

# Simultaneous lightness contrast on plain and articulated surrounds

Paola Bressan, Rossana Actis-Grosso  
Dipartimento di Psicologia Generale, Università di Padova,  
Via Venezia 8, 35131 Padova, Italy  
e-mail: [paola.bressan@unipd.it](mailto:paola.bressan@unipd.it)

## **Abstract**

Simultaneous lightness contrast is stronger when the dark and light backgrounds of the classic display (where one of the targets is an increment and the other is a decrement) are replaced by articulated fields of equivalent average luminances. Although routinely attributed to articulation per se, this effect may simply result from the increase in highest luminance in the light articulated, vs plain, background; by locally darkening the decremental target, such an increase would amplify the difference between the targets. We disentangled the effects of highest luminance and articulation by measuring, separately, the magnitude of lightness contrast on dark and light plain and articulated backgrounds. We found that highest luminance and articulation contribute separately to the final illusion.

## 1 Introduction

A region seen against a dark background looks lighter than an identical region seen against a light background (simultaneous lightness contrast, or SLC). In the classical SLC display the target region on the dark background is a local luminance increment, whereas the identical target region on the light background is a local luminance decrement (one increment and one decrement, I-D). A weaker effect also obtains (Bressan and Guadagnucci, in preparation) when the luminance of the two target regions is lower than both backgrounds' (double decrements). A still weaker, yet significant, illusion has been reported (Bressan and Actis-Grosso 2001) when the luminance of the two target regions is higher than both backgrounds' (double increments).

It has been informally shown (Adelson 2000) that SLC is strengthened when the dark and light backgrounds of the classic display (one increment and one decrement) are replaced by articulated fields of equivalent average luminances, as in figure 1. "Articulation", a concept first introduced by Katz (1935; see Gilchrist and Annan 2002 for a comprehensive review), refers here to the number of distinct reflectances within a region.

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Figure 1 about here  
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Why is simultaneous contrast enhanced with articulated surrounds? The explanation favored by Gilchrist et al (1999) is based on anchoring.

The anchoring theory of lightness (Gilchrist et al 1999) assumes that a visual scene is divided into perceptual groups, or frameworks, on the basis of Gestalt grouping principles. Frameworks can be local or global. The lightness of any given surface is a weighted average of the lightness of the surface when anchored to its local framework and the lightness of the surface when anchored to the global framework. Within each framework, the role of anchor is always assigned to the highest luminance, which is given a value of white. All other regions will be perceived as shades of grey, depending on their luminance ratio to such white. An additional rule is that any area that takes up more than half of the framework tends to lighten, and the larger it becomes, the lighter it appears.

Consider now the plain display (figure 1, top panel): the local framework of each target patch is its immediate surround, and the global framework is the entire display (if we temporarily disregard the rest of the context, such as the page on which the display is printed). In the global framework, the light background works as an anchor, and the two target patches are assigned identical grey values relative to it. In the local frameworks, however, the lightness assignments are different for the two patches. Nothing changes for the patch on the light background, but the patch on the dark background is locally white, being the highest luminance in its local framework. Thus the patch on the light background is globally grey and locally grey; the patch on the dark background is globally grey and locally white. When local and global values are averaged, the patch on the dark background yields a perceptually lighter grey.

According to Gilchrist et al (1999), increasing the degree of articulation within a framework strengthens anchoring within that framework. In the articulated display (figure 1, bottom panel), such a mechanism would lighten

the incremental patch, which is locally white and globally grey, by increasing the weight of the local white relative to the global grey.

However, the light surround in the articulated display contains many small squares of different luminances, some of which are higher than the luminance of the plain display's surround. Thus, the highest luminance is higher in the articulated than in the plain display. Disregarding any effects of articulation, a higher luminance entails, *per se*, the following consequences:

(i) in the global framework, both patches darken equally (hence this step can be ignored);

(ii) in its local framework, the incremental patch does not change (ie, it is still white), being itself the local anchor;

(iii) in its local framework, the decremental patch darkens, because its local anchor has now a higher luminance.

