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Brightness assimilation in bullseye displays

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Abstract

In simultaneous brightness contrast displays, a gray target square G_B bordered by black appears brighter than an identical gray target square G_W bordered by white. Here we demonstrate that this effect can be reversed if G_B is surrounded by bands that alternate outward from black to white, while G_W is surrounded by bands that alternate outward from white to black. With these simple "bullseye" displays assimilation generally occurs—G_B appears darker than G_W. Experiments 1 and 2 used a 2AFC design with a 2.2 s display duration. The results of these experiments indicate that (i) substantial assimilation occurs for target Weber contrasts (relative to the gray background) of −0.25, 0, and 0.25, but assimilation was maximal when target contrast was −0.25 and decreased as target contrast increased, (ii) assimilation effects were the same whether the width of the four surround bands was 20% of the target or 40% of the target, and (iii) assimilation occurs with as few as 2 surround-bands and the magnitude of the effect increases slightly as the number of bands increase. When experiment 1 was re-run using the method of matching (experiment 3), however, the results changed dramatically: (moderate) assimilation effects were found only when target contrast was −0.25; when target contrast was 0.25, there was a brightness contrast effect; when target contrast was 0, there was no illusion. Assimilation effects in bullseye displays are not predicted by the CSF model described in DeValois and DeValois [Spatial Vision, Oxford University Press, New York, 1988], the anchoring model of Gilchrist et al. [Psychological Review, 106(4) (1999) 795], or Blakeslee and McCourt's [Vision Research 39 (1999) 4361] ODOG model. We propose that this assimilation effect is the result of a contrast inhibition mechanism similar to that proposed by Chubb et al. [Proceedings for the National Academy of Science, vol. 86, 1989, p. 9631] to underlie contrast effects.

Keywords: Assimilation; Brightness; Edge contrast

1. Introduction

For almost two centuries it has been known that the brightness of a patch is much affected by regions adjacent to the patch (Chevreul, 1824). Perhaps the most well known of these effects is illustrated by brightness contrast displays. In these displays a gray patch that is a local contrast increment appears brighter than an identical gray patch that is a local contrast decrement. The robustness of this effect along with both psychophysical evidence (e.g., Jameson & Hurvich, 1964; McCourt & Kingdom, 1996; Whittle, 1994a) and physiological evidence (e.g., Hartline, Wagner, & Ratliff, 1956; Kuffler, 1953), has suggested to many that lateral inhibitory interactions among low-level neurons are a fundamental component of brightness perception—as was originally suggested by Mach (1886).

Recently, however, a number of studies have revealed numerous image configurations that give rise to brightness perceptions that are difficult to explain solely by lateral inhibition (e.g., Adelson, 1993; Gilchrist, 1977; Knill & Kersten, 1991; Logvinenko, 1999; Purves, Shimpi, & Lotto, 1999; Williams, McCoy, & Purves, 1998a, 1998b). It is almost impossible, however, for any of these studies to definitively rule out lateral inhibition as a fundamental process underlying brightness perception. With such studies it can usually be argued that image configuration may induce other (usually presumed to be higher order) processes that significantly augment or depress the effects of lateral inhibition—especially if the configuration implies inhomogeneous illumination (e.g., Kingdom, Blakeslee, & McCourt, 1997; Shevell, Holiday, & Whittle, 1992; Whittle, 1994b).

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Indeed, there are few examples of stimuli in which a gray patch that is a local contrast decrement at *all* of its edges is perceived as brighter than an identical patch that is a local contrast increment at all of its edges. De Valois and De Valois (1988) term such effects "similitude". More commonly such effects are termed "assimilation". However, the meaning of the latter term varies in the literature. Some authors (e.g., Whittle, 1994b) describe the illusory effects such as those presented in Shapley and Reid (1985) as assimilation even though *both* gray targets are a local contrast increment (or decrement) at all of their edges. In the present paper we reserve the term "assimilation" for only those brightness illusions that are opposite to brightness contrast: images in which a gray patch that is a local contrast decrement at all of its edges is perceived as brighter than an identical gray patch that is a local contrast increment at all of its edges.

Two recent examples of assimilation are Bressan's (2001) dungeon illusion and the "cube" illusion of Agostini and Galmonte (2002). However, both illusions are highly structured, and thus higher-order processes may play a primary role in the obtained assimilation effects. Indeed, the authors rely on perceptual grouping to explain the illusions.

More intriguing is the illusion presented by De Weert and Spillman (1995). A variation of the illusion is shown in Fig. 1. Although all of the gray pincushions are equal in luminance, most observers perceive the pincushion bordered by white as brighter than the pincushion bordered by black—an assimilation effect. However, De Weert and Spillman only measured the magnitude of the illusion indirectly. Observers adjusted the luminance of a round matching field displayed on a uniform background of the same luminance as the test field of the pincushion, until it matched the brightness of the test field. Their observers matched both the pincushion surrounded by black and the pincushion surrounded by white to (almost identical) luminances that were less than the pincushion luminance. They thus concluded that assimilation occurred only for the pincushion surrounded by black; when the pincushion was surrounded by white, there was a brightness contrast effect. Note, however, that because both the pincushion surrounded by black and the pincushion surrounded by white were matched to nearly identical luminances, if the observers had been asked to adjust the luminance of the pincushion bordered by black until it matched the brightness of the pincushion bordered by white, it is unclear that there would have been much difference in luminance between these two pincushions. In other words, their results suggest that if they had tried to measure the magnitude of the illusion directly, De Weert and Spillman might have found scant evidence of an illusion. In light of Fig. 1, this might seem implausible, but we shall present evidence that tends to confirm this prediction.

