Anchoring versus spatial filtering accounts of simultaneous lightness contrast

Elias Economou Department of Psychology, University of Crete, Rethymnon, Crete, Greece

Suncica Zdravkovic Psychology Department, University of Novi Sad, Novi Sad, Serbia, Lab of Experimental Psychology, University of Belgrade, Belgrade, Serbia

Alan Gilchrist Department of Psychology, Rutgers University, Newark, NJ, USA

The oldest lightness illusion is called simultaneous contrast. A gray square placed on a black background appears lighter than an identical gray square placed on a white background. For over a hundred years, this illusion has been generally attributed to lateral inhibition or spatial filtering. Receptor cells stimulated by the gray square on the white background are strongly inhibited by nearby cells stimulated by the bright white background. Recently, a new explanation for this illusion was proposed as part of a larger theory of lightness called anchoring theory. The lightness of each target square is computed relative to the highest luminance in its local framework (consisting of only the target and its surrounding background) and relative to the highest luminance in the entire display. For each target, perceived lightness is held to depend on a weighted average of these two computations. According to this story, the contrast illusion stems mostly from the tendency of the gray square on the black background to rise toward white, its computed value in its local framework. We report six experiments in which these two theories of simultaneous contrast are pitted against each other. In each case, the results favor the anchoring model. The difficulty of deriving predictions from the spatial filtering models is discussed, along with the ease of deriving highly specific predictions from the anchoring model.

Keywords: lightness, simultaneous contrast, contrast, illusion, anchoring, grouping, spatial filtering, brightness

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Introduction

The oldest illusion known to lightness perception is called simultaneous lightness contrast. When two identical gray squares are placed on white and black backgrounds, respectively, the square on the white background appears darker than the one on the black background. The illusion was studied by Chevreul (1839) and described by both Alhazen (1883/1989) and the ancient Greeks.

In the modern era, simultaneous contrast gained significance by defying the early assumption that visual experience corresponds to local stimulation and showing the role of context. Since the time of Hering (1874/1964; see also Mach, 1922/1959), the illusion has been attributed to "reciprocal interaction in the somatic visual field," or what later was called lateral inhibition. Recording from a single facet of the limulus eye in Hartline, Wagner, and Ratliff (1956), showed that when the intensity of light stimulating a facet is held constant, its rate of firing is inversely proportional to the intensity of light stimulating adjacent facets. The application of this finding to simultaneous contrast is straightforward. Without lateral inhibition, the two gray squares would produce equal rates of firing in the corresponding retinal areas. However, the bright light from the white background is thought to inhibit the firing rates of cells corresponding to the surrounded gray square, causing it to appear darker. This account of simultaneous contrast, which is almost universally presented in textbooks, is featured in two well-known models, those of Cornsweet (1970) and of Jameson and Hurvich (1964). We will refer to these models as contrast theories.

A glitch in this story immediately arises because lateral inhibition has a limited spatial reach. Thus, the square on the white background should not appear homogeneous. Its darkening should be most pronounced near its border with the white background. To solve this problem, different writers have suggested that either (1) the square does not really appear homogeneous (Cornsweet, 1970; Davidson, 1968), (2) the rates of firing are averaged within borders, or (3) the lateral inhibition only creates edge signals and the regions between edges are filled in by higher processes.

With the advent of the computer came more sophisticated theories of lightness, based on perceptual decomposition of the retinal image (Bergström, 1977; Gilchrist 1979). These models gave a much stronger account of lightness

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constancy. However, they were not able to address simultaneous lightness contrast. According to Gilchrist's intrinsic image model (Gilchrist 1979; Gilchrist, Delman, & Jacobsen, 1983), for example, the two targets in the contrast display should appear identical.

Models based on lateral inhibition have also grown more sophisticated in recent decades. These are not lightness models per se. They are called brightness models because they claim to model the human response to luminance. They generally fail to model images that contain either illumination edges or depth edges. These models incorporate the more modern view that lateral inhibition in humans takes the form of receptive fields, either with on-centers and off-surrounds or vice versa. There are more than a dozen such models. All of them start by taking a difference of Gaussians at multiple scales. The models vary in terms of how the outputs from the filters are combined. Watt and Morgan (1985) combine the outputs from all scales and then apply interpretation rules, whereas Kingdom and Moulden (1992) apply the interpretation rules to each scale before combining scales. Morrone and Burr (1988) use even- and odd-symmetric filters. Kingdom and Moulden use on-center cells only, whereas other models (Pessoa, Mingolla, & Neumann, 1995) use both on- and off-center cells. Some of the models predict illusory brightness scallops near boundaries, even in cases where observers fail to see them. Grossberg and Todorović (1988) and Pessoa et al. (1995) solve this problem by filling in homogeneous regions based on edge signals, whereas Heinemann and Chase (1995) average all activation within boundaries. McArthur and Moulden (1999) have published one of the few 2D models although, as they admit, there are serious failures.

In this paper, we will consider only the oriented difference of Gaussians (ODOG) model of Blakeslee and McCourt (2003), as it seems to be regarded as the best exemplar of this class of models. The ODOG model is 2D and, in addition to the conventional multiple scales, this model uses oriented filters with multiple orientations. Each filter consists of a central excitatory region flanked by a pair of inhibitory regions. For each point in the stimulus, the output of every filter, including all scales and all orientations, is summed with one important qualification. The outputs of each orientation are normalized to the same maximum value. This latter feature allows the model to account, at least qualitatively, for White's (1981) illusion, a kind of reverse simultaneous contrast illusion.

A brief summary of anchoring theory

Recently, a new general theory of lightness perception was published (Gilchrist et al., 1999), which includes a very different explanation of simultaneous contrast based on the concept of anchoring within frames of reference. It is generally recognized that lightness depends on relative luminance values. However, relative luminance values can produce only relative lightness values. Specific lightness values can be produced only by invoking an anchoring rule. The basic anchoring rule is that the highest luminance is automatically assigned the value of white and this serves as the standard for darker regions. Li and Gilchrist (1999) showed that in the simplest possible image that produces the appearance of surface lightness, that is two gray surfaces that fill the observer's entire visual field, the lighter region always appears white, even if it is objectively dark gray. The following equation predicts perceived reflectance in such a simple image:

$$\text{Perceived reflectance (lightness)} = (L_t/L_h * 90\%), \quad (1)$$

where L_t is the luminance of the target and L_h is the highest luminance.

Two additional anchoring rules, one concerning relative area and one concerning luminance range, seem to exhaust the computation of lightness in simple images. An area rule claims that surfaces will appear lighter as they become larger, as long as the darker region occupies at least half of the area. Because this rule plays no important role in the classic simultaneous contrast display, it will not be described in detail here, but those details can be found in Gilchrist (2006).