Therefore, we expect stronger simultaneous contrast in articulated I-D displays *whether or not articulation matters*. Note that such an increase would depend entirely on the articulation of the light surround (which locally affects the decremental patch). No effects on SLC would be expected via articulation of the dark surround. On the opposite, articulation *per se*, if it works by augmenting the local weight as suggested by Gilchrist et al (1999), would affect the incremental patch only, and not the decremental patch. The decremental patch always receives identical local and global assignments, thus shifts in weight between the two would entail no consequence.

Gilchrist et al (1999)'s paper shows a display, similar to our Figure 1, where the highest luminance of the light articulated surround is equal to the luminance of the plain white surround. This version is interesting in that it lacks the highest-luminance confound of Adelson's (2000) figure (although, of course, it introduces a difference in the average luminances of the plain and articulated surrounds). Unfortunately no experimental data are presented, nor is it possible to disentangle the lightness changes in the incremental and decremental patches, to see whether these are consistent with an anchoring account. If articulation plays no role, SLC should increase with articulation of the light surround only, but it should not be influenced by articulation of the dark surround only. If articulation does play a role, however, SLC should augment in either case, and become even stronger when the two effects are added by articulating both surrounds at the same time, as in the bottom display of Figure 1.

In this work, we addressed this issue by comparing, independently, the effects of plain and articulated surrounds on incremental and decremental patches.

## **2 The experiment**

### *2.1 Methods*

*2.1.1 Subjects.* Twenty-two observers (13 females and 9 males) took part in the experiment. They had normal or corrected-to-normal vision.

*2.1.2 Apparatus and stimuli.* Stimuli were generated by an Apple Macintosh PowerPC 8500 connected to an 18-inch LaCie monitor. Each stimulus consisted of two 18 deg x 26.3 deg surrounds placed side by side; they covered the entire screen. Each surround could be uniform or articulated. A 4

deg x 3.2 deg adjustable patch was centred within one surround; an identical comparison patch was centred within the other.

We used a light plain surround (82.4 cd/m<sup>2</sup>); a dark plain surround (10.2 cd/m<sup>2</sup>); a light articulated surround (a checkerboard with an average luminance of 82.4 cd/m<sup>2</sup>); and a dark articulated surround (a checkerboard with an average luminance of 10.2 cd/m<sup>2</sup>). Each checkerboard consisted of 128 small rectangles (2 x 1.6 deg) of different luminances; four of them were occluded by the target patch. Luminances ranged from 0.17 to 20.3 cd/m<sup>2</sup> in the dark checkerboard and from 63.2 to 106.2 cd/m<sup>2</sup> in the light checkerboard. Such luminances were distributed at random, but with two constraints: (a) there were no adjacent squares with identical luminances; (b) the luminances of the 12 squares directly adjacent to the target patch were chosen so that their average luminance was identical to the average luminance of the whole checkerboard.

The initial luminance of the adjustable patch was set to a random value between 23.3 and 32 cd/m<sup>2</sup>. The comparison patch had always a luminance of 27.2 cd/m<sup>2</sup>, hence it represented a full increment relative to dark surrounds (being its luminance higher than the highest luminance of the dark checkerboard) and a full decrement relative to light surrounds (being its luminance lower than the lowest luminance of the light checkerboard). Since we presented all possible pairs of different surrounds, the two target patches could be double increments, double decrements, or one increment and one decrement. All luminances were measured with a Minolta Luminance Meter LS100 photometer.

Each of the 12 stimuli was shown twice (with the adjustable patch once on the right surround and once on the left surround), for a total of 24 trials.

*2.1.3 Procedure.* Observers viewed the monitor from a distance of 60 cm, in a dark laboratory. The laboratory was entirely painted matte black, and all non-black surfaces (such as the computer case) were covered with black cardboard. The highest luminance in the observer's visual field was always the highest luminance presented on the computer's screen. Before each trial, a black arrow was displayed on the side of the monitor where the test patch was going to appear. Observers used the method of adjustment: they varied the luminance of the test patch to match the achromatic colour of the comparison patch. They pressed the '+' key to increase the test patch luminance and the '-' key to decrease it; when they were satisfied with their match, they pressed the space bar to start the following trial.

