorelDRAW™ (Corel Inc., Dallas, TX).

The cards had homogeneous lightness gray levels between 0% (white) and 100% (black) in program-specific 5% steps and were printed by a 600-dots/inch laser printer. A calibration curve for the standard cards was ob-

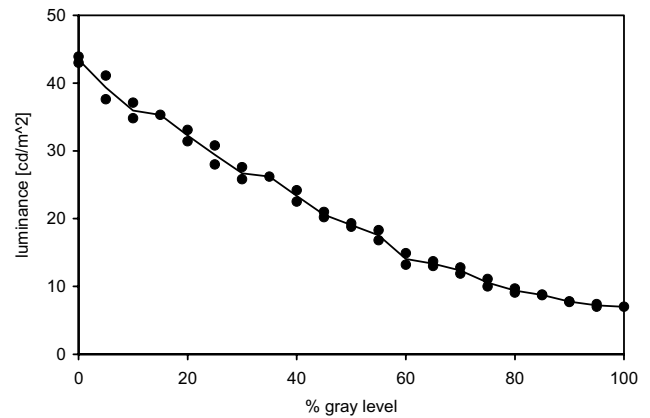


Fig. 3. Calibration curve for the standard gray cards and the stimuli cards. There is a slight compression of lightness at high gray levels. The curve is the average between two calibrations indicated by the data points.

tained using a photometer (Optometer Model 370, Graseby Optronics, Orlando, FL) and is given in Fig. 3.

The stimuli consisted of 102 cards with dimensions 11 cm × 11 cm evenly divided (except the smallest target size, see below) among the three context conditions given in Fig. 2. These cards were prepared using the same equipment as described above. Each card had a white (or black) cross/frame, black (or white) squares, and a target circle (in most cases, an amodal circle). The width of the cross/frame was 1 cm; each of the four squares within the frame had sides extending 4-cm in length. Six different circle sizes with the following diameters were used: 0.5, 2.5, 4.5, 6.5, 8.5, and 10.5 cm. The target gray level was either 25%, 50%, or 75% with corresponding luminances of 29.4, 19.0, and 10.6 cd/m². A background surface for comparing the stimuli with the standard gray cards had a homogeneous 50% gray level with added Gaussian luminance noise ($\mu = 0$ cd/m², $\sigma = 4.6$ cd/m²). The spatial density of the noise was 35 pixels/mm².

2.2. Procedure and design

The experiment was performed under constant ambient illumination. At the start of each experimental session, the stimuli cards were thoroughly shuffled. The 102 stimuli were randomly presented one at a time to the subject. The instructions given to the subject described the task, which was to select the standard gray card which had the closest lightness to the perceived lightness of the target circle on the stimuli. The subject made a comparison between the test and the 21 standard cards, which were arrayed on the background surface in order of reflectance; thus, all the standard cards were simultaneously visible. No time limit was imposed on the subject's decision. Each experimental session lasted

about 30–60 min. A break was given in the middle of the session.

2.3. Subjects

Five subjects were tested in the experiment. They all had normal or corrected-to-normal acuity and reported no known color-vision abnormalities. The male subjects were 70, 54, and 26 years old. The female subjects were 53 and 27 years old. The subjects were naïve as to the purpose of the experiment. The experiment adhered to NIH ethical guidelines for testing human subjects.

2.4. Data analysis

Subjects' responses were recorded and the matching errors (subject's selected lightness match minus the veridical reflectance match) were determined. Veridicality refers to the correct match as determined by the printed gray level. The errors are expressed as gray-level percentages. The contrast effect was measured as the lightness match in the white frame condition minus the lightness match in the black frame condition. To assess effects of practice, errors were plotted sequentially (not shown) in the order that the subject made the responses. The performance trend of each subject was close to constant, showing no practice effects.

3. Results

The contrast effect—the lightness match in the white-frame condition minus the lightness match in the black-frame condition—was analyzed separately for the three target contexts. Analysis of variance on the magnitude of the contrast effect revealed that there was no significant effect of target size or reflectance in Context A, Context B, or Context C, and no interaction between size and reflectance for targets of 2.5 cm and larger (all p 's > 0.05). The three contexts are not distinct when the size of the target is 0.5 cm, so this target size was included in a separate analysis of Context A (for which the target is unoccluded by other surfaces irrespective of target size). For this analysis the effect of size, but not luminance, was significant ($p < 0.001$).

Given the lack of an interaction between target size and luminance on the magnitude of the White–Todorović effect, we compared data for targets of different sizes and of different luminances on white and black frames. The effects of target reflectance were examined after pooling across data for the different target sizes; likewise, the effects of target size were examined after pooling across data for the different target luminances. We did this separately for each of the three contexts.

3.1. Effects of target size

The error in the perceived lightness of the circle is plotted as a function of circle diameter in Fig. 4 for Context A. In this context, the circle is unoccluded and seen as occluding the frame and the squares. Primary concern is with targets of size 2.5 cm and larger, for which the three contexts are distinct. Excluding the smallest (0.5-cm) target, there are no statistical differences between the results for black- and white-frame stimuli (black versus white circular data points in Fig. 4); except for the smallest target (2.5-cm diameter) condition, the error is not significantly different from zero at the 0.05 level. The p -values obtained from one-sample t -test for each diameter ($n = 15$) are as follows: for the black frame, 0.048, 0.698, 0.774, 0.364, 0.827 for diameters 2.5, 4.5, 6.5, 8.5, and 10.5 cm, respectively; and for the white frame, 0.001, 0.217, 0.458, 0.324, 0.500 for the same order of diameters.