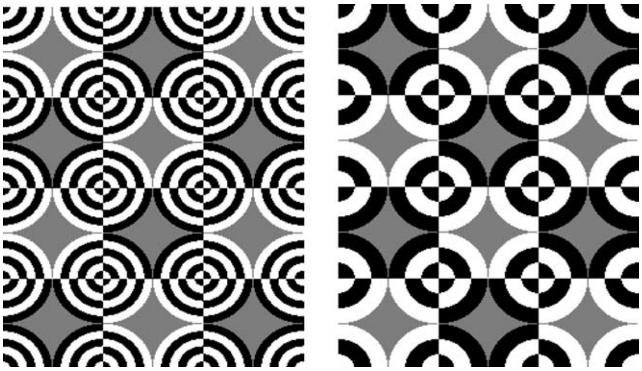

Fig. 1. The De Weert and Spillman (1995) pincushion illusion. Most observers perceive the pincushion bordered by white to be brighter than the pincushion bordered by black—an assimilation effect.

A simpler image in which assimilation can be found is the checkerboard contrast illusion of Gilchrist et al. (1999, pp. 817–818) based on images from De Valois and De Valois (1988, p. 229)—see also Bressan (2001, pp. 1036–1037). In this illusion a white square and a black square in a checkerboard display are replaced by two identical gray squares, yielding the perception that the gray square completely abutted by white, G_W, is brighter (to most observers) than the gray square completely abutted by black, G_B (Fig. 2(A)). (Using an image slightly modified from the one presented here, De Valois & De Valois (1988) actually argued that observers' perceptions were consistent with brightness contrast.) According to the model proposed by Gilchrist et al. (1999), the illusion is produced by grouping effects. Under this account, G_W is part of a strong perceptual grouping with the black squares diagonal to it, and G_B is part of a strong perceptual grouping with the white squares diagonal to it. As G_W is more luminant than all other regions within its perceptual group and G_B is less luminant than all other regions within its perceptual group, anchoring effects within these groups cause G_W to appear brighter than G_B.

It turns out that a simple variation of the checkerboard contrast illusion produces an assimilation effect that cannot be explained by the anchoring model of Gilchrist et al. (1999); replacing all the squares within a large diamond formed by the black (white) diagonals with gray results in the perception that the gray diamond completely abutted by white is substantially brighter than the gray diamond completely abutted by black (Fig. 2(B)). In a manner of speaking, this image comprises two identical gray patches, each surrounded by alternating black and white bands, such that one patch is completely abutted by white and one patch is completely abutted by black. Note that this parallels the description of the pincushion illusion described above. If it is only these features that are responsible for the assimilatory perceptions found in the modified checkerboard image,

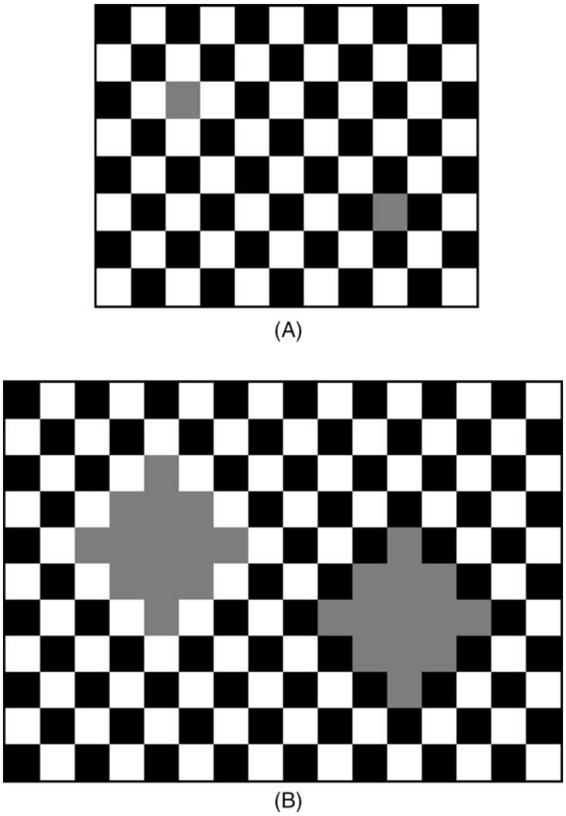

Fig. 2. (A) The checkerboard contrast illusion (De Valois & De Valois, 1988; Gilchrist et al., 1999). The gray square that is a decrement to its four abutting squares is usually perceived as brighter than the gray square that is an increment to its four abutting squares. Gilchrist and colleagues argue that the target abutted by black (white) is perceptually grouped with the white (black) squares diagonal to it and anchoring effects within each diagonal grouping yield the illusion. (B) Such an explanation is not valid for this variation. Yet the overall effect is the same—the decrement target diamond is perceived as brighter than the increment target diamond.

there may be even simpler images with the above features that also give rise to assimilation effects.

Fig. 3 shows that this is the case. We refer to images such as those in Fig. 3 as bullseye images. While the brightness percepts arising from these images are occasionally subject to reversals consistent with brightness contrast, informal polling from numerous observers indicates that most see fairly strong assimilation effects. The variety of these images testifies to the robustness of the basic effect; assimilation occurs despite changes in the number of surrounding bands (Fig. 3(B)), contrast of the surrounding bands (Fig. 3(C)), shape of the target and surrounding bands (Fig. 3(D)), luminance of the background (Fig. 3(E) and (F)), and width of the surrounding bands (Fig. 3(H)). Note that in all of these images the bullseyes are vertically displaced. It was the informal judgment of the first author that such a displacement makes reversals less likely to occur; most observers still see an assimilation effect when there is no vertical displacement of the targets (Fig. 3(G)).