## *2.2 Results and discussion*

A repeated-measures ANOVA was performed on the logarithmic values of the matches, with comparison patch (decrement, increment), surround of comparison patch (plain, articulated), and surround of adjustable patch (plain, articulated) serving as factors. Statistical significance was reached by all main effects, and by the interaction of comparison patch with either surround (all p values <0.003). The t-tests reported below are two-tailed, and represent the pre-planned paired comparisons deriving from the hypotheses.

*2.2.1 One increment and one decrement.* In the plain displays, observers adjusted the patch on the light surround to 94.4 cd/m<sup>2</sup> to make it look the same as the 27.2 cd/m<sup>2</sup> patch on the dark surround, and they adjusted the

patch on the dark surround to  $0.81 \text{ cd/m}^2$  to make it look the same as the  $27.2 \text{ cd/m}^2$  patch on the light surround (see the two leftmost data points in figure 2). This amounts to a mean logarithmic difference between the two patches of about 1.05, a striking simultaneous lightness contrast. Much weaker effects have been reported so far, from around 0.10 (Gilchrist 1988) to 0.41 log differences (Agostini and Bruno 1996).

We see two separate possible reasons for the exceptional strength of our contrast effect: first, the considerable size of the surrounds relative to the target patches; and second, the very dark, homogeneous environment. On the first point, Burgh and Grindley (1962) reported no effect of area on lightness using the traditional SLC display. However, they increased the area by magnifying the entire display. As a consequence, the relative area between surround and target was kept constant.

On the second point, the variable magnitude of contrast effects obtained in different laboratories makes sense if we accept that the final lightness of a region is a compromise between its value in a local framework and its value in a global framework. This assumption is consistent with the finding that lightness contrast decreases when a larger portion of the surrounding scene (global framework) is included within the beam of light that illuminates the SLC stimulus (Agostini and Bruno 1996). Globally, both patches have the same lightness; hence, the stronger (ie, the larger and more articulated) the global framework, the smaller the simultaneous lightness contrast. Gilchrist (1988) had paper stimuli presented in a well-lighted classroom – a remarkably strong global framework. Agostini and Bruno (1996) had a CRT condition, but their targets sat on small surrounds ( $3.5 \times 5 \text{ deg}$ , as opposed to the  $18 \times 26.3 \text{ deg}$  surrounds used in our experiment). In addition, in both experiments observers performed matching to a Munsell scale, rather than adjustment. Matching introduces a fully articulated global framework.

The articulated version of our display yielded a significantly stronger illusion than the plain version. As depicted by the two rightmost points in figure 2, observers chose a higher luminance match for the patch on the light surround (mean adjusted luminance  $104.5 \text{ cd/m}^2$ ,  $t(21) = 11.31$ ,  $p < 0.0001$ ), and a lower luminance match for the patch on the dark surround (mean adjusted luminance  $0.45 \text{ cd/m}^2$ ,  $t(21) = 5.89$ ,  $p < 0.0001$ ). The corresponding mean log difference between the two targets is about 1.23, suggesting a contribution of articulation of about 0.18 log units.

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Figure 2 about here  
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*Articulating the dark vs light surrounds.* Breaking the light surround into many different regions so that there is no change in average luminance has one certain consequence, increasing the highest luminance, and one uncertain consequence, providing some effect of articulation *per se*. On the dark surround, the same manipulation entails the latter effect only. Two of our conditions permitted separate assessments of dark- and light-surround articulation in I-D displays (four central data points in figure 2).

For each stimulus, we measured the magnitude of SLC as the absolute logarithmic difference between the adjusted luminance and the objectively matching luminance. We then computed the average SLC for each pair of symmetrical stimuli (ie, stimulus with adjustable patch on one surround and

identical stimulus with adjustable patch on the other surround). A significant increase in SLC was observed both by articulating the light surround only (from 1.05 to 1.12,  $t(21)= 4.25$ ,  $p<0.0001$ ), and by articulating the dark surround only (from 1.05 to 1.14,  $t(21)= 4.05$ ,  $p= 0.001$ ). The difference was enhanced when both surrounds were articulated (from 1.05 to 1.23,  $t(21)= 7.19$ ,  $p<0.0001$ ). The corresponding mean increases in SLC for single-surround articulation, respectively 0.09 (articulating the dark surround only) and 0.07 (articulating the light surround only), were not different from each other ( $t<1$ ), but each of them was significantly smaller than the mean increase in SLC when both the dark and light surrounds were articulated ( $p<0.0001$ ). The latter increase amounted to 0.18, suggesting an additive effect.