A scale normalization rule describes a tendency for the perceived range to shift toward that of the standard white to black range (30:1). When the range within the image is truncated relative to the standard range, some perceptual expansion occurs, the coefficient of which is proportional to the degree of truncation of the range. The equation for the normalized range is

$$\text{Perceived range} = (1 + (0.56 * (\log 30 - \log R))) * R, \quad (2)$$

where R is the actual range. The value 0.56 represents the slope of the regression line obtained by plotting perceived range against actual range in a disk/Ganzfeld experiment reported by Gilchrist and Bonato (1995).

The applicability assumption

Of course a critical question is how these rules should be applied to complex images. Here anchoring theory makes an important claim, called the applicability assumption. The model asserts that the rules of anchoring found in simple images also apply to frames of reference embedded within complex scenes. Intuitively, a frame of reference is a region of uniform illumination. Functionally, it is a region of the image within which a patch of a given luminance will appear as the same lightness, regardless of its location. Frames of reference are held to result from the perceptual segmentation of the retinal image based on two main factors: fuzzy boundaries (penumbrae) and depth edges (corners and occlusion edges). Weak frameworks are also said to be produced by a set of grouping factors, including T-junctions, X-junctions, luminance ramps, and many of the gestalt grouping principles.

Codetermination

The rules of anchoring found in simple images are applied to each of these frameworks with one additional caveat. Anchoring is never exclusively confined to a single framework. Rather there is crosstalk between frameworks, consistent with the principle of codetermination advanced by Kardos (1934) many years ago. The lightness of a given region results from a weighted average of the lightness computed for that region within each framework of which it is a member. Typically, perceived lightness is an average of two values computed for a given target: one within its local framework and another within the whole retinal image, called the global framework.

$$\text{Lightness} = W_l(L_t/L_{lh} * 90\%) + (1 - W_l)\left(L_t/L_{gh} * 90\%\right), \quad (3)$$

where W_l is the weight of the local framework, $1 - W_l$ is the weight of the global framework, L_{lh} is the highest local luminance, and L_{gh} is the global highest luminance.

The weight of the local framework depends on the size of the framework, the number of separate elements within the framework (called articulation), and the strength of its segmentation.

The application of this model to the simultaneous contrast display is shown in Figure 1. The display is segmented into two adjacent local frameworks that together compose a global framework (ignoring for the moment the larger visual context). In this global framework, both squares are assigned the same value (middle gray), given by the luminance ratio

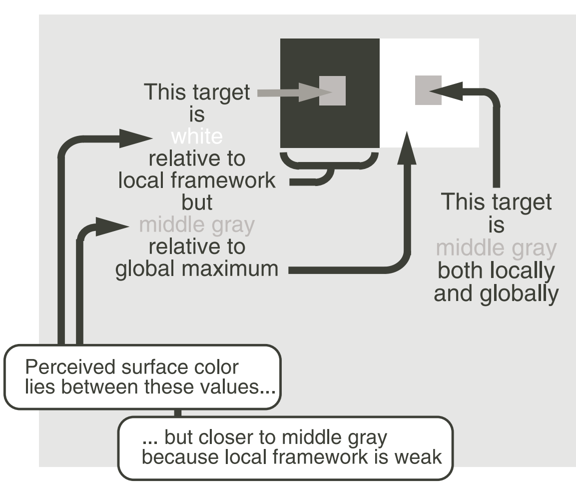

Figure 1. Most of the simultaneous contrast illusion is produced by anchoring the highest luminance to white within each framework.

between each square and the global maximum, namely, the white background. However, within each local framework, the squares receive different values. The square on the black background takes the value of white because it is the highest luminance in that local framework. This is held to be the main factor producing the illusion. The local/global weighting strongly favors the global values because the local frameworks are poorly segmented (neither by fuzzy boundaries nor by depth edges) and poorly articulated (only two elements within each framework). The essence of this model of simultaneous contrast was proposed by McCann in 1987. In the anchoring model, a weak scale normalization effect also applies to each framework given that the luminance range within each is only about half of the standard 30:1 white–black range. Because the highest luminance in each framework is anchored at white, the only target affected by range expansion is that on the white background, causing it to darken slightly. Thus, the predicted perceived reflectance of the target on the white background is derived by dividing the predicted reflectance of the white background by the expanded range instead of by the actual range (R in the equation):

$$\text{Reflectance} = 90\%/(1 + (0.56 * (\log 30 - \log R))) * R. \quad (4)$$

In sum, the illusion is mainly attributed to a strong lightening of the target on black due to its position as highest luminance in the local framework. A weaker darkening of the target on white is predicted based on scale normalization.

We report seven experiments in which this anchoring model is pitted against both the traditional lateral inhibition model and the ODOG model. Specifically, we tested four predictions made by the anchoring model: (1) the illusion depends much more on the lightening of the square on black than it does on the darkening of the square on white; (2) the illusion should be strongest with dark gray targets and weakest with light gray; (3) the illusion should be absent when both targets are increments; and (4) the illusion should be stronger when the local backgrounds are articulated. Predictions based on contrast theories and brightness models are less clear but clear enough to allow these tests. For the anchoring predictions, it will be helpful to keep in mind that the illusion stems from local anchoring. Completely global anchoring would produce a veridical percept (i.e., the targets would appear equal).

The experiments

General method

These methods apply to all the experiments unless otherwise specified.

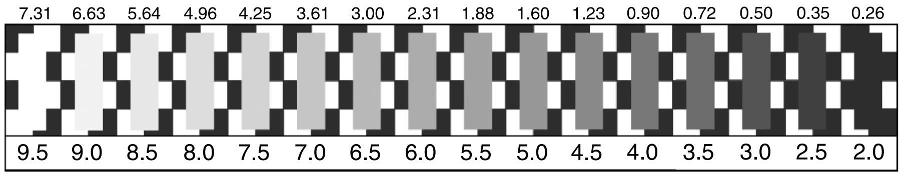

Figure 2. Munsell chart used for lightness matches. Luminance values of chips (in cd/m^2) shown above.

Subjects

The observers in these experiments were undergraduate students who volunteered to fulfill a course requirement. All had normal or corrected to normal vision.

Displays and laboratory arrangement

Except as noted, the stimulus displays were presented on a computer screen viewed from a distance of 80 cm. The room was normally illuminated by florescent lights. We will ignore the role of this largest frame of reference as its influence would be constant across conditions.

Lightness matches

Observers matched the lightness of target patches by selecting a matching chip from a Munsell scale that was either presented on paper or simulated on the computer screen. The Munsell scale consisted of a series of 16 small rectilinear patches ranging in lightness from black to white and presented on a black and white checkerboard background, as shown in Figure 2.