The contrast effect is the difference between the errors for the target circle on the black frame and the white frame. This error difference is plotted with square symbols in Fig. 4. The t -test fails to reject the hypothesis that the difference in errors is equal to zero for each circle diameter ($p = 0.082, 0.670, 0.104, 0.595, \text{ and } 0.836$ for diameters 2.5, 4.5, 6.5, 8.5, and 10.5 respectively). These results indicate that subjects do not perceive a contrast effect in Context A; the perceived lightness of the target circle is the same in black-frame and white-frame displays. However, the 2.5-cm diameter circle is perceived somewhat darker than its actual lightness in both black- and white-frame conditions of Context A. Note that in Context A, the 2.5-cm diameter circle is large enough to partially cover the four squares. Thus, except for the smallest (0.5-cm) target size, Context A differs from

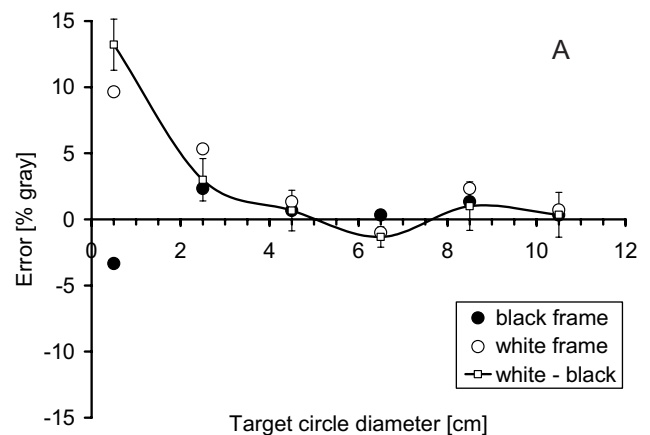


Fig. 4. The matching errors as a function of target size in Context A. The data points are averages. The error bars are standard errors of the mean. The curve is the difference of matching errors and indicates the contrast effect observed between stimuli with black and white frame arrangements.

the standard simultaneous-contrast stimulus configuration, in which the target stimulus is surrounded by a uniform region of different lightness.

The results for Context B appear in Fig. 5. In this context, the gray circle is partially occluded by the squares. Similar to Context A, no significant lightness errors were produced when the frame was black. The black circular data points in Fig. 5 do not differ significantly from zero (one-sample *t*-test; $n = 15$ for each data point). The *p*-values are 0.784, 0.752, 0.089, 0.363, 0.595 for 2.5-, 4.5-, 6.5-, 8.5-, and 10.5-cm target diameters, respectively. However, the white-frame arrangement produced high positive lightness errors; the target circles are perceived darker than their actual gray levels. The average gray-level error in this arrangement is 5.1%. There is no statistical difference between the individual data points for the white frame and this average: $p = 0.531, 0.553, 0.655, 0.715,$ and 0.660 for 2.5-, 4.5-, 6.5-, 8.5-, and 10.5-cm target diameters, respectively.

The difference between white and black data points yields the contrast effect, which is highly significant in this context. The gray circle on the white frame is always perceived darker than the gray circle on black frame. The average gray-level contrast effect is 7.0%. The *p*-values (one-sample *t*-test) for the difference between the square data points and this 7.0% average are 0.606, 0.553, 0.820, 0.203, 0.337 for the five target circles in order of increasing diameter. These results indicate a robust contrast effect in Context B. The magnitude of this effect is independent of target size.

The target circles in Context C are occluded by the frame rather than by the squares, as in Context B; the frame and the squares have opposite luminance polarities. The results for Context C are opposite of those found for Context B (Fig. 6). In the white-frame condi-

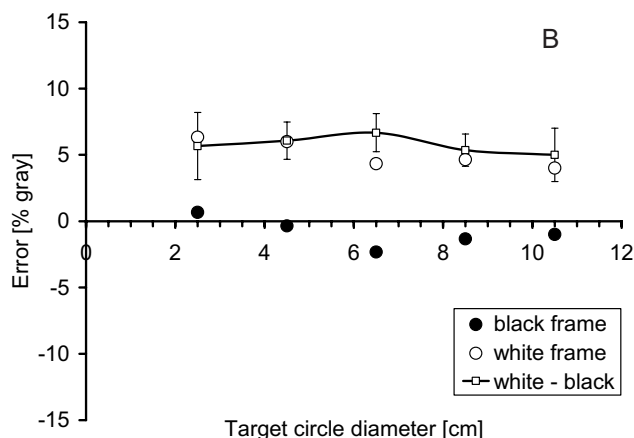


Fig. 5. The matching errors as a function of target size in Context B. The data points are averages. The error bars are standard errors of the mean. The curve is the difference of matching errors and indicates the contrast effect observed between stimuli with black and white frame arrangements.