2.2.2 *Double decrements.* As can be seen in figure 3, top panel, the comparison decremental patch on the light checkerboard (right display) looked darker than the comparison decremental patch on the luminance-equivalent plain surround (left display). Observers adjusted the patch on the plain surround to 16.3  $\text{cd/m}^2$  to make it look the same as the 27.2  $\text{cd/m}^2$  patch on the checkerboard; but they adjusted the patch on the checkerboard to a higher value, ie 19.1  $\text{cd/m}^2$ , to make it look the same as the 27.2  $\text{cd/m}^2$  patch on the plain surround,  $t(21)=7.63$ ,  $p<0.0001$ . This corresponds to a mean log difference between the two patches of about 0.18 log units.

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Figure 3 about here  
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The darkening of the target on checkerboard is expected simply on the basis of the higher local highest luminance. In Gilchrist et al's (1999) model, articulation would increase local anchoring relative to global, but the local and global values for a target on a light checkerboard are identical. Therefore, 0.18 log units would be the contribution of the highest luminance only.

2.2.3 *Double increments.* As can be seen in figure 3, bottom panel, the comparison incremental patch on the dark checkerboard (right display) looked lighter than the comparison incremental patch on the luminance-equivalent plain surround (left display). Observers adjusted the patch on the plain surround to 20.7  $\text{cd/m}^2$  to make it look the same as the 27.2  $\text{cd/m}^2$  patch on the checkerboard; but they adjusted the patch on the checkerboard to a lower value, ie 15.9  $\text{cd/m}^2$ , to make it look the same as the 27.2  $\text{cd/m}^2$  patch on the plain surround,  $t(21)= 12.41$ ,  $p<0.0001$ . This amounts to a mean log difference between the two patches of about 0.17 log units. This difference can only be due to articulation, because there is no change in the highest luminance (the targets themselves).

These data are at odds with the anchoring theory's predictions in two different respects. First, they conflict with the assumption that the anchor is determined solely by highest luminance and area. The theory predicts no lightness differences between two identical targets that represent the highest luminance in the scene, because both targets are given a default value of white. The lightening of the target on checkerboard cannot be explained by means of a larger surround tending to white and pushing the target towards luminosity, either. The areas of the plain and articulated surrounds are equal; if anything, the larger uniform area is the plain surround. Adding a factor of

scale normalization (a tendency of the perceived range of shades to expand toward that between black and white) would predict an effect in the wrong direction. That is, one may reason that the perceived difference between the dark background and the light target increases, and this expansion is also expressed as a lightening of the target. In this case, however, the relative lightening would be larger on the background where the range of luminances is smaller, ie on the uniform surround; but this is the opposite of what is observed.

Second, our double-increment data conflict with the assumption that the effect of articulation is due to a shift in weight between local and global highest-luminance anchoring. Being at the same time local and global anchor, each target must receive identical values locally and globally. Thus, altering the local weight relative to the global would make no difference on the final weighted average.

### **3 Conclusions**

The experiment reported here shows that the plain, traditional simultaneous lightness contrast display can produce a huge illusion when it nearly fills the observer's visual field, in an otherwise perfectly dark environment. As far as we know, ours is the first report of SLC of striking magnitude obtained simply by enlarging the surrounds and showing the display in the dark, rather than by providing fake illumination cues such as apparent lights and shadows.

Our increment-decrement articulation data confirm previous reports of enhanced SLC with articulated surrounds (Arend and Goldstein 1987; Schirillo 1999), and show that this is the outcome of two separate events – a lightening of the incremental target and a darkening of the decremental target. Whereas the latter effect necessarily results from the change in highest luminance that follows surround articulation, the former does not, indicating that surround articulation *per se* is a contributing factor in lightness assessment. Incidentally, this conclusion agrees with the finding that SLC increases when two uniform chromatic surrounds differing in luminance are replaced by two articulated surrounds, each consisting of equiluminant colors (Lotto and Purves 1999). This case is especially interesting because articulation was manipulated while both the highest luminance and the average surround luminances remained the same. However, Lotto and Purves measured the mean adjustment required to match the two targets, thus the effect could have arisen from either one.