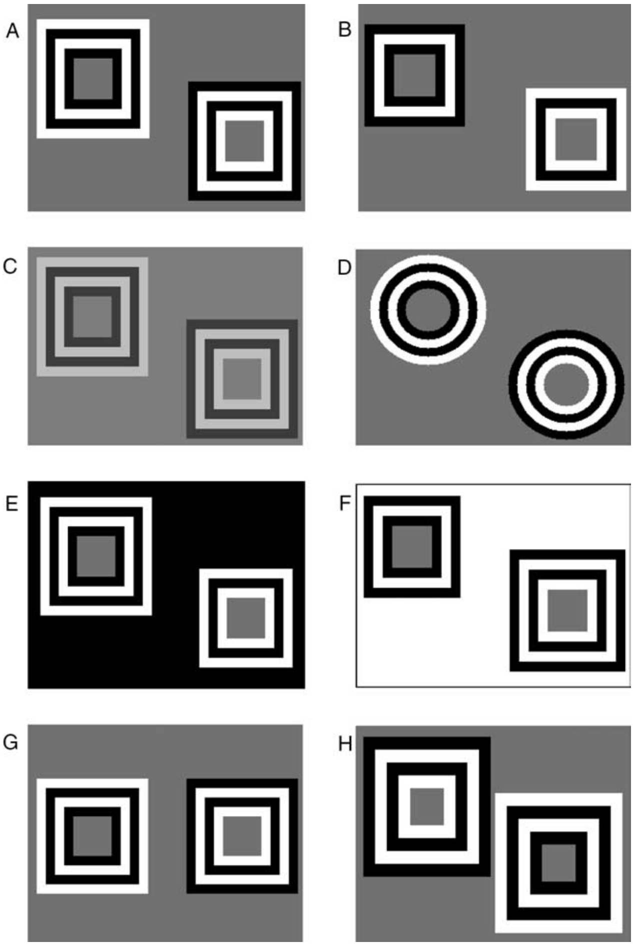

Fig. 3. Various bullseye displays. For a wide variety of conditions observers generally perceive the gray square bordered by white as brighter than the gray square bordered by black—an assimilation effect. Some observers find that rotating the figure 90° increases the effect.

We now describe three experiments whose purpose is to document and quantify the illusion. Experiments 1 and 2 each use a 2AFC design with a 2.2 second display duration. In experiment 1 we measure how changes in the surround-band width and target contrast (relative to the gray background) affect the magnitude of assimilation. In experiment 2 we measure the effect of varying the number of surround bands. Finally, in experiment 3 we measure the same independent variables as in experiment 1, but we used the method of adjustment rather than a 2AFC design. In all experiments, observers were free to view the displays however they wished.

2. Experiment 1

2.1. Methods

Fifteen naïve undergraduate students with normal or corrected to normal vision participated in this experiment. Trials were run on a 100 MHz, Apple PowerMac

7500, with a 15” Sony Trinitron monitor. Stimuli were generated using Matlab 5.1 with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

On each trial, participants were asked to judge which of two gray, target squares concurrently presented for 2.2 s appeared brighter (Fig. 4). At the unrestrained viewing distance of 132 cm, each target square subtended 0.608° in width. One square, G_{B}, was framed by 4 bands that alternated outward with a black–white–black–white profile; the other, G_{W}, was framed by 4 bands that alternated outward with a white–black–white–black profile. Thus G_{B} was completely bordered by black (1 cd/m^2) while G_{W} was completely bordered by white (118 cd/m^2). The distance between the centers of the two target squares subtended a visual angle of 3.0°. One target was 1.2° higher and 2.7° to the left of the other. Background luminance was 60 cd/m^2.

There were two independent variables: surround-band width and reference target contrast (RTC). Surround-band width had two levels: thick (the width of each band subtended 0.243°—40% of the target side length) or thin (the width of each band subtended 0.122°—20% of the target side length). RTC was defined by the luminance of G_{W}, denoted $L(G_{\mathrm{W}})$. $L(G_{\mathrm{W}})$ had three levels: 45, 60, or 75 cd/m^2 corresponding to Weber contrasts (relative to the gray background) of −0.25, 0, and 0.25. The resulting 2×3 factorial design yielded six main conditions. For each main condition, the luminance assigned to G_{B}, $L(G_{\mathrm{B}})$, could be one of five levels: $L(G_{\mathrm{W}})-14$, $L(G_{\mathrm{W}})-7$, $L(G_{\mathrm{W}})$, $L(G_{\mathrm{W}})+7$, or $L(G_{\mathrm{W}})+14$ cd/m^2. Each of these five levels yielded some proportion of trials in which the participant judged $L(G_{\mathrm{B}})>L(G_{\mathrm{W}})$. A psychometric function was fit to the resulting data and used to estimate a point of subjective equality (PSE) for each main condition.

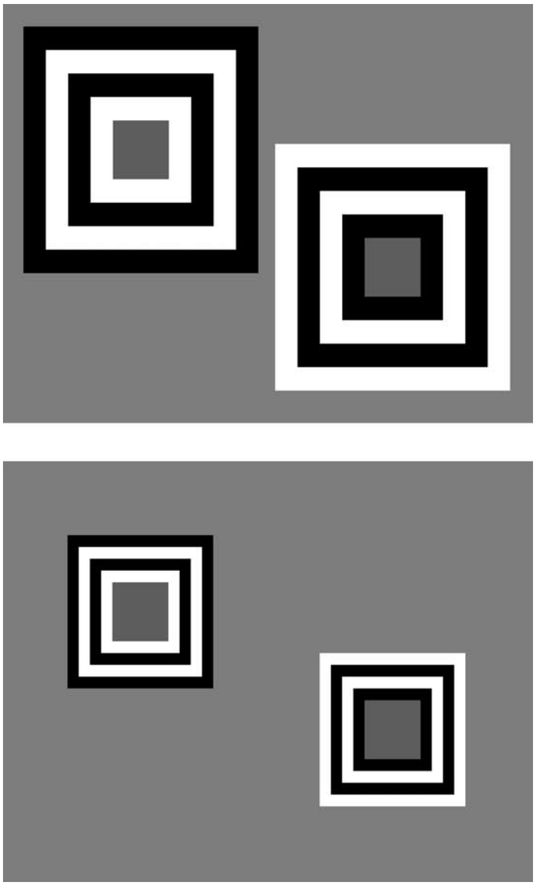

Fig. 4. Sample stimuli from experiment 1. Surround-band width could be thick (top) or thin (bottom). The square surrounded by white served as the reference. The contrast of this square relative to the gray background (RTC) could be either −0.25, 0, or 0.25.