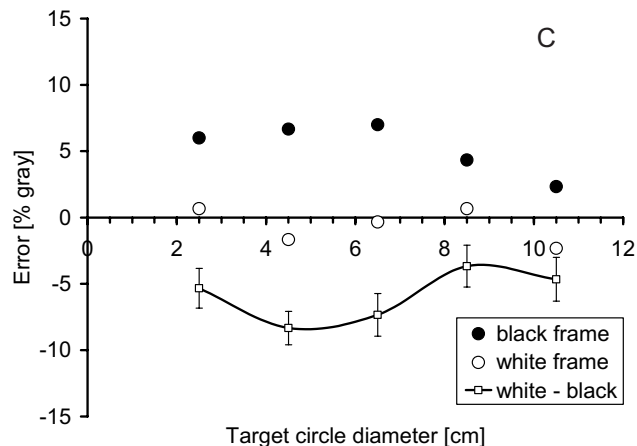


Fig. 6. The matching errors as a function of target size in Context C. The data points are averages. The error bars are standard errors of the mean. The curve is the difference of matching errors and indicates the contrast effect observed between stimuli with black and white frame arrangements.

tion no significant errors were found ($p = 0.764, 0.353, 0.827, 0.433,$ and 0.068 , for 2.5-, 4.5-, 6.5-, 8.5-, and 10.5-cm circles, respectively, by one-sample *t*-test). However, in the black-frame condition, the gray circles are always matched to a standard that is darker than a reflectance-matching standard. The average gray-level error is 5.3%. The hypothesis that each black data point has 5.3% error cannot be rejected using one-sample *t*-test ($p = 0.601, 0.383, 0.284, 0.627,$ and 0.137 for 2.5-, 4.5-, 6.5-, 8.5-, and 10.5-cm circles, respectively). The contrast effect is given by the square data points of Fig. 6. There is a significant negative contrast error. In all cases the gray circles occluded by a white frame are perceived as lighter than the gray circles occluded by a black frame. The average magnitude of the effect is -5.9% and the data for individual circle sizes are very close to this average (one-sample *t*-test; $p = 0.712, 0.074, 0.388, 0.179,$ and 0.468). These results indicate a robust contrast effect in Context C, one that, as expected, is in the opposite direction from what was observed in Context B. As in Context B, there is no systematic effect of target size. As in Context B also, the matching errors were asymmetrical for black- and white-frame conditions. More will appear on this point in Section 4.

3.2. Effects of target luminance

In Fig. 7, matching errors are presented as a function of target reflectance level for Context A. In the black-frame condition (black columns in Fig. 7), matching errors for the 25%-gray-level target had a mean gray-level value of 5.0%, which is significantly different from zero (one-sample *t*-test, $n = 25$; $p < 0.001$). However, the matching error was not significant when the target gray

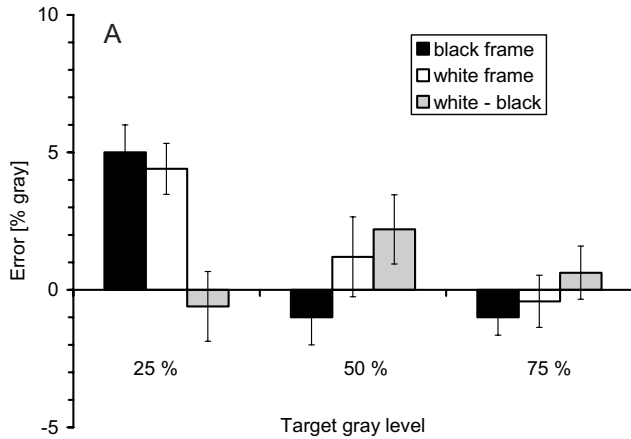


Fig. 7. The matching errors as a function of target lightness in Context A. The data columns are averages. The error bars are standard errors of the mean. The gray columns are the differences of matching errors and indicate the contrast effects observed between stimuli with black and white frame arrangements.

level was 50% or 75% ($p = 0.327$ and 0.134 , respectively). The white-frame condition produced similar results. The mean error was 4.4% when the target gray level was 25%, which is statistically significant from zero ($p < 0.001$), but the errors are non-significant when the target gray level was 50% or 75% ($p = 0.417$ and 0.664 , respectively). The contrast effect (gray columns in Fig. 7) is not significant in Context A ($p = 0.641$, 0.094 , and 0.524 for 25%, 50% and 75% target gray level, respectively).

The matching errors in Context B show a peculiar trend as a function of target reflectance. This is shown in Fig. 8. When the target gray level was 25%, the errors were high and in the same direction (positive, indicating darkening) for both the black and the white frames. As

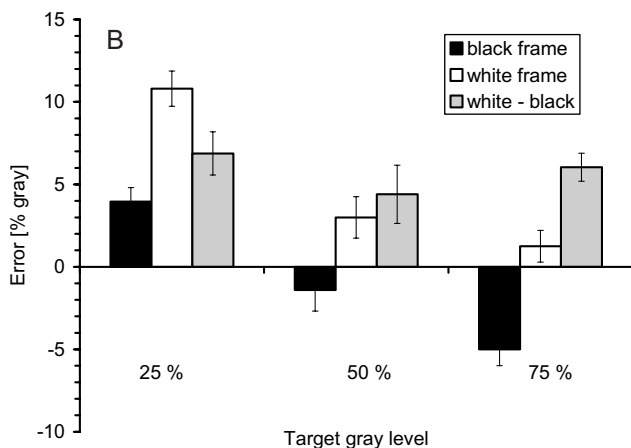


Fig. 8. The matching errors as a function of target lightness in Context B. The data columns are averages. The error bars are standard errors of the mean. The gray columns are the differences of matching errors and indicate the contrast effects observed between stimuli with black and white frame arrangements.