Our double-decrement data are consistent with the predictions of Gilchrist et al's (1999) anchoring theory: on the articulated surround, the decremental target darkens. However, our double-increment data are inconsistent with the theory's predictions: on the articulated surround, the incremental target lightens even though it is the highest luminance. The theory predicts no effect of surround articulation for a target that is the highest luminance in the field, because such a target is locally and globally white. Thus, altering the local weight relative to the global cannot possibly affect the final weighted average.

A modified version of the theory, where anchoring is replaced by double anchoring (Bressan, in press; Bressan, submitted), makes the same prediction as Gilchrist et al's theory for the decremental target, but a different

prediction for the incremental target. In this model, objects are independently anchored to the highest luminance (Highest-Luminance Step) and to the average luminance of their surround (Surround Step). The lightness value of a region is the weighted average of the ratios computed at the two steps. Surround articulation increases the weight of the Surround Step relative to the Highest-Luminance Step. Incremental patches are white at the Highest-Luminance Step and superwhite at the Surround Step: articulation increases the weight of the local superwhite relative to the local white. This results in a lightening of the incremental target on the articulated surround relative to the same target on the plain surround, exactly as observed.

Our findings also suit accounts of lightness other than those based on anchoring. We will give two examples of such accounts here. The first is the suggestion that lightness estimates are made on the basis of luminance samples gathered within a window (Adelson 2000). When the samples are too few (as in the plain-surround display) the window needs to grow, but in so doing it includes samples coming from the adjacent surround, thus dampening local contrast effects. When the samples abound (as in the articulated-surround display) SLC increases because the window can remain small. The second is the argument that lightness is generated according to the frequency of the possible sources of visual stimuli, derived from the accumulated experience of the species and the individual (eg Lotto and Purves 1999, Yang and Purves 2004). In this perspective, articulating a bipartite scene without changing the average luminances augments the probability that one of the two arrays is in shadow and the other in light, and that the two targets are therefore differently reflective regions.

These three diverse accounts – the weighted anchoring to highest luminance and surround, the gathering of luminance statistics within an adaptive window, the computation of the most probable source – end up with the same prediction. This is unlikely to be accidental. The underlying notion is that a variegated scene provides sounder information, whether this increased reliability is concretely represented by a heavier weighting of surround anchoring, by a smaller adaptive window, or by a different probability distribution function of the possible target luminances ever experienced in that context.

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## **Acknowledgements**

We are very grateful to Alessandro Soranzo, who developed all the software used in the experiment.

## Figure captions

**Figure 1.** Simultaneous lightness contrast is stronger with articulated surrounds. Compare top (plain surrounds) and bottom (articulated surrounds) versions.

**Figure 2.** Mean adjusted luminance for the four pairs of one-increment-and-one-decrement displays (averaged, for each subject, across right- and left-side presentations). Articulated surrounds are conventionally represented here as 2x2 checkerboards. The adjustable patch was on the light surround in the top (and on the dark surround in the bottom) display of each symmetrical pair. Note that, for convenience of representation, the y-axis is split into two different scales. Bars depict the standard error of the mean.

**Figure 3.** Mean adjusted luminance for the two symmetrical double-decrement (top panel) and double-increment (bottom panel) displays. Data are averaged, for each subject, across right- and left-side presentations. Articulated surrounds are conventionally represented here as 2x2 checkerboards. The adjustable patch was on the articulated surround in the leftmost, and on the plain surround in the rightmost, display of each symmetrical pair. Standard errors of the mean are smaller than the symbols.