Each observer ran the entire experiment in a single block that consisted of 16 trials in each of the five subconditions for all six main conditions—yielding a total of 480 trials. The order of presentation was completely randomized. Moreover, on each trial G_{B} was randomly assigned to the left or right side of the display. On each trial the observer fixated a central cue spot (subtending 0.15°) and then initiated a trial with a mouse click. This immediately produced the stimulus for 2.2 s followed by the cue spot again. The observer then entered her response with a button press, with a beep indicating the computer had registered the response.

2.2. Results

Although pilot studies had indicated that, for a given value of $L(G_{\mathrm{W}})$, the PSE for $L(G_{\mathrm{B}})$ was likely to be less than $L(G_{\mathrm{W}})+14$ cd/m^2, this proved not to be the case in some conditions for some participants. In 26 instances, fewer than 25% of the black-bordered targets with luminance $L(G_{\mathrm{B}})=L(G_{W})+14$ cd/m^2 were judged brighter than the white-bordered target (with luminance $L(G_{\mathrm{W}})$). In these cases we are restricted to the conclusion that PSE $> L(G_{\mathrm{W}})+14$ cd/m^2.

Table 1 displays, for each observer and condition, the estimate of the percent difference between $L(G_{\mathrm{B}})$ and $L(G_{\mathrm{W}})$ required to make the two targets appear equal in brightness. For example, if for a given condition, $L(G_{\mathrm{W}})=60$ cd/m^2 (corresponding to an RTC of 0) then a score of 25% indicates that when $L(G_{\mathrm{B}})=75$ cd/m^2 the two patches would be judged approximately equal in brightness. The 25 out-of-range PSEs are indicated by >31%, >23%, or >19% (corresponding to 14/45, 14/60, and 14/75) depending on the RTC.

Looking at this table, two trends seem apparent. First, overall there was a large assimilation effect; in only 5 of the 90 conditions were the observer’s perceptions (minimally) consistent with brightness contrast (indicated by a negative score). Second, this assimilation effect seems largest when RTC is −0.25 and decreases as RTC increases: pooling results across the two surround bandwidth conditions, PSEs were greater than reference by at least 29.3%, 21.0%, and 13.5% for RTCs −0.25, 0, and 0.25 respectively. (Statistical tests (see below) indi-

Table 1
The results of experiment 1

Observer	Reference target contrast					
	−0.25		0		0.25	
	Surround band width					
	Thin	Thick	Thin	Thick	Thin	Thick
1	30.9	26.0	23.3	22.1	20.3	15.8
2	15.0	16.0	3.5	1.4	0.2	−1.6
3	425	33.7	25 0	9.9	8.0	−0.4
4	>31	>31	25.9	>23	25.5	>19
5	>31	>31	31.8	52.0	17.6	30.0
6	24.1	16.6	18.2	17.5	14.2	15.4
7	>31	>31	>23	>23	26.3	>19
8	26.1	17.7	16.8	5.7	7.7	−1.9
9	>31	21.8	28.5	10.1	11.0	4.2
10	24.3	15.3	6.7	8.1	−7.0	−3.9
11	>31	>31	>23	>23	>19	>19
12	47.4	46.1	24.0	32.4	22.8	36.2
13	>31	39	25.9	23.2	10.1	12.4
14	34.4	>31	26.9	20.8	12.5	15.8
15	>31	>31	>23	>23	>19	>19
	Means					
	>30.1%	>27.9%	>22.3%	>19.7%	>13.8%	>13.1%
	↘	↙	↘	↙	↘	↙
	>29.3%		>21.0%		>13.5%	

Each value indicates the estimate of how much the target abutted by black, $L(G_B)$, would need to be increased (as a percent) to make it appear equal in brightness to the reference target surrounded by white $L(G_W)$. Positive values indicate assimilation effects; negative values indicate brightness contrast effects.

cate that assimilation effects were, in fact, significantly different for the three RTCs.)

For the inferential statistics our approach is more complicated. We first tested for main and interaction effects across the two independent variables (surround-band width and target luminance). However, any valid test for these effects necessitates that for each observer we have accurate estimates of all 6 PSEs. In the present case this meant omitting from analysis the data from those 8 observers who generated the 25 out of range PSEs. A repeated measures factorial ANOVA was run on the 7 remaining observers. The results indicated that there was no significant interaction effect ($F_{2,12} = 2.01$, $p = 0.18$), and the effect of surround-band width was also not significant ($F_{1,6} = 3.35$, $p = 0.12$). The effect of RTC, however, was significant ($F_{2,12} = 24.49$, $p = 0.0001$). Moreover, multiple t-tests indicated that pairwise differences between RTC-specific effects were all significant ($p < 0.01$ for each of the three tests); assimilation effects were greatest when RTC was −0.25 and decreased as RTC increased (see Table 1).

We next tested whether there was indeed an assimilation effect in all conditions. A binomial (or sign) test was used for this task because we were unsure of the actual scores for the 25 out-of-range PSEs. Furthermore, because the results of the ANOVA indicated no significant difference between groups with different surround-band width but the same RTC, we considered three groups of scores, one for each RTC. The results of these tests indicated that the assimilatory effects obtained for each group were significant ($p < 0.0005$ for each test).