the target reflectance was decreased, the errors shifted towards the opposite direction. That is to say, the mean error first decreased and then became negative, indicating lightening. The error for the 25% target gray level differs significantly from the error for the 50% target gray level in both the white-frame condition (two-sample t -test, $n = 25$; $p < 0.001$) and the black-frame condition ($p = 0.001$). The error for the 50% target gray level does not differ significantly from the error for the 75% target gray level in the white-frame condition ($p = 0.278$), but the difference is significant in the black-frame condition ($p = 0.031$). Thus, the target circle is perceived as darker than its reflectance-matched standard when the circle is high in luminance and the error decreases as the circle is made lower in luminance. When the circle is made dark enough, the error is reversed in the black frame arrangement and the circle is perceived as lighter than its reflectance-matched standard.

Despite the variation in errors with target reflectance, the contrast effect—the difference between the errors for the white-frame and black-frame conditions—remained approximately constant (gray columns in Fig. 8). Gray circles on white frames are perceived as darker than the gray circles on black frames, by a similar amount regardless of target luminance. The mean gray-level contrast effect is 5.8% and none of the values for the three target-luminance conditions differs significantly from this average (one-sample t -test; $p = 0.419$, 0.435 , and 0.779 for 25%, 50%, and 75% target gray level, respectively). Thus, the contrast effect is significant for all three target luminance levels ($p < 0.001$, 0.021 , and 0.001 , respectively) and positive, indicating a compression of target lightness in Context B (see Fig. 10 for the compression effect).

It was expected from the results in the previous section, and from considerations of symmetry, that the effects of target gray level in Context C would be opposite to those in Context B. This is what was found, as seen in Fig. 9. Data for black and white frames are reversed relative to Context B, but the same trends are present. The targets occluded by the black frame were always perceived as darker than their reflectance-matched standards and this error decreased as the target reflectance was decreased. In the black-frame condition, the error for the 25% gray-level target was significantly higher than for the 50% gray-level target (two-sample t -test, $n = 25$; $p < 0.001$) and the error for 50% was significantly higher than that for 75% ($p = 0.026$). In the white-frame condition, the matching error was positive for the 25% gray-level target, then it decreased and shifted direction as target reflectance was decreased. The error for the white frame decreased significantly as the target reflectance was lowered from 25% to 50% gray level ($p = 0.008$). However, the absolute error increased as the target reflectance was lowered further, from 50% to 75% ($p < 0.001$), where the target circle

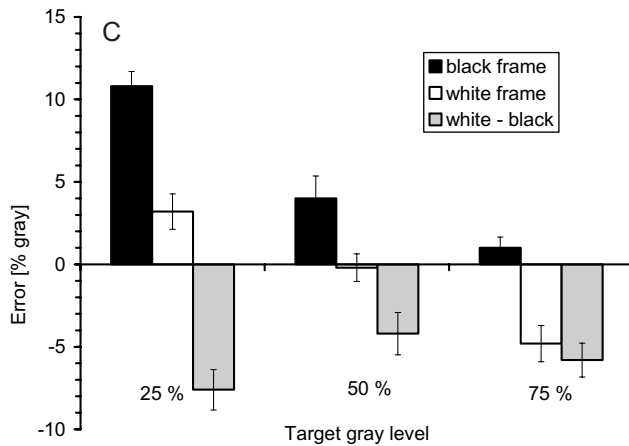


Fig. 9. The matching errors as a function of target lightness in Context C. The data columns are averages. The error bars are standard errors of the mean. The gray columns are the differences of matching errors and indicate the contrast effects observed between stimuli with black and white frame arrangements.

was seen as lighter than its reflectance-matched comparison. Thus, as was found in Context B and Context C induces compression in lightness of the target.

The contrast effect is approximately constant as a function of target gray level, again as in Context B; this is shown by the gray columns in Fig. 9. The average difference of matching errors for black and white frames is -5.9% and the individual contrast values (gray columns in Fig. 9) are not statistically different from this average ($p = 0.179, 0.197, \text{ and } 0.923$ for 25%, 50% and 75% target gray level, respectively). For each target reflectance level the contrast effect is significantly different from zero ($p < 0.001, 0.003, \text{ and } 0.001$, respectively). Thus,

regardless of target reflectance, the gray circle occluded by the white frame is always perceived as lighter than the gray circle occluded by the black frame, a contrast effect paralleling that of Context B.

4. Discussion

In this study, a lightness contrast effect like the White–Todorović effect was found in Contexts B and C. The effect—the difference between perceived target lightness on black and white inducers—was robust, as it was for the related stimuli used by Todorović (1997). Maximum magnitude of this effect was about 10% gray level—about a tenth of the range separating the inducing black from the inducing white. The average magnitude was considerably less than this, largely because the size of the illusion was modulated by two intriguing effects, the effect of target luminance and the asymmetry between black and white inducers; these effects are discussed below. The effect was generally larger in Contexts B and C than in Context A, where the White–Todorović effect was not expected to appear. The exception was the relative large effect observed for the smallest (0.5-cm) target, which was entirely surrounded by the frame; thus, this is an instance of classical simultaneous lightness contrast, not the White–Todorović effect.