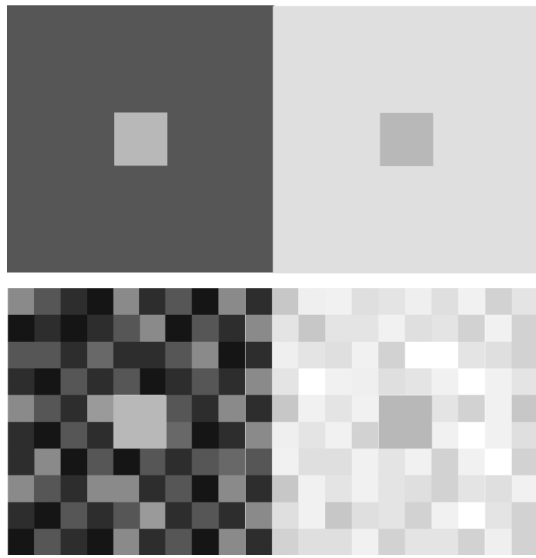


FIGURE 1

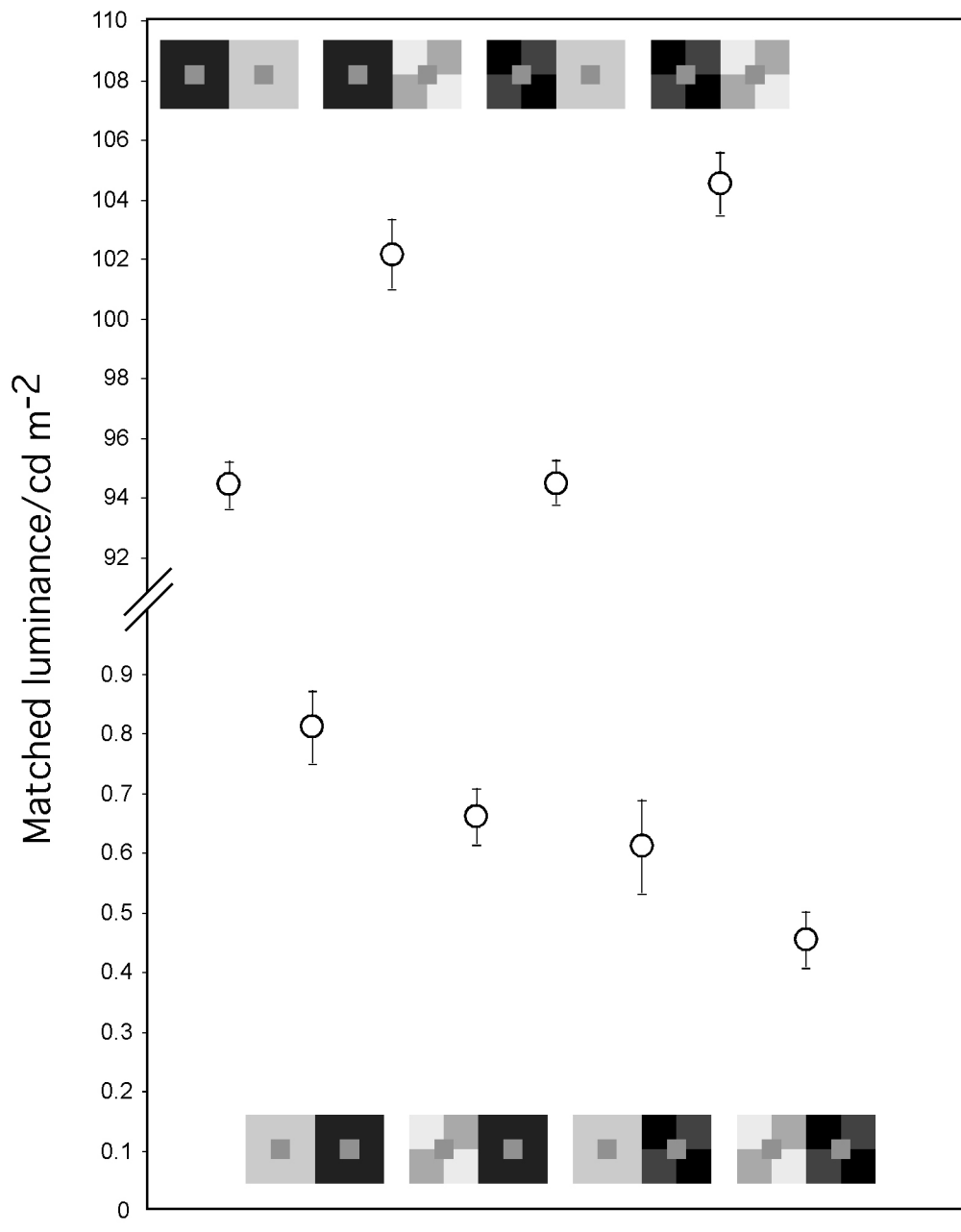