3. Experiment 2

3.1. Methods

The experimental design was similar to experiment 1 except for the following modifications. There was one independent variable—number of surround-bands. It had 4 levels: 2, 3, 4, or 5. Surround-band width was midway between the two widths used in experiment 1; the width of each band subtended 0.183°—30% of the target side length. The target abutted by white again served as the reference. This target was assigned the same luminance on all trials: 60 cd/m^2. As this luminance was the same as the background, RTC was 0 on every trial. For each surround-band number, the luminance assigned to the gray square abutted by black, $L(G_B)$, could be one of *six* levels: $L(G_W) - 14$, $L(G_W) - 7$, $L(G_W)$, $L(G_W) + 7$, $L(G_W) + 14$, or $L(G_W) + 21$ cd/m^2, with the range expanded from experiment 1 to enable estimation of the PSEs for all observers.

Eleven naïve undergraduate students with normal or corrected to normal vision participated in the experiment. Each observer ran the entire experiment in a single block that consisted of 16 trials in each of the 6 sub-conditions for all 4 levels of the independent variable—yielding a total of 384 trials.

3.2. Results

As in experiment 1, for each level of the independent variable we fitted a Gaussian cdf to the percent correct in each of the 6 sub-conditions. Table 2 shows how much (as a percent) $L(G_B)$ needed to be increased relative to $L(G_W)$ to make the two targets appear equal in brightness. Positive entries again indicate an assimilation effect, and negative entries again indicate a brightness contrast effect. Strong assimilation effects were observed in all conditions ($p < 0.001$ for each condition). It appears that the magnitude of the assimilation effect increases slightly as the number of bands increases. A repeated measures ANOVA was borderline in significance ($F_{3,30} = 2.66$, $p = 0.06$), while the distribution-free analog of this test (Friedman's rank test) was also borderline in significance ($p = 0.04$). These results in conjunction with the means for each condition indicate that the magnitude of the assimilation effect probably increases slightly as the number of surround-bands increases. However, there is substantial inter-observer variability.

4. Experiment 3

In experiment 3 the independent variables were the same as experiment 1, but we used the method of adjustment rather than a 2AFC design. Thus the viewing conditions were substantially different: (i) observers could view each stimulus presentation for as long as they wished, and (ii) they had to adjust the luminance of one of the targets and then check to see if the brightness of the two targets appeared to match. Otherwise the design of experiment 3 was quite similar to experiment 1.

Table 2
The results of experiment 2

Observer	Number of surround bands			
	2	3	4	5
1	2.7	7.6	17.3	16.6
2	34.5	28.0	36.9	33.4
3	11.0	15.3	21.6	20.7
4	12.1	18.9	18.9	22.1
5	16.6	35.4	22.1	25.2
6	18.0	21.0	18.8	24.9
7	19.9	26.8	24.2	29.1
8	13.4	10.1	16.2	9.1
9	11.6	13.7	20.6	20.9
10	1.9	9.0	4.8	7.3
11	22.4	5.7	6.0	18.6
Mean	14.9%	17.4%	18.9%	20.7%

Each value is an estimate of how much $L(G_B)$ needed to be increased relative to $L(G_W)$ to make the two targets appear equal in brightness. Positive values indicate assimilation effects; negative values indicate brightness contrast effects.

4.1. Methods

The viewing distance, size of the targets, luminance of the bands, number of surround-bands, and distance between the centers of the targets (3.0°) was the same as in experiment 1. On each trial, participants were asked to adjust the luminance of the target-square on the left until its brightness matched (as closely as possible) the reference target-square on the right. The target-square on the left, G_B, was always completely bordered by black, while the target-square on the right, G_W, was always completely bordered by white. As in experiment 1, the horizontal distance between the target centers was 2.7°, while the vertical distance between the centers was 1.2°. In contrast to experiment 1, however, the target on the left was not always higher; on half the trials the target on the right was higher.

The levels of the two independent variables were exactly the same as in experiment 1. Surround-band width had two levels: thick (each of the four bands subtended 0.243°—40% of the target side length) or thin (each of the four bands subtended 0.122°—20% of the target side length). RTC was defined by the luminance of G_W, denoted $L(G_W)$. $L(G_W)$ had three levels: 45, 60, or 75 cd/m^2 corresponding to Weber contrasts (relative to the gray background) of −0.25, 0, and 0.25.

At the start of each trial the luminance of G_B, $L(G_B)$, was randomly assigned one of five levels: $L(G_W) - 10$, $L(G_W) - 5$, $L(G_W)$, $L(G_W) + 5$, or $L(G_W) + 10$ cd/m^2. The observer then adjusted $L(G_B)$ in increments of approximately ±1 cd/m^2 until she decided (with a key press) that the brightness of G_B and G_W were approximately equal. This setting of equal brightness served as the dependent variable in the experiment.

Eight naïve undergraduate students with normal or corrected to normal vision participated in the experiment. Each observer ran the entire experiment in a single block that consisted of 15 trials in each of the six main conditions—yielding a total of 90 trials. The order of presentation was completely randomized.