No contrast effect was expected, and none was found, in Context A. Here the target circle occludes the other elements of the display and is occluded by none of them. In terms of T-junctions, the circle is associated with neither the squares nor the frame. In Context B, the circle

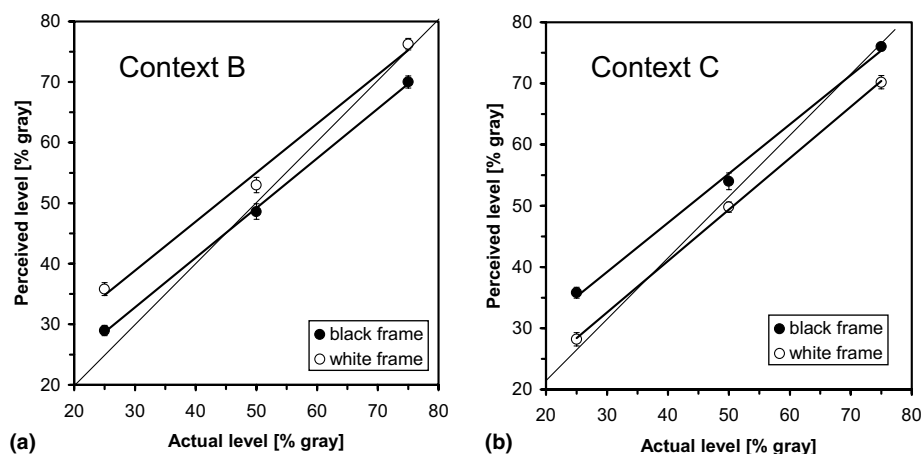


Fig. 10. Compression and asymmetry effects in (a) Context B and (b) Context C. The data points are averages based on Figs. 8 and 9. The error bars are standard errors of the mean. The thick lines through the data points are the best linear fits. The slopes of the best-fitting lines are smaller than one (cf. the diagonal line), indicating that perceived level ranges are compressed. Note the asymmetry between the fitted lines for the black- and white-frame conditions with respect to the midpoint of the diagonal line in each context. Although the best-fitting line of one condition is always at darker-than-veridical levels, the best-fitting line of the other condition crosses the diagonal line. The magnitudes of compression and asymmetry are similar in both contexts.

and the frame lie on opposite sides of the stem of T-junctions and so are grouped together; in Context C, the T-junctions group the circle with the square. The contrast effect is in the direction expected from these T-junction groupings: Contrast is specific to the collinear stimuli that form the stem of the junction. In Context B, the circle is collinear with the frame at the T-junctions, so the frame induces a lightness effect on the circle; in Context C, the circle is collinear with the squares and the reverse effect is observed.

Thus, perceptual grouping or belongingness, as specified by T-junctions or other occlusion cues, is adequate to explain the direction of the contrast effect (although in three-dimensional configurations it may prove to be inadequate; see Zaidi et al., 1997). Though the standard account of the White–Todorović effect treats it as an instance of lightness contrast, we will see later that there is an alternative interpretation which expresses the effect as the outcome of a process of assimilation, instead.

4.1. Effect of stimulus size

In all three contexts, enlarging the circle increases its border length with the squares; in Context C it also increases the circles' border length with the frame. The border-length:circle-area ratio also varied with circle size. Yet in no case did the size of the target circle influence the magnitude of the contrast effect.

In measures of simultaneous contrast using contiguous dark and light patches, Li and Gilchrist (1999) found that the lightness of two surfaces depended not only on their relative luminances but also on their relative areas. With luminance held constant, the perceived lightness of both a gray and a white surface increased as the relative area of the white surface decreased from 50%. Our data show no effect of the relative area of the white (or black) and gray regions on either side of the stem of T-junctions. This reinforces the evidence from border length (Spehar et al., 2002), mentioned in the Introduction, that the White–Todorović illusion is not an instance of the classical simultaneous contrast effect, to which Li and Gilchrist's area effect applies. The invariance of the contrast effect across test-stimulus size is consistent with the finding of Moulden and Kingdom (1989) that a spatially confined inducer is sufficient to create the effect.

4.2. Effect of stimulus luminance

Moulden and Kingdom (1989) used a matching technique and found an unexpected asymmetry between the White effect produced by black and white inducing bars. The expectation, of course, is that a black inducer would lighten the gray test bar and a white inducer would darken it (compared to the appearance of the gray test bar against a background that is the averaged luminance of

the two inducers). Instead, Moulden and Kingdom found that the test bar appeared darkened against both black and white inducers, though much more against white inducers than black. This asymmetry would not have been detected by a nulling procedure that culminated in a match between test bars presented simultaneously against black and white inducers. Instead Moulden and Kingdom (1989) presented only one test bar and had their subjects adjust a comparison bar presented on luminance-averaged background, a method analogous to ours.