Although we collect data using a Munsell scale, we plot our results neither in Munsell units nor in linear units of reflectance, but in log reflectance, consistent with Weber's law and the Wallach ratio principle. Nevertheless, for all of our experiments, the results are qualitatively the same when plotted either in simple reflectance or, except for Experiment 2 (as noted), in Munsell units.

Procedure

The observer was seated in front of the display and instructed to choose the chip from the Munsell chart that appeared to be most similar to the target in black, white, or gray surface color. After making the appropriate matches, the observer was briefly informed about the purpose of the experiment.

Design

A between-subjects design was employed with a separate group of observers in each condition.

Experiment 1: Locus of error

The anchoring model claims that the bulk of the contrast illusion is caused by the lightening of the target on the black background due to its tendency to appear white as the highest luminance in the local framework. Some darkening of the target on white should occur due to scale normalization, but this effect should be small relative to the main anchoring effect.

It is not clear what the locus of error prediction would be for contrast theories. These models would most likely predict symmetrical errors. However, it might be argued that the main error would occur for the target on the white background because of the strong inhibition at that location. The ODOG model predicts symmetrical errors (Blakeslee & McCourt, 2003, p. 51).

Probing the locus of error requires matching both targets to a third standard, but this must be done fairly. Using a Munsell scale with chips on a white background, for example, would not be fair. One would expect the target on the white background to be correctly matched in that case. We chose to use a set of Munsell chips on a black and white checkerboard background, so that each chip bordered black and white regions equally.

Method

We ran the experiment three times. Condition 1: paper display and paper chart; Condition 2: display and chart were presented on CRT; and Condition 3: display on CRT and chart on paper.

Target luminance, equivalent to Munsell 5.0, was 5.48 cd/m^2 (on screen) and 2.4 cd/m^2 (on paper). The black background (Munsell 2.0) was 0.89 cd/m^2 (on screen) and 0.38 cd/m^2 (on paper). Finally, the white (Munsell 9.5) had a luminance of 25.0 cd/m^2 (on screen) and 10.6 cd/m^2 (on paper). CRT luminance values were converted to reflectance values by assigning the "white" background a reflectance of 90% and by treating lower values in proportion to relative luminance. Illumination was assumed to be homogeneous.

Target size was 3.4 $\times$ 3.4 cm and background size was 13.5 $\times$ 13.5 cm. At a viewing distance of approximately 80 cm, the visual angles for the targets and backgrounds were 2.4° and 9.7°, respectively. Seventeen observers participated in each condition.

Results

The errors in all three conditions are shown in Figure 3 as deviations in log reflectance from the actual value of the

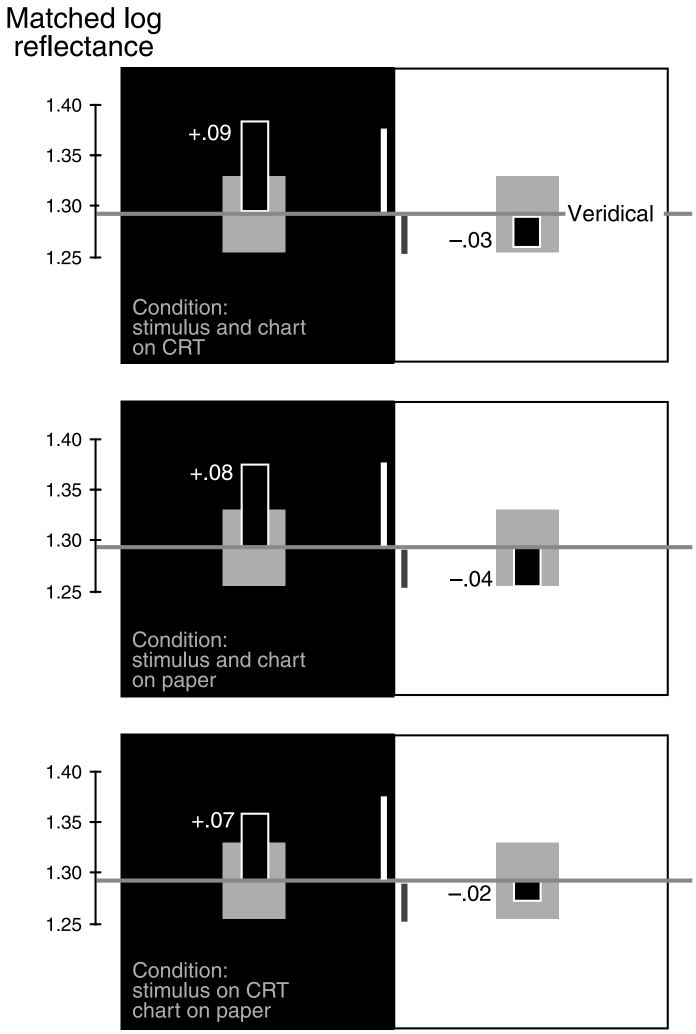

Figure 3. Most of the error is expressed by the target on black. Thin bars in the center represent model predictions.

two targets (1.295 log reflectance), indicated by the horizontal line. As can be seen, the larger error in all three conditions occurred for the target on the black background. At the same time, a small darkening is observed for the target on the white, consistent with a small scale normalization effect predicted by anchoring theory. Predictions of the anchoring model, shown by the thinner bars near the center of each display, were calculated using local and global weights of 0.125 and 0.875, derived from McCann's (1987) report on the size of the illusion as one Munsell step.

The mean perceived log reflectance for the target on the black in Condition 1 was 1.39. The mean for the target on the white was 1.28. The absolute error for the target on the black background ($|1.30 - 1.39| = 0.09$) was significantly different than the absolute error on the target on the white background ($|1.30 - 1.28| = 0.02$), $t(32) = 2.26$, $p < .05$.

The mean perceived log reflectance for the target on the black in Condition 2 was 1.38. The mean for the target on the white was 1.26. The absolute error for the target on the black ($|1.30 - 1.38| = 0.08$), however, was not significantly different than the absolute error on the target on the white ($|1.30 - 1.26| = 0.04$), $t(32) = 1.58$, $p = 0.06$.

The mean perceived log reflectance for the target on the black in Condition 3 was 1.37. The mean for the target on the white for the same condition was 1.28. The absolute error for the target on black ($|1.30 - 1.37| = 0.07$) was significantly different than the absolute error on the target on white ($|1.30 - 1.28| = 0.02$), $t(32) = 1.67$, $p < .05$.

The deviation for the target on black was larger than the deviation for the target on white by the following ratios in our three conditions, respectively: 5.9:1, 2.3:1, and 4.6:1.