4.2. Results

Table 3 shows how much (as a percent) $L(G_B)$ needed to be increased relative to $L(G_W)$ to make the two targets appear equal in brightness. Positive entries again indicate an assimilation effect, and negative entries again indicate a brightness contrast effect. To compare effects

Table 3
The results of the experiment 3

Observer	Reference target contrast					
	−0.25		0		0.25	
	Surround band width					
	Thin	Thick	Thin	Thick	Thin	Thick
1	16.7	27.9	13.3	13.1	−4.7	−2.9
2	6.6	8.7	2.8	0.3	−2.0	−0.6
3	5.6	−4.7	4.7	−8.5	−14.0	−14.7
4	1.7	7.0	−2.6	−2.8	−10.3	−11.4
5	17.8	15.5	5.7	−1.4	−8.6	−5.8
6	2.7	6.2	0.6	1.4	3.6	1.7
7	18.6	15.0	5.3	3.8	−8.6	−9.7
8	−5.1	−4.0	−7.3	−8.5	−4.7	−6.9
	Means					
	8.1%	9.0%	2.8%	−0.3%	−6.2%	−6.3%
	↘	↙	↘	↙	↘	↙
	8.5%		1.2%		−6.2%	

Each value indicates the average percent $L(G_B)$ was increased relative to $L(G_W)$ to make the two targets appear equal in brightness. Positive values indicate assimilation effects; negative values indicate brightness contrast effects.

across the two independent variables, a repeated measures factorial ANOVA was run on the data. The results of this test were nearly identical to those obtained in experiment 1. There was no significant interaction effect ($F_{2,14} = 2.41$, $p = 0.13$), the effect of surround-band width was also not significant ($F_{1,7} = 0.39$, $p = 0.69$), while the effect of RTC was again significant ($F_{2,14} = 15.11$, $p = 0.0003$). Unlike experiment 1, however, *t*-tests indicated that assimilatory effects were found only when RTC was −0.25 ($p < 0.01$), and the magnitude of the effect was generally rather small. When RTC was 0.25 there was actually a significant brightness contrast effect ($p < 0.01$), and when RTC was zero there was no significant difference ($p > 0.40$) between $L(G_B)$ and the reference (neither brightness contrast nor assimilation).

5. Discussion

Experiments 1 and 2 show that under certain viewing conditions assimilation occurs in bullseye displays: a gray square completely bordered by white is seen as substantially brighter than an identical gray square bordered by black. The results of experiment 1 indicate that (i) the assimilation effect is significantly larger when RTC is −0.25 and decreases as RTC increases, and (ii) the strength of the assimilation effect is the same whether the surround-band width is 20% or 40% of the target width. The results of experiment 2 indicate that there is a substantial assimilation effect for as few as 2 surround-bands, and that the magnitude of the effect slightly increases as the number of surround bands is increased.

We obtained the above results from 2AFC experiments in which observers were asked to report only their perceptions of the relative brightness of the two targets—they made no manipulations of the image. The stimulus presentation time was also limited to 2.2 s.

When experiment 1 was repeated using the method of matching (experiment 3), however, a dramatic change in the results occurred. While manipulations of surround-band width again had no effect on observers' perceptions, assimilatory effects were found only when RTC was −0.25—and the size of this effect was not large. When RTC was 0.25 there was actually a moderate brightness contrast effect (the square bordered by black was perceived as brighter than the square bordered by white); when RTC was 0 there was neither an assimilation effect nor a brightness contrast effect. The fact that no effect was found when RTC was 0 is consistent with the results of De Weert and Spillman (1995). Using a method of matching, they found that observers matched G_B and G_W to nearly identical luminances, suggesting that had they attempted to directly compare G_B to G_W, they would have found no illusion.

It is unclear why a 2AFC procedure induces strong assimilation effects whereas an adjustment procedure does not. One difference between the two paradigms is that the display duration is unrestricted in the adjustment procedure but fixed at 2.2 s in the 2AFC procedure. We think it unlikely, however, that the contrast in results was caused by this difference; in informal free viewing presentations with naïve observers, assimilation is the dominant perception. Another possible explanation for the difference in results is that participants in the 2AFC procedure tended to maintain fixation between the two targets whereas participants in the adjustment procedure tended to move fixation back and forth from target to target. If this were the case, then participants in the 2AFC task would tend to view the targets simultaneously and peripherally whereas participants in the adjustment procedure would tend to view the targets sequentially and foveally. Finally, it is possible that the difference in results is due to the fact that observers' use a smaller attentional window in the adjustment procedure than in the 2AFC procedure. Under this account, the attentional window used in the 2AFC design includes much of the surrounding bullseye pattern whereas the attentional window used in the adjustment procedure includes the target and little else. If this were the case, one might expect that perceptions of target luminance obtained in the adjustment procedure are relatively immune to the surrounding bullseye pattern in comparison to judgments made in the 2AFC procedure—as was experimentally observed. Further research will be needed to determine which (if any) of these factors underlies the much larger levels of assimilation observed in the 2AFC procedure versus the adjustment procedure.

While we obtained little or no assimilation effects using the method of adjustment, we consider "real world" perceptions to be better reflected by the strong assimilation effects obtained in experiments using a 2AFC design. Outside of vision experiments, rare are the times when one is asked to adjust the luminance of one region to match the brightness of another. Furthermore, in numerous informal presentations of bullseye displays to non-vision-scientists, observers have *always* reported that the target bordered by white is substantially brighter than the target abutted by black. (When vision scientists are the observers, the results are more mixed (especially for those who have studied brightness/lightness), although a majority still report assimilation.)

In light of the wide range of simple images that give rise to assimilation effects (Fig. 3), and the experimentally documented magnitude of the effect, the bullseye assimilation illusion poses an important challenge for any model of brightness (lightness) coding. Accordingly, we now check the predictions of a few recent models of brightness/lightness as to the appearance of the stimuli used in this experiment.

5.1. How current models of brightness predict the illusion

As we have suggested, the anchoring model of Gilchrist et al. (1999) cannot explain the present assimilation effect. The basic reason is as follows. Assimilation effects were predicted in the original checkerboard contrast display because each target was part of a powerful grouping along the diagonal; each target was also part of a grouping based on retinal proximity that always induces brightness contrast effects, but these effects were not large enough to counteract the effects arising from grouping along the diagonals. In the present displays, however, there can be no grouping along the diagonal, so differences in target brightness would be based primarily on grouping by retinal proximity—which induces brightness contrast. Thus for all stimulus configurations the appearance of the targets would be consistent with brightness contrast, and Gilchrist's model cannot account for the assimilation effect.