Results for our 50% circles are roughly similar: The white inducer darkens the test circle, while the black inducer has essentially no effect (Figs. 8 and 9; see also averaged data in Figs. 5 and 6). However, data for circles of higher and lower luminance show that this result is not general but instead varies with the test luminance. While Moulden and Kingdom (1989) found no difference between the results for test bars differing in luminance, their test luminances were varied over the narrow range of 20 ± 4 cd/m². This suited their purpose, which was to avoid matching biases, not to assess effects of test luminance. Our test circles, which varied over a factor of 2.8 in luminance, display a systematic effect on matching luminance that shows the asymmetry in Moulden and Kingdom's (1989) data to fit into a more general pattern.

The manipulation of test luminance shows that there are two effects at work. There is, first, an overall effect of test luminance: A light-gray test circle appears darker than its luminance-matched comparison stimulus and a dark-gray test circle appears lighter than its luminance-matched comparison stimulus—a compression effect. Second, there is an effect of inducer polarity: Black inducers make test circles of any particular luminance appear lighter than do white inducers—the White–Todorović effect. Thus, the test stimulus might appear lightened or darkened depending on the luminances of both the test stimulus and the inducer. Rather than always darkening the test stimulus, the inducer in the Todorović pattern compresses the perceived target-brightness range relative to the comparison stimuli. The compression can be seen in Fig. 10 as the less-than-unity slopes of the perceived gray level plotted against actual gray level. In both Contexts B and C and for both black and white frames, these slopes are very close to 0.8.

The compression of the perceived lightnesses of the circle in Contexts B and C as compared with the actual lightness range is not due to the slight flattening of the calibration curve at high gray levels (see Fig. 3); the target gray levels used in the experiment, 25%, 50%, and 75%, cover a quite linear region of the curve. Light targets (25% gray level) were always perceived darker in comparison to their actual luminance match. This agrees with Moulden and Kingdom's (1989) data, in which

targets were perceived as darkened on both white and black inducers. However, our data show that this error decreased as the target was made darker. For some conditions, the error was reversed as the target was made darker, with dark targets perceived as lightened in comparison to their actual luminance levels. In Context B, the target in the white-frame condition was always perceived as darker than the target in the black-frame condition. In Context C, the effect was opposite. In the white-frame condition, the 50% range in target gray levels was compressed to about 40% in Context B and to about 42% in Context C. In the black-frame condition, the 50% range was compressed to 41% in Context B and to 40% in Context C. Because of this compression, the contrast effect remained constant as target luminance level varied.

4.3. Role of T-junctions and grouping

Though the presence of T-junctions correctly predicts the contrast effects observed with our three versions of the Todorović pattern, it is unclear whether T-junctions are actually used by the mechanism that governs brightness perception. T-junctions might simply be non-causally associated with the mechanism's effective stimulus. The contrast effects we observed were quite regular and predictable across stimuli that varied in spatial configuration (Contexts B and C) and luminance polarity (white frame and black frame patterns). We therefore examined the results in light of two models, one of which should show sensitivity to configuration and the other to polarity. Blakeslee and McCourt's (1999) oriented difference-of-Gaussians (ODOG) model uses the normalized output of oriented filters of various scales to predict the brightness contrast effects without refer-

ence to T-junctions or other geometrical features. As noted earlier, the three versions of the Todorović stimulus we used are well suited for pitting filtering models and T-junction models. The visible portions of the test circles in these configurations differ in spatial-frequency and orientation content and in their T-junction constraints. The anchoring model (Gilchrist et al., 1999), by comparison, can support contrast effects within groups defined by T-junctions. However, it predicts a luminance polarity effect because anchoring is asymmetrical between light and dark.

4.3.1. Filter responses

Responses by the ODOG model to all our stimuli were simulated using filters of various ranges of spatial frequency. We also examined the effect of modifying the stimulus configuration to match that used by Blakeslee and McCourt (1999); in these cases the outer edge of the frame was expanded vertically and especially horizontally, and reversed-polarity versions of the Todorović pattern were presented simultaneously, in horizontal adjacency (see their Fig. 9). Simulation results showed contrast effects in every case, but in no case did Contexts B and C generate contrast effects with opposite directions. Thus the simulations did not match the data for human observers. In addition, Context A showed a contrast effect in the simulation data, but not in the human data. Typical results from the simulations appear in Fig. 11, plotted in the format of Fig. 10.

The stimuli used in generating the data shown in Fig. 11 were those used in our experiment and model responses were recorded independently for each stimulus. Luminance values were expressed on the gray-level scale used in this experiment (Fig. 3). Filter frequencies, ori-