Discussion

The results resemble the predicted values and show that the main error is the lightening of the target on the black background. Logvinenko, Kane, and Ross (2002) found the same result, writing "…the difference in lightness induction between [the two targets] arises from the dark surround." Güçlü and Farell (2005) presented results that appear to show a larger error on the white background. However, some or all of these results can be attributed to their use of a gray background for their matching chips.[1]

In fact, the locus of error can be determined by inspection alone when one views exceptionally strong contrast illusions, such as the one in Figure 4. There the target on the dark background clearly approaches white more than the target on the light ground approaches black.

Figure 4. Strong version of simultaneous lightness contrast.

The results are inconsistent with predictions based on contrast theories or brightness models.

Experiment 2: Target reflectance

The anchoring model predicts that the strength of the contrast illusion should increase as darker targets are used. Remember that the error is mainly attributed to the target on the black background. As this target gets darker, there is a greater discrepancy between its value in the local framework (always white) and its value in the global framework (veridical). Hence, the averaging of local and global values will result in a perceived value that deviates farther from veridicality as the target gets darker. The weak darkening of the target on the white background, caused by expansion of the truncated range, is expected to weaken as darker targets are used because the truncation of the range in that local framework (and its corresponding expansion) is gradually eliminated.

It is not entirely clear what predictions are made by contrast theories based on lateral inhibition. The ODOG model predicts the largest contrast effect with mid-gray (Kingdom, McCourt, & Blakeslee, 1997), so that a negative U-shaped contrast function should be observed.

We measured the strength of the contrast illusion using light gray, middle gray, and dark gray targets. Both the contrast display and the matching chart were presented on the CRT screen. We ran this experiment twice, with slightly different luminance values in the second run.

Method

The equivalent Munsell values of the three target values in the first run were 3.0, 7.0, and 8.0, with corresponding luminance values of 1.7, 12.4, and 17.0 cd/m^2. Otherwise, the spatial dimensions and the background luminance values were the same as the computer screen display used in Experiment 1. Separate groups of 10 observers served in each of the first two conditions, and 9 observers served in the third condition. In the second run, the luminance values of the targets in the three conditions were 2.47, 5.48, and 19.3 cd/m^2. Ten observers served in each of the conditions.

Results

The results of the three conditions of the first run are shown in Figure 5. As the luminance of the targets decreased, the size of simultaneous lightness contrast increased, consistent with anchoring theory.

The overall effect of target luminance on the size of the simultaneous lightness contrast illusion was significant, $F(2, 26) = 13.31$, $p < .001$ (one-way ANOVA). The average illusion size for the dark gray targets was 0.32, for the middle gray targets was 0.16, and for the light grays

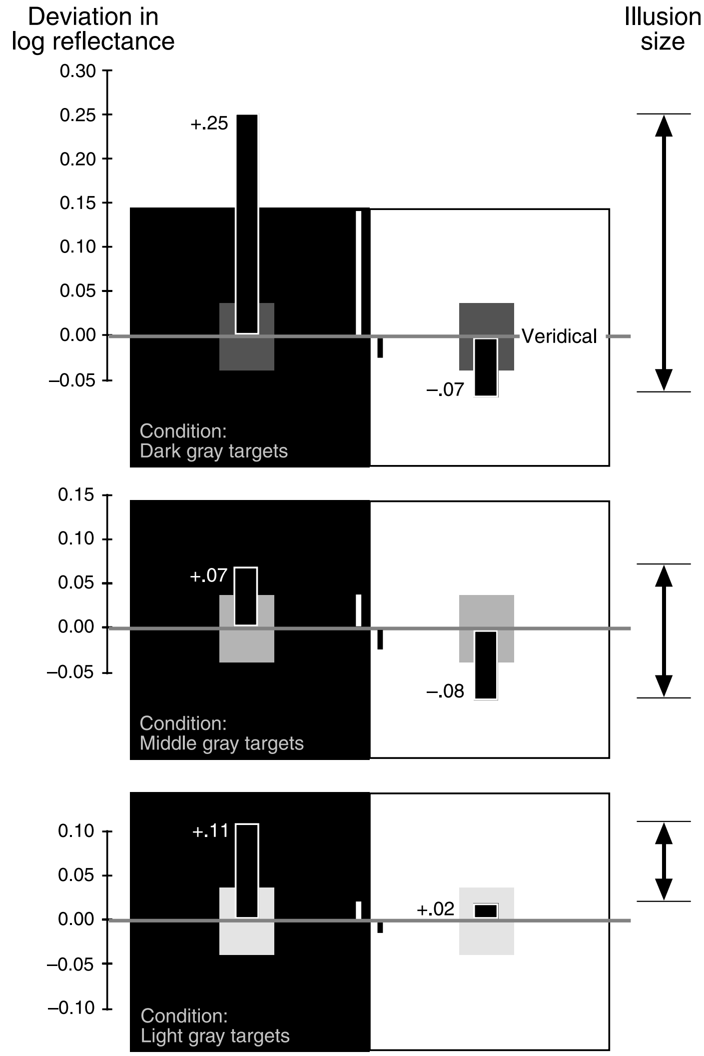

Figure 5. Larger illusion with darker targets.

was 0.09. All means were significantly different from each other. The mean for the dark grays was different from the mean for the middle grays, $t(13) = -1.77$, $p < .05$, and from the mean for the light grays, $t(11) = -5.22$, $p < .001$. The mean for the middle grays was different from the mean for the light grays, $t(17) = -3.02$, $p < .01$.

In terms of simple reflectance, illusion size was 40% for dark gray targets, 15% for middle gray, and 1.5% for light gray.

The results for the second run are shown in Figure 6, again showing a larger illusion size for darker targets.