De Valois and De Valois (1988) argue that assimilation effects arise from the threshold contrast sensitivity function (CSF). As evidence they cite (pp. 163–166) perceptions of a simple image that consists of a lower frequency, vertically oriented sinusoid modulated by a substantially higher frequency vertically oriented sinusoid. When observers are asked to compare the brightness of a peak and trough of equal luminance made by the higher frequency modulator, assimilation effects can be found, provided that the contrast sensitivity to the higher spatial frequency is lower than the contrast sensitivity to the lower spatial frequency. More generally, they argue that the CSF explains assimilation even in complex images.

To check whether such a model could explain the assimilation effects found in the present experiment, we filtered the bullseye images according to the threshold CSF reported by De Valois and De Valois (p. 149). Specifically, we proceeded as follows. First the Fourier transform of the image was taken. Then the coefficients of this transform—at all orientations and spatial frequencies—were weighted according to the threshold CSF. Thus a coefficient corresponding to about 4 cpd was multiplied by 1 (maximum weight), while a coefficient corresponding to any other frequency was multiplied by a lesser value that reflected the relative sensitivity to that spatial frequency. Finally, these adjusted coefficients were then used as the input to the inverse Fourier transform, the output of which was used to predict the perception of the bullseye targets.

We first ran the stimuli used in experiments 1 and 3 through this CSF model. For each target contrast when the targets were surrounded by thick bands, the model predicted a slight assimilation effect, but when the targets were surrounded by thin bands the model predicted a substantial brightness contrast effect. It turns out that this model is very sensitive to viewing distance. If, for instance, the viewing distance were increased by a factor of 3/2, then the model predicts assimilation effects for *all* stimulus configurations, but if the viewing distance were decreased by a factor of 2/3, then the model predicts brightness contrast effects for all stimulus configurations. While we have made no empirical tests of how viewing distance affects the magnitude of the illusion, over a wide range of distances we have generally found assimilation and not brightness contrast—although the assimilation effect is possibly larger at greater viewing distances. Furthermore, De Weert and Spillman (1995) found assimilation effects (at least for the pincushion bordered by black) over a wide variety of distances.

We also checked how the number of surround-bands affected predicted performance—we ran the stimuli from experiment 2 through the model. At the viewing distance used in our experiments, the model predicted substantial brightness contrast effects when the number of surround-bands was 2, 4, or 5, but substantial assimilation when the number of surround-bands was 3.

Taken as a whole, the results of these simulations indicate that the CSF account of De Valois and De Valois (1988) cannot explain the assimilatory perceptions arising from bullseye displays.

An intriguing recent model of brightness perception is the oriented difference of Gaussian (ODOG) model of Blakeslee and McCourt (1999), which is an extension of Blakeslee and McCourt's (1997) DOG model. In the ODOG model, the predicted perception of an image is formed from a weighted sum of the output of six oriented filters (orientations: 0°, 30°, 60°, 90°, 120°, and 150°) convolved with the input image. The weight of each filter depends on the input image; for any input image, the outputs from each orientation are normalized so that their energies are equal. Each oriented filter consists of the linearly weighted sum of seven anisotropic difference of Gaussian (DOG) filters, each with a 1:2 ratio of center/surround space constants. The space constants were set so that the center frequencies of the seven DOGs were spaced at octave intervals from 0.1 to 6.5 cpd. Each of the seven DOGs was weighted by a power function with an exponent of 0.1. This weighting system is consistent with the much shallower low-frequency falloff found for the suprathreshold CSF (Georgeson & Sullivan, 1975) expected to be found with what are normally suprathreshold brightness stimuli.

The ODOG model predicts various grating induction effects (Blakeslee & McCourt, 1997; Zaidi, 1989), simultaneous brightness contrast, Shapley and Reid's (1985) "assimilation" effect, the induced spots seen at the street intersections of the Hermann Grid, White's illusion (White, 1979; White & White, 1985), and Todorovic's (1997) illusions.

In terms of bullseye displays, however, the ODOG model does not predict observer perceptions. Fig. 5 shows the predictions of ODOG for both thick (5A) and thin (5B) surround-bands when both targets have contrast 0. As can be seen in the figure, for both wide and narrow bands, the target abutted by black is predicted to appear brighter than the target abutted by white—a brightness contrast effect (this effect is larger when surround-bands are thick). In fact no matter the number of surround-bands, the thickness of the surround-bands, or the luminance of the targets, when the bullseye images used in the experiments were input into ODOG, the model always predicted brightness contrast. Furthermore, when we tested some of the stimuli under the assumption that the viewing distance had been quartered, halved, doubled, or quadrupled, the model always predicted perceptions of brightness contrast. Thus, like the models of Gilchrist et al. (1999) and De Valois and De Valois (1988), the ODOG model fails to predict the assimilation perceptions found in the present study.