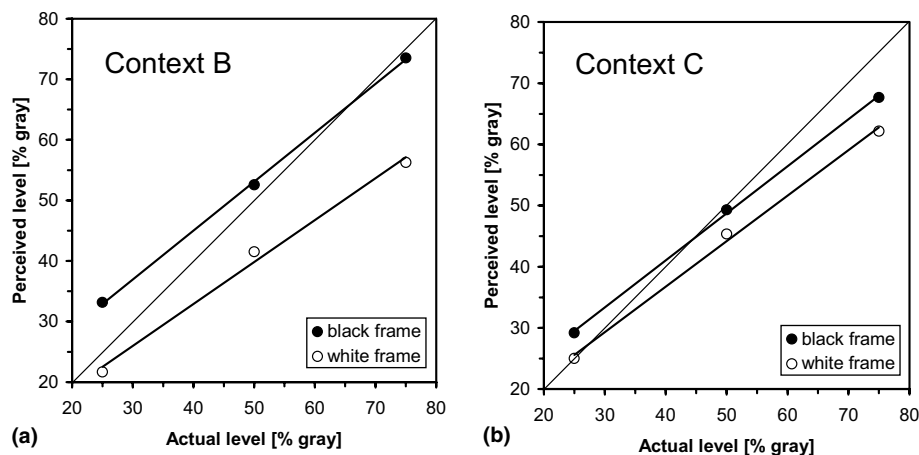


Fig. 11. Simulation results from Blakeslee and McCourt's (1999) oriented difference-of-Gaussians model for (a) Context B and (b) Context C, plotted in the format of Fig. 10. The thick lines through the data points are the best linear fits. The slopes of these fits are smaller than one (cf. the diagonal line), indicating that perceived level ranges are compressed. Note that simulation results in both contexts show contrast effects. However, the direction of the simulated effect for Context B is opposite to that of the White–Todorović effect. Context A produced results similar to those shown here.

entations and other parameters are those used by Blakeslee and McCourt (1999). Under these conditions, the contrast effect generated by the ODOG model in response to Context C is similar to the contrast effect displayed by humans to this pattern (compare Fig. 10b and Fig. 11b). However, in response to Context B the model produces a contrast effect in the same direction, and with a larger magnitude, whereas humans display a contrast effect with the reverse polarity and similar magnitude (compare Fig. 10a and Fig. 11a). In our simulations the ODOG model always produced a contrast effect in the same direction for Contexts B and C, regardless of which of these stimuli yielded an effect in simulation that matched human data. This was the case for any range of filter frequencies that resulted in a contrast effect for Contexts B and C. These ranges also yielded a contrast effect for Context A, which as similar in magnitude and direction to those for Contexts B and C at all target sizes but the smallest, which was unique to Context A.

The contrast effects shown in Fig. 11 are based on the average of all target pixel values. Similar results follow any other reasonable comparison of target brightnesses. However, filtering renders the target regions non-uniform in brightness, so contrast effects in regions of different shapes, such as the target of the three Todorović stimulus types, are not strictly comparable quantitatively. Differences in the contrast effect for the three stimulus types should be regarded as qualitative differences, indicative of the relative direction of the effect rather than relative magnitude. The magnitude of the simulated contrast effects also depends on incidental stimulus parameters, such as frame width and whether the width of the interior and exterior bars of the frame were the same or different. None of these stimulus variations, however, yielded the reversed contrast effects between Contexts B and C that were found in the human data.

The ODOG model did capture the compression effect, however. This finding suggests that the model and humans may employ functionally similar luminance processing, while the inability of T-junctions to predict the direction of the model's contrast effect suggests that the model and humans differ in the use of junctions, and presumably other geometrical cues, to selectively apply this processing to subregions of the visual display. The model makes no explicit use of T-junctions or other image features, so the different versions of the Todorović stimulus produce model responses that vary solely in response to variation in their Fourier spectra. The ODOG model showed an effect of target size that was, like that of human observers, quite small.

4.3.2. Anchoring

If the target regions of the three variations of the Todorović pattern were grouped identically with the

patterns' frames and squares, anchoring theory (Gilchrist et al., 1999) would predict no brightness difference between them. Supposing that grouping for Contexts B and C stimuli is determined by T-junctions (Gilchrist et al., 1999), the anchoring theory would predict a contrast effect that depended on the color of the contextual frames or squares with which the target regions were grouped. When grouped with white frames or squares, the gray target circle should show minimal matching error and when grouped with black frames or squares it should show the maximal effect. In the context of black frames or squares, the gray target is the brightest region and so takes the role of the 'white' anchor, shifting it toward increased brightness.

The data of Fig. 10 do not show agreement with expectations of the anchoring theory. For both Contexts B and C the largest matching errors occurred when the target circle was grouped with a white inducer. A black inducer could lead to the target circle appearing lighter, darker, or unchanged relative to a luminance match. However, the results do support the importance of grouping or belongedness, which in the anchoring theory is crucial for determining lightness perception in complex scenes.

4.4. Compression and assimilation

The compression effect and the White–Todorović effect can be linked as instances of a more general phenomenon akin to contrast-contrast. In contrast-contrast, a texture appears to have a lower contrast when surrounded by a high-contrast texture of similar spatial-frequency content than when surrounded by a low-contrast texture (Chubb, Sperling, & Solomon, 1989). Bindman and Chubb (2004) have argued that a similar effect can account for brightness assimilation of the gray center of a black and white bull's-eye pattern. Assimilation results from inhibition of units coding the increment or decrement of luminance at the edge separating the gray center from the adjacent ring of the bull's eye. The source of this inhibition is the rectified response of units coding the higher contrast edges between white and black. The rectification ensures that the inhibition affects luminance differences generally, rather than being specific to contrasts of a particular polarity.