Discussion

Although the deviations obtained are larger than those predicted by the anchoring model, the results are roughly consistent with the model. They are also consistent with results reported by Logvinenko and Ross (2005, Figure 17) and by Güçlü and Farell (2005) when those results are plotted in log reflectance.[2] On the other hand, contrast

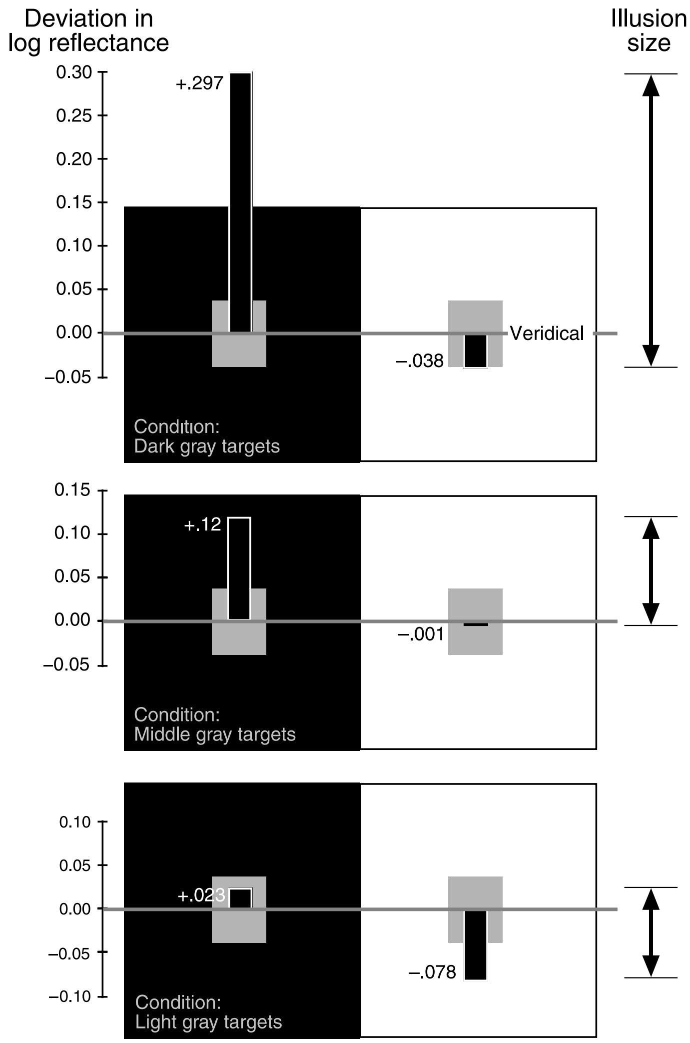

Figure 6. Results from the second run of Experiment 2.

theories fail to predict the outcome of this experiment. In addition, the ODOG model makes the wrong prediction.

Experiment 3: Staircase contrast—increments and decrements

Many writers (Cornsweet, 1970; Hering, 1874, p. 125; McArthur & Moulden, 1999, p. 1212; Shapley, 1986, p. 51) have presented a display that might be called staircase contrast: a series of identical targets on a series of adjacent backgrounds that vary stepwise in luminance. Half of the targets are decrements and half are increments. According to the anchoring model, only the decremental targets should appear to differ from each other. All the incremental targets should appear equal because the anchoring model predicts no contrast illusion when both targets are increments. Remember that, according to the model, the illusion stems from local anchoring. In the global framework, the targets have identical values. However, when both targets are increments, they have identical values locally as well because each is computed as white in its local framework.

Contrast theories, including the ODOG model, appear to predict symmetrical contrast effects for increments and decrements.

Displays

The staircase contrast display we used is shown in Figure 7. Background luminance decreased in equal log steps from left to right: 70.9, 45.9, 27.1, 14.7, 7.54, and 3.77 cd/m^2. Background size was 3.8 × 7.5 cm; target size was 1.7 × 1.3 cm. The targets subtended 1.21° horizontally and 0.93° vertically, whereas the backgrounds

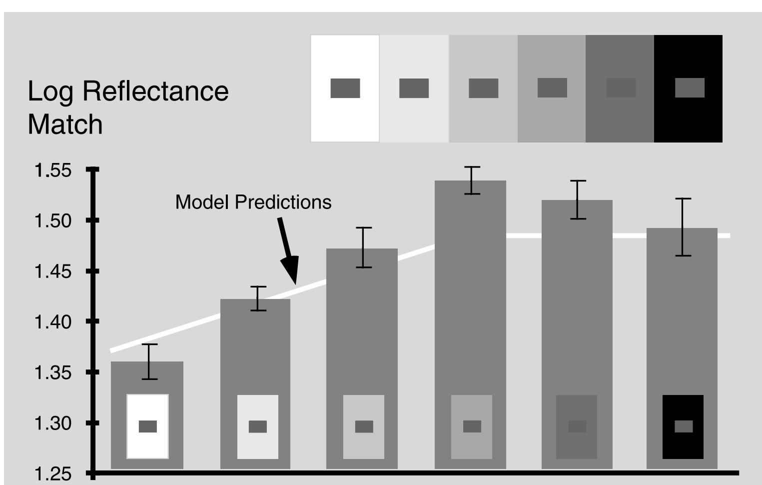

Figure 7. Contrast effect obtained for decrements but not for increments. Theoretical predictions derived from the equations given in the introduction are shown by the white line.

subtended 2.72° horizontally and 5.37° vertically. Target luminance was 20.6 cd/m^2. Thus, the three left-most grays were decrements, whereas the three right-most grays were increments. Nineteen observers participated. Each observer matched all six targets.

Results

The results are shown in Figure 7. The means for the six targets (left to right) were 1.36, 1.42, 1.47, 1.54, 1.52, and 1.49. The overall effect of background luminance on target lightness was significant, $F(5, 108) = 11.55$, $p < .001$ (one-way ANOVA). The left-most target was significantly different from all other targets at least at $p < .01$. The second target also differed significantly from all other targets at least at $p < .05$. The third target differed significantly from Target 4, $t(36) = -2.64$, $p < .01$, but not from Target 5, $t(36) = -1.56$, $p < .05$, or Target 6, $t(36) = -.51$, $p < .05$. Finally, there were no significant differences (at $p < .05$) among increments (Targets 4, 5, and 6). Obviously, the same knee in the curve would appear if the data were plotted in simple reflectance values.

Discussion

These results are consistent with the specific predictions of the anchoring theory, but not with those of contrast models or the ODOG model. Despite the (at least implicit) claims of Cornsweet (1970), Hering (1874/1964), and others that contrast illusions are observed between all targets in their displays, we failed to find any effect between increments. Indeed, among increments, one sees what appears to be a slight negative slope. Although this difference did not reach significance, we decided to explore this trend in a further experiment in which all six targets were increments.

Experiment 4: Staircase contrast—all increments

Method

The display we used can be seen in Figure 8. Everything was identical to Experiment 3 except for the luminance of the targets and background. The background luminance increased in equal log steps (from left to right: 26.7, 18.2, 13.0, 9.25, 6.17, and 3.77 cd/m^2). Target luminance was set at 34.26 cd/m^2. Nine observers participated in this experiment.

Results

The results of the experiment are shown in Figure 8. No difference was found among the targets. The averages for all six were very close: 1.74, 1.74, 1.74, 1.74, 1.73, and 1.76. The overall effect of background luminance on target lightness was not significant, $F(5, 48) = .26$, $p > .05$ (one-way ANOVA).