FIGURE 2

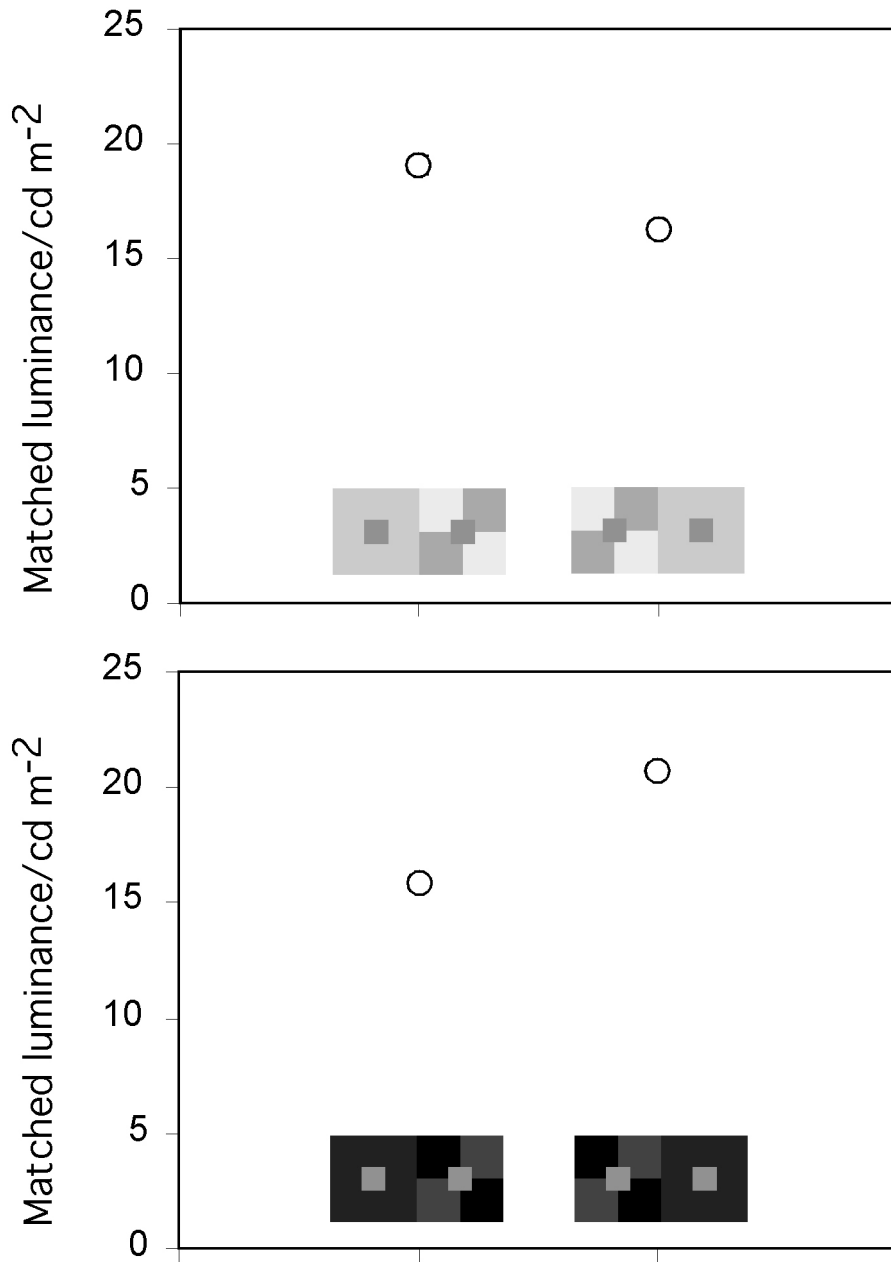


FIGURE 3