In our stimuli, too, inhibition would come from the rectified response of units coding the high contrast between black and white frames and squares. The inhibition would reduce the response to the increment or decrement at the edge between the gray test circle and an adjacent black or white frame or square. For example, the circle is a luminance increment relative to a black stimulus and inhibiting responses to this luminance difference would make the circle appear less incremental; it would appear darkened, assimilated toward black. The magnitude of the deviation from a veridical

match would depend on the magnitude of the increment; for a large increment from black—a light gray—the matching error would be large, whereas the same light gray would be a small decrement from white and so would yield a small error, in the opposite direction.

Such an assimilation process agrees well with the compression effects shown in Fig. 10. However, to fit the data the circle would have to assimilate to the luminance of the *squares* in Context B and to the luminance of the *frame* in Context C (see the white-frame condition in Fig. 10a and the black-frame condition in Fig. 10b). This association is the opposite to the association that is assumed to be created by T-junctions; that is, the effect operates between surfaces on either side of the T's cross-bar, rather than between surfaces on either side of its stem. Yet because assimilation and contrast are opposite in direction, assimilation across the cross-bar of the T and contrast across the stem would result qualitatively in the same lightness effect. Thus, both assimilation and contrast, operating across different edges of T-junctions, can account for the White–Todorović effect. The advantage of the assimilation theory is that it is better able to account for the lightness compression observed here.

Neither the compression effect nor the contrast effect is observed in Context A, despite the similarity of its textural background with those of Contexts B and C. The White–Todorović effect, as well as the Benary and bull's-eye effects among others, show that the perceived lightness of a target depends on processes of assimilation and contrast that are highly selective, being gated by rather detailed features of the spatial arrangement of target and background. It would appear that even low-level theories would have to include sensitivity to such spatial features, such as T-junctions, to account for lightness perception.

Acknowledgments

We gratefully thank Daniel Bindman and Charles Chubb for sharing their MATLAB implementation of the ODOG model. This work was supported by NEI grant EY R01-12286 to Dr. Farell and Boğaziçi University Research Fund 04HX101 to Dr. Güçlü.

References

- Agostini, T., & Galmonte, A. (2002). Perceptual organization overcomes the effects of local surround in determining simultaneous lightness contrast. *Psychological Science*, *13*, 89–93.
- Agostini, T., & Proffitt, D. R. (1993). Perceptual organization evokes simultaneous lightness contrast. *Perception*, *22*, 263–272.
- Anderson, B. L. (2001). Contrasting theories of White's illusion. *Perception*, *30*, 1499–1501.
- Anderson, B. L. (2003). Perceptual organization and White's illusion. *Perception*, *32*, 269–284.
- Bindman, D., & Chubb, C. (2004). Brightness assimilation in bullseye displays. *Vision Research*, *44*, 309–319.
- Blakeslee, B., & McCourt, M. E. (1999). A multiscale spatial filtering account of the White effect, simultaneous brightness contrast and grating induction. *Vision Research*, *39*, 4361–4377.
- Blakeslee, B., & McCourt, M. E. (2004). A unified theory of brightness contrast and assimilation incorporating oriented multiscale spatial filtering and contrast normalization. *Vision Research*, *44*, 2483–2503.
- Chubb, C., Sperling, G., & Solomon, J. A. (1989). Texture interactions determine perceived contrast. *Proceedings of the National Academy of Science*, *86*, 9631–9635.
- Gilchrist, A. L. (1977). Perceived lightness depends on perceived spatial arrangement. *Science*, *195*, 185–187.
- Gilchrist, A., Kossyfidis, C., Bonato, F., Agostini, T., Cataliotti, J., & Li, X., et al. (1999). An anchoring theory of lightness perception. *Psychological Review*, *106*, 795–834.
- Grossberg, S. (2001). Theory versus speculation in visual perception. *Perception*, *30*, 1505–1507.
- Kelly, F., & Grossberg, S. (2000). Neural dynamics of 3-D surface perception: Figure-ground separation and lightness perception. *Perception and Psychophysics*, *62*, 1596–1618.
- Li, X., & Gilchrist, A. (1999). Relative area and relative luminance combine to anchor surface lightness values. *Perception and Psychophysics*, *61*, 771–785.
- Moulden, B., & Kingdom, F. (1989). White's effect: A dual mechanism. *Vision Research*, *29*, 1245–1259.
- Palmer, S. E. (1999). *Vision Science: Photons to phenomenology*. Cambridge, MA: MIT Press, p. 118.
- Ross, W. D., & Pessoa, L. (2000). Lightness from contrast: A selection integration model. *Perception and Psychophysics*, *62*, 1160–1181.
- Spehar, B., Clifford, C. W. G., & Agostini, T. (2002). Induction in variants of White's effect: Common or separate mechanisms? *Perception*, *31*, 189–196.
- Todorović, D. (1997). Lightness and junctions. *Perception*, *26*, 379–394.
- Wallach, H. (1948). Brightness constancy and the nature of achromatic colors. *Journal of Experimental Psychology*, *38*, 310–324.
- White, M. (1979). A new effect of pattern on perceived lightness. *Perception*, *8*, 413–416.
- Zaidi, Q., Spehar, B., & Shy, M. (1997). Induced effects of backgrounds and foregrounds in three-dimensional configurations: The role of T-junctions. *Perception*, *26*, 395–408.