Discussion

Consistent with the predictions of the anchoring model, we found no contrast effect for increments. The absence of contrast effects for increments has also been found by Agostini and Bruno (1996), Arend and Spehar (1993), Diamond (1953), Heinemann (1955), Kozaki (1963, 1965), Gilchrist (1988), and Jacobsen and Gilchrist (1988). Several investigators have found contrast effects with increments (Bressan & Actis-Grosso, 2001; Rudd & Zemach, 2005), although these effects are substantially weaker than those found with the standard display.

Experiment 5: Articulated backgrounds

The anchoring theory predicts a stronger contrast illusion when the white and black backgrounds are replaced by

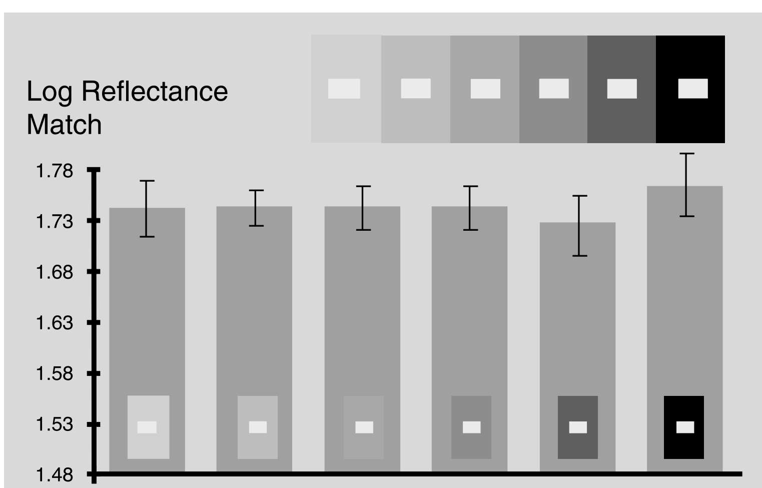

Figure 8. No contrast effect with incremental targets.

articulated Mondrian patterns. According to the theory, the two main factors that determine the weight of a local framework are its size and degree of articulation. These principles originally come from Katz (1935), who concluded based on his empirical work that lightness constancy is best with large fields of illumination and with articulated fields. According to anchoring theory, failures of constancy (unlike the errors in simultaneous contrast) are caused by global anchoring. Thus, large, articulated fields typically[3] produce better constancy because they lead to stronger local anchoring. Because the contrast illusion is attributed to local anchoring in this model, articulating the backgrounds is predicted to increase the strength of the illusion.

Both the contrast theories and the ODOG model would appear to predict a reduction in contrast strength because we articulated the white background by replacing it with light grays and the black background with dark grays, thus reducing the difference in average luminance between the two backgrounds.

Method

Articulated and standard versions of the simultaneous contrast display were tested, as shown in Figure 9. In both displays, target luminance was 5.48 cd/m^2. In the articulated display, the black background was replaced by a Mondrian pattern containing patches between the target luminance and black. The white background was replaced by a Mondrian containing patches between the target luminance and white. Separate groups of 10 observers each made matches in the articulated and the homogenous conditions, respectively.

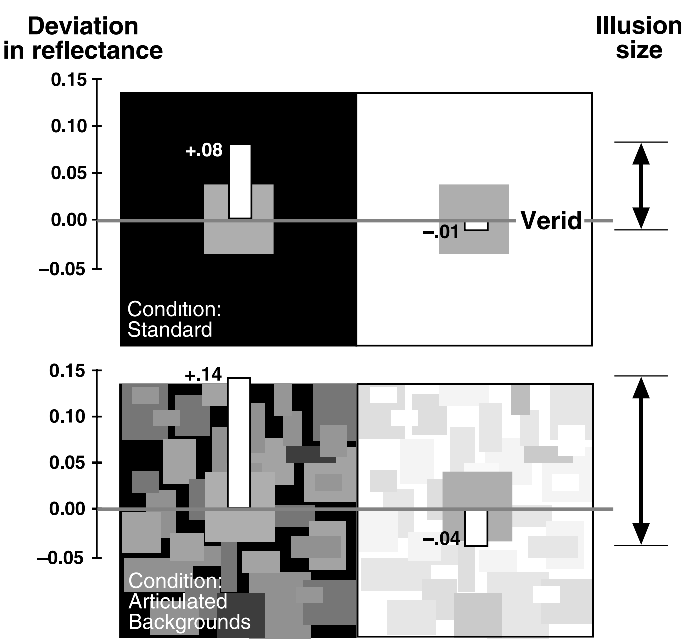

Figure 9. Stronger contrast illusion with articulated backgrounds.

Results

The results from this experiment are shown in Figure 9. The overall size of the contrast illusion was 0.09 log units (0.5 Munsell steps) for the homogeneous condition but 0.18 log units (1.1 Munsell units) for the articulated display, a significant difference, $t(18) = 2.03$, $p < .05$. In simple reflectance terms, illusion size was 4.6% (homogeneous) and 9.0% (articulated).

In both conditions, the illusion was primarily due to the lightening of the target on the black background, consistent with the anchoring model and with the results of Experiment 1. In the homogeneous condition, the error on the black background was 0.08 log units, and the error on the white background was 0.01 log units, a significant difference, $t(18) = 2.59$, $p < .01$. In the articulated condition, the error on the black background was 0.14 log units, whereas the error on the white background was 0.04 log units.

Discussion

These results are consistent with predictions made by the anchoring model and with previous reports. Adelson (2000) reported a doubling of the contrast illusion using articulated backgrounds that were equal in average luminance to the homogeneous backgrounds. In our experiment, the average luminance of our articulated backgrounds differed by less than that of our homogeneous backgrounds. Bressan and Actis-Grosso (2006) replicated the Adelson experiment and his results. Teasing apart the factors of greater articulation and higher maximum luminance in the articulated display, they found that both of these lead to a stronger illusion.

Experiment 6: Background lightness

The anchoring model also makes a prediction about background lightness in the contrast display. Although the white background (being the highest luminance in both its local and global framework) is predicted to look white, the black background is predicted to appear a bit lighter than black. In fact, there are three components of the anchoring model that should impact on the computation of lightness for the black background. First, if the target on the black background moves toward white due to local anchoring, the black should move up the lightness scale by the same proportion. Averaging the amount of this upward movement in the three conditions of Experiment 1 suggests that the black background should lighten by 0.08 log units. That would produce a Munsell value of 2.2, given an actual value of 2.0. However, the area effect and scale normalization would also affect this value, although in opposite directions. Given that the area of the black background is about 15 times that of the gray target, it would be expected to lighten a bit. On the other hand, given the truncated range in the local framework (6.6:1, from gray of reflectance 20% to black of reflectance 3%), scale normalization predicts a slight darkening of the black background. According to the applicability assumption, the combined effect of area and scale normalization can be estimated based on results from unpublished experiments in our laboratory (Gilchrist & Radonjic, 2005) using dome interiors containing only two shades of gray with similar range (3.75:1) and similar area ratio (16:1). Combining this estimate with the relatively modest weight given to the local framework suggests a further lightening of the black background from 2.2 to 2.4.