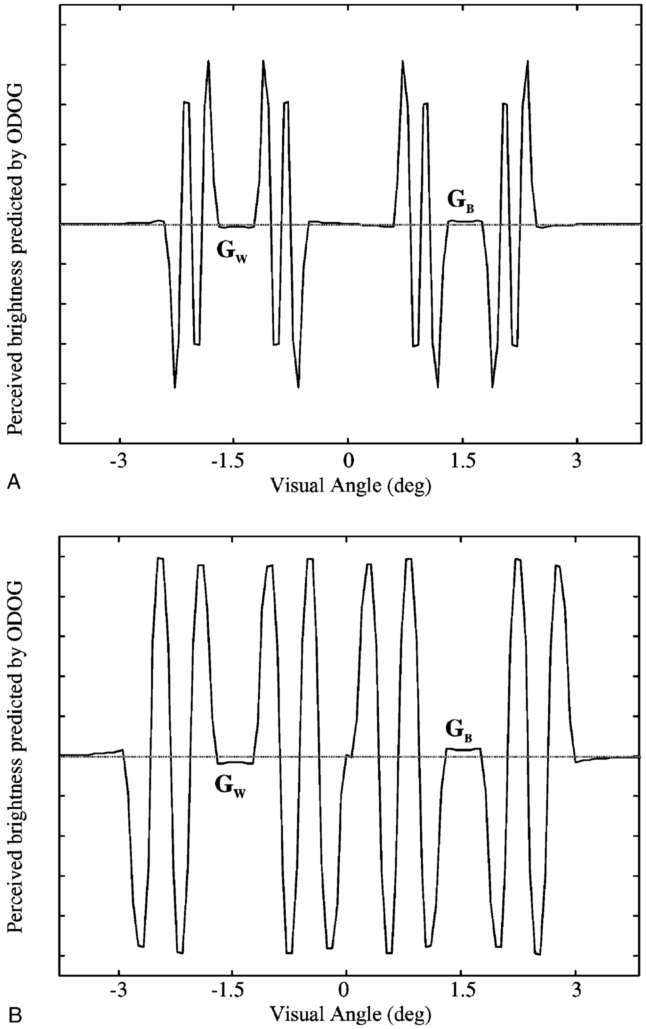

Fig. 5. The predictions of Blakeslee and McCourt's (1999) ODOG model to our stimuli. In each panel, the solid line represents the output of the model across the horizontal center of the two bullseyes; the dashed line represents the veridical perception of the two targets (G_{B} and G_{W}). Target contrasts in both panels were 0. For both thin bands (A) and wide bands (B) brightness contrast was predicted: the target bordered by black (G_{B}) was predicted to appear brighter than the target bordered by white (G_{W}).

It is not our intention to assess the performance of all of the many recent brightness models (e.g., Grossberg & Todorovic, 1988; Kingdom & Moulden, 1992; Watt & Morgan, 1985). The failure of the three models we have considered suggests, however, that the bullseye assimilation effect does pose an important challenge for any current model of brightness coding.

5.2. An explanation for assimilation effects in bullseye displays

It is well known that a medium contrast texture patch surrounded by high contrast texture appears to have a lower contrast than an identical patch surrounded by low contrast texture (Cannon & Fullenkamp, 1996; Chubb, Sperling, & Solomon, 1989; Olzak & Laurinen, 1999; Singer & D'Zmura, 1994, 1995; Solomon, Sperling, & Chubb, 1993; Spehar, Arend, & Gilchrist, 1995). Chubb et al. (1989) noted that this contrast contrast effect was spatial frequency specific: the effect was greatly diminished if the surrounding noise was filtered into a different spatial frequency band than the noise in the target patch. To account for these findings, Chubb and colleagues proposed that the responses of band-tuned cortical neurons (e.g., simple cells) are subject to lateral inhibition from similarly tuned neurons, where the degree of inhibition exerted by a neuron (on neurons with nearby receptive fields) is an increasing function of the rectified response of that neuron.

A similar model can be invoked to account for the assimilation effects observed in the current study. First, suppose (as suggested by Grossberg & Todorovic, 1988) that the brightness assigned to target patch T in some heterogeneous surround S (not necessarily a bullseye display) is derived from the responses of edge-selective linear neurons N_i, aligned with the boundary between S and T. A given such neuron N_i registers the signed contrast as one steps across the boundary from S to T at a particular point. Second, suppose (similar to the Chubb et al. proposal above) that the neurons N_i are subject to lateral inhibition from the rectified output of similarly tuned neurons activated by other parts of the display. Finally, we submit that under any plausible model of brightness assignment, the difference between T's brightness and that of T's immediate surround must have a strong positive correlation with the mean response of the neurons N_i: if the mean response of these neurons is substantially negative (positive), we expect T's brightness to be substantially less (greater) than that of T's immediate surround.

Now consider the bullseye displays studied here. In these displays the edges formed by the black and white bands in the surround are approximately double in Weber contrast to the edge formed by the innermost band and the bullseye. Thus our model predicts that the neurons N_i that gauge the (signed) contrast across the edge from the innermost band to the bullseye will be inhibited by the neurons that gauge contrast across the black and white bands. As a result, we predict the magnitude of the responses of the neurons N_i to be suppressed, which will compress the difference in brightness between the innermost band and the bullseye.

Such compression could result in either reduced brightness contrast effects or assimilation. To know which, we need to know what level of suppression of the neurons N_i results in neutral (veridical) perceptions. The fact that assimilation occurs with bullseye displays indicates that the suppression of the neurons N_i exceeded this level.

For comparison consider the classical simultaneous contrast display, in which identical, mean gray targets are presented in the centers of two large, abutting fields, one of which is white and the other black. Because the background local to either target boundary is homogeneous (rather than riddled with high contrast edges as in the bullseye display), the response of nearly any neuron that might laterally inhibit any of the neurons N_i is 0. Thus, the neurons N_i are much more highly activated than are the other neurons within their lateral inhibitory cohort. Under these circumstances, we expect the responses of the neurons N_i to be *under*suppressed—unbridled by contervailing activity in similarly tuned neurons, which will lead to an expansion of the difference in brightness between the background and the target—i.e., brightness contrast effects.

In summary, we propose that the bullseye assimilation effect is the result of a general mechanism of brightness coding: assimilation occurs for a given region *R* when (i) the contrast difference at *R*'s border is small in comparison to the contrast difference of edges in the general neighborhood of *R*, and (ii) the density of edges in the neighborhood of *R* is high.

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