Thus, the predicted lightening of the black background is quite modest; however, there is no evidence that it lightens at all. We can suggest a hypothetical supplement to the anchoring theory that would accommodate the lack of a lightening effect on the black background. There may be an asymmetrical relationship of belongingness between regions of figure and ground. Specifically, it may be that figure belongs to ground more than ground belongs to figure. We tested this idea in the following experiment.

The stimulus display is shown in Figure 10. The targets are identical gray frames, each of which borders both black and white regions. Perceptually of course each target is perceived as a gray square lying on top of a black (or white) background, with a white (or black) figure lying on top of the gray target. One can see merely by inspection that the target on the right appears darker than the target on the left, a result that is consistent with our suggested hypothesis.

Method

Ten observers viewed the display shown in Figure 10. Both the display and the Munsell chart were presented on the CRT screen.

Results

The average match made to the right-hand target was 1.32, significantly darker, $t(22) = 4.38$, $p < .001$, than the match for the left-hand target, which was 1.43. These results support the idea of a figure/ground asymmetry in belongingness. That asymmetry implies that although the targets are seen in relationship to the background regions, each background region is seen only (or at least more strongly) in relation to the other background.

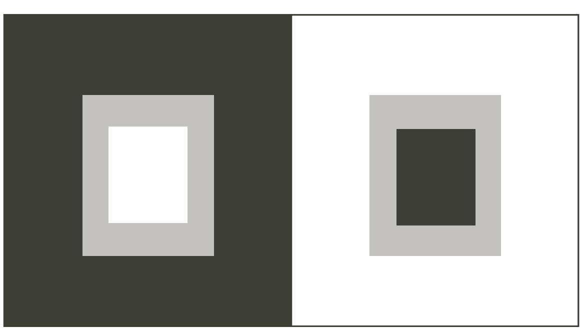

Figure 10. This illusion suggests that figure belongs to ground more than ground belongs to figure.

This result appears to contradict both the contrast models and the ODOG model.

General discussion

In general, these results are consistent with the predictions of the anchoring theory of simultaneous lightness contrast. According to the anchoring model, most of the illusion is caused by the tendency of the gray target on the black background to anchor on white because it is the highest luminance in its local framework. If nothing else were visible except the gray and black that compose this framework, the target would appear completely white. This has been demonstrated in experiments in which two regions, one gray and one black, fill the observer's entire visual field (Li & Gilchrist, 1999). The gray region appears completely white.

According to the applicability assumption of the anchoring model, the same rules of anchoring found in such simple visual fields are also applied to any local framework embedded in a complex image. In the latter case, however, the values so computed must be averaged together with values computed within the whole display, called the global framework. Because each local framework in the contrast display is poorly articulated and only weakly segmented, its weight should be weak relative to the global framework.

The results of Experiment 1 (locus of error) confirm that the target on the black background is indeed responsible for most of the illusion. We found this result for all three combinations of CRT and paper displays we ran. We also found the same result in two of the three conditions of Experiment 2 and in both conditions of Experiment 5. In the articulated condition of Experiment 5, the deviations from veridical are quite pronounced. In addition, here it is readily seen, both in the data and in the display, that the target on the dark background deviates more from middle gray than the target on the light background.

Also as predicted by the anchoring model, we found in Experiment 2 a stronger illusion with darker targets and a weaker illusion with lighter targets. This is consistent with the anchoring model because, as darker targets are used, there is an increasing difference between the local value computed for the target on black (always white) and the global value (equal to its veridical value). Thus, the weighted average of these two deviates farther from its veridical value as darker targets are used.

The results of Experiments 3 and 4 show that, as predicted by the model, contrast effects occur among decremental targets but not among incremental targets. Thus, the curve representing target lightness against a staircase sequence of backgrounds shows a knee at the decrement/increment boundary.

Because the illusion stems from local anchoring according to the anchoring model, any factor that increases the weight of the local framework should enhance the illusion. The two main factors that determine the weight of a framework are framework size and degree of articulation (Katz, 1935). Both have been shown to work. Articulating the local frameworks increased the strength of the illusion in Experiment 5, a result that has been confirmed by Adelson (2000) and Bressan and Actis-Grosso (2006). Bressan and Actis-Grosso (2001, 2006) obtained very strong contrast effects using a relatively large display. Burgh and Grindley (1962) found no effect of a fourfold change of viewing distance on the strength of the contrast illusion. Other works on effects of size on lightness (Bonato & Gilchrist, 1999; Cataliotti & Gilchrist, 1995) have shown that it is perceived size, not retinal size, that matters. Thus, the Burgh and Grindley results may not pose a problem because they varied only retinal size.

Framework size and degree of articulation are factors identified by David Katz in his early experiments on lightness constancy. Katz claimed that high articulation and large field size produce greater constancy. According to the anchoring model, these factors do not necessarily lead to greater constancy. Rather they increase the strength of the framework. In experiments such as those of Katz, increasing framework strength does produce greater constancy. However, in frameworks such as those in the contrast display, these factors lead to a reduction in constancy. They increase the size of the illusion because the illusion is held to derive from local anchoring. Consistent with this prediction, we found in Experiment 5 that articulating the black and white backgrounds increases the size of the contrast illusion.

Any factor that can be used to further segregate the two local frameworks from each other is also predicted to increase the strength of the contrast illusion. One way to do this, according to the anchoring model, is to replace the sharp border between the white and black backgrounds with a luminance gradient. Luminance gradients, such as penumbrae, function to segregate frameworks (suggesting an illumination boundary) within the anchoring model. Several reports (Agostini & Galmonte, 2002; Shapley, 1986) have shown that separating the backgrounds with a luminance gradient does indeed produce a stronger contrast illusion.

Laurinen, Olzak, and Peromaa (1997) have shown that the contrast illusion is weakened when the target squares have a texture whose spatial frequency is identical to each other, but different from that of the background regions. Here the weakened belongingness of each target to its background, based on grouping by similarity, can be said to weaken each local framework, which in turn weakens the illusion.

Rigor of models

Contrast theories based on lateral inhibition (Cornsweet, 1970; Jameson & Hurvich, 1964) did not perform well in our experiments. Where we could derive predictions from these models, our results contradicted those predictions. However, it is worth commenting on the difficulty we found in deriving predictions from contrast theories. Such theories have often been considered superior to other models, especially gestalt models, due to their rigor and close connection to known physiological mechanisms. However, neural plausibility aside, there appears to be little basis for attributing rigor to these models. We were unable to derive predictions from contrast models on locus of error and the effect of target reflectance on strength of the contrast illusion. This difficulty is not limited to these questions. For example, one cannot get a clear prediction from contrast models on the effect of simply adding a bright outer ring to a disk/ring stimulus. Does the outer ring further darken the disk by adding additional inhibition, or does it lighten the disk by disinhibiting the inner ring?

Where predictions can be derived from lateral inhibition theories, those predictions were found to be wrong. Specifically, no contrast illusion was found for increments, and a stronger illusion was found for articulated displays, even when this reduced the difference in average luminance of the two backgrounds.

Clear predictions can be made from the ODOG model of Blakeslee and McCourt (2003), but these predictions clearly failed for Experiments 1, 2, 3, and 4. For the two remaining experiments, Experiments 5 and 6, the predictions we believe follow from that model also failed.

Predictions made by the anchoring model, on the other hand, are highly specific, possibly making it the first model to predict lightness values in exact values of reflectance. In addition, the five predictions listed in the introduction were strongly supported in terms of the overall pattern of results.

In recent years a series of illusions, shown in Figure 11, have appeared that also directly challenge the contrast account based on lateral inhibition. In White's (1981) illusion, gray bars that are mostly surrounded by white appear lighter than gray bars that are mostly surrounded by black. This seems to occur because the former bars are perceptually grouped with black stripes, whereas the latter bars are perceptually grouped with white stripes. White's illusion is a more dramatic example of the topologically equivalent Benary (1924) illusion produced by Wertheimer in 1924. More radical examples have been created by Agostini and Galmonte (2002), Bressan (2001), and Economou, Annan, and Gilchrist (1998). In these examples, a target completely surrounded by white, but perceptually grouped with black, appears lighter than a target completely surrounded by black, but perceptually grouped with white.

The ODOG model claims to explain White's (1981) illusion, and this is true qualitatively due to its unique

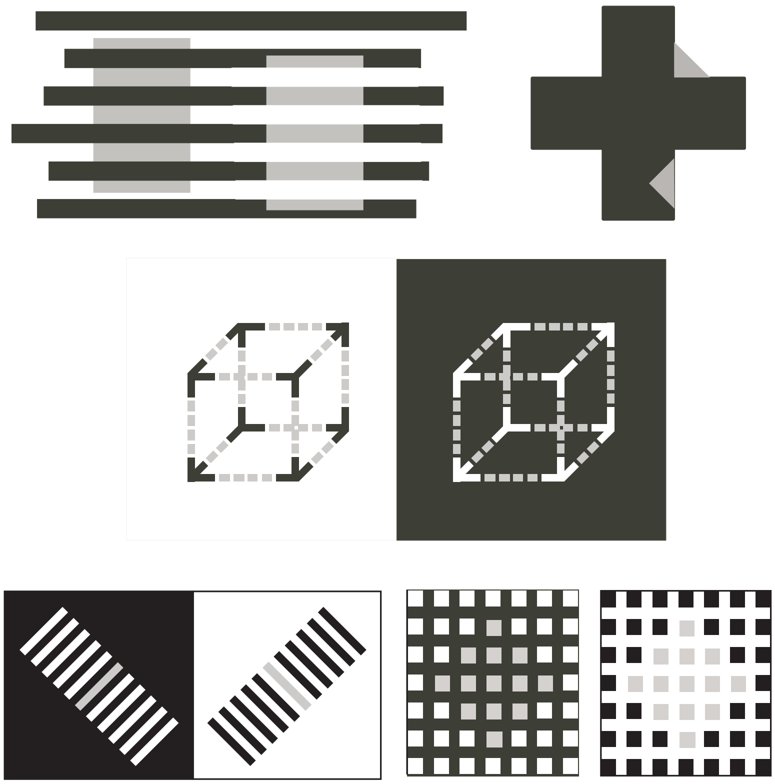

Figure 11. Various reverse contrast figures. Top: White (1981) and Benary (1924); middle: Agostini and Galmonte (2002); bottom: Economou et al. (1998) and Bressan (2001).

feature of normalizing the luminance range within each orientation channel. However, it predicts that White's illusion is more than three times weaker than simultaneous contrast (see Figure 4.7 in Blakeslee & McCourt, 2003), a prediction at odds with data published from neutral laboratories. As for the other illusions shown in Figure 11, it does not appear that the ODOG model can account for them, even in direction of effect.

The ODOG model is highly rigorous in the important sense that it is instantiated in a computer model. Although its predictions are often not intuitively obvious, they can be obtained by running the model, assuming one has the model programmed on a computer. However, even this computer output gives the results only in relative values; it does not give an output in lightness values (i.e., perceived reflectance).

The ODOG model accounts qualitatively for the simultaneous lightness contrast display itself, predicting that the target on black will appear lighter than the target on white. However, quantitatively the model predicts that the targets will appear to differ in lightness almost as much as do the black and white backgrounds, a predicted illusion greatly exceeding obtained results.

This is not to suggest that the anchoring model has no limitations. It cannot account for gradient induction, the flagship illusion of the ODOG model. Indeed the anchoring model is unable to explain any cases in which a homogeneous region appears nonhomogeneous. In addition, a list of additional failures of the model can be found in Gilchrist (2006, p. 354).

However, it should be kept in mind that the scope of anchoring theory extends far beyond the simultaneous contrast illusion studied in these experiments. The anchoring model explains all of the six main lightness errors found in lightness constancy experiments (see Gilchrist, 2006, pp. 312–314) The anchoring model performs well across a wide range of lightness phenomena, from simple bipartite domes to complex real-world images. It accommodates the important distinction between reflectance and illuminance edges. It incorporates the crucial role of depth in lightness. By comparison, the ODOG model is unable to deal with images that contain either depth edges or multiple regions of illumination, excluding from its ken almost all the images normally encountered in the visual environment.

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Corresponding author: Alan Gilchrist.

Email: alan@psychology.rutgers.edu.
Address: Psychology Department, Rutgers University, Newark, NJ 07102.

Footnotes

[1]This would cause the chips to appear lighter, leading the observer to select darker chips. This would appear to throw more of the error to the white background.

[2]Plotting the data in Munsell units yields roughly the same size illusion for light and dark gray targets, but the anchoring model predicts lightness in terms of log reflectance, not Munsell values.

[3]When the field is an illumination field and a white is present.

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