Surround articulation. II. Lightness judgments

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It has been hypothesized that to achieve color constancy, lightness judgments require an estimate of the illuminant. A companion paper [J. Opt. Soc. Am. A **16**, 793 (1999)] suggests that surround articulation enhances the likelihood that a global luminance edge will be interpreted as being due to changes in illumination rather than in reflectance. Articulation is the process of adding equally spaced incremental and decremental patches within a surround while preserving the surround's space-average luminance. Such a process results in lightness judgments that correlate perfectly with equal local ratio matches. For decrements, lightness constancy does not require articulation. These findings help explain why Arend and Goldstein [J. Opt. Soc. Am. A **4**, 2281 (1987)] obtained color constancy with complex Mondrian surrounds but not with simple center surrounds.
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1. INTRODUCTION

Lightness constancy occurs when the apparent surface reflectance between a small test patch on a dim surround and a small comparison patch on a more intense surround appear identical [see Fig. 1(a) of Ref. 1].[2–5] This occurs when the local contrast ratio is proportional between the test and comparison patches and their respective surrounds. One way to equate local contrast ratios is to have an accurate representation of the illumination gradient (i.e., global contrast) between the surrounds. This would occur if the two surrounds were interpreted as sharing a common reflectance while being under different levels of illumination. In such a case the dim surround would appear to be in shadow. However, simple center-surround stimuli can also be perceived as four separate surfaces each with a different reflectance, all under a single level of illumination. Thus whether the global surround luminance edge is the result of a change in illumination or a change in reflectance is ambiguous on such a background, making veridical lightness judgments difficult.

It is hypothesized that adding articulation to the surrounds of center-surround stimuli (i.e., introducing several patches with different gray levels while preserving the space-average luminance of the surround) strengthens the inference that the two surrounds share a common reflectance and are under different levels of illumination. The resulting level of inferred illumination represents a possible illumination gradient more accurately than is inferred with simple center-surround stimuli that underestimate the illumination gradient. Consequently, articulation leads to better lightness constancy, as suggested in the early Gestalt works[6] of Burzlaff,[7] Gelb,[8] Henneman,[9] Katona,[10] and MacLeod.[11]

Previous research has been unable to demonstrate that lightness and brightness are directly coupled, the way loudness and pitch are correlated.[12] However, one hypothesis is that both perceptual qualities require making an inference regarding how a scene is illuminated. This inferred illumination gradient is incorporated into brightness judgments and is discounted in lightness judgments. Arend and Goldstein[2] found that lightness judgments showed near-perfect constancy with Mondrian patterns, in contrast to the case of uniform surrounds. Likewise, their brightness judgments looked more like ratio matches with Mondrians than with center-surround stimuli. An exploration of brightness judgments in a companion paper[1] suggests that articulation increases the likelihood that a global luminance edge will be inferred to be due to a change in illumination rather than to a change in reflectance. In the current study, articulation is again used to systematically alter center-surround stimuli until they appear as Mondrians so that we can better understand the perceptual shifts that occur with lightness judgments. The use of articulation demonstrates that the perceptual qualities of brightness and lightness are distinct, as Arend and Goldstein[2] propose, and that both require the inference of global illumination gradients.

Articulation, given the present context, has been generated in a specific way (see Ref. 1 for details). In essence, four articulation patches are positioned within each surround. Each articulation is either an increment or a decrement by either 1.4% or 2.8% of the immediate surround luminance level, making the local space-average luminance of the four articulation patches identical to the surround luminance within which they are embedded [see Fig. 1(b) of Ref. 1]. Across conditions, the number of articulations is systematically increased by reiterating the initial four articulation patches to make either 8 or 16 articulations per background [see Figs. 2(a), 2(b), and 3(a) of Ref. 1]. This process can be extended to ultimately create the appearance of two Mondrians, (i.e., 20 articulations) each under a separate illuminant [see, Fig. 3(b) of Ref. 1]. Articulation thus defined is suggested to provide a gray scale against which to make lightness judgments. More important, it is hypothesized that articulation strengthens the perception of an illumi-

nation gradient between surrounds with different mean luminance levels, thus increasing the accuracy of making veridical lightness judgments.

2. METHOD

Details regarding observers, apparatus, stimuli and procedures are given in Ref. 1. Observers used a method of adjustment to vary the luminance of the achromatic test patch (T) to match the lightness, or apparent reflectance, of the comparison patch (C). That is, they made the two center patches appear "as if they were cut from the same piece of paper." [2]

3. EXPERIMENTS

A. Experiment 1: Uniform versus Articulation Surrounds

The global luminance edge between surrounds in Fig. 1(a) of Ref. 1 may be due to a difference in illumination, a difference in reflectance, or both.[4,13,14] Corroborating the companion paper's conclusions regarding brightness,[1] the current lightness study will demonstrate how adding articulation to the surrounds decreases this ambiguity by increasing the inference that the edge between the two surrounds is an illumination edge.

The luminance ratio between surrounds differed between blocks of trials and could be 6:1 (test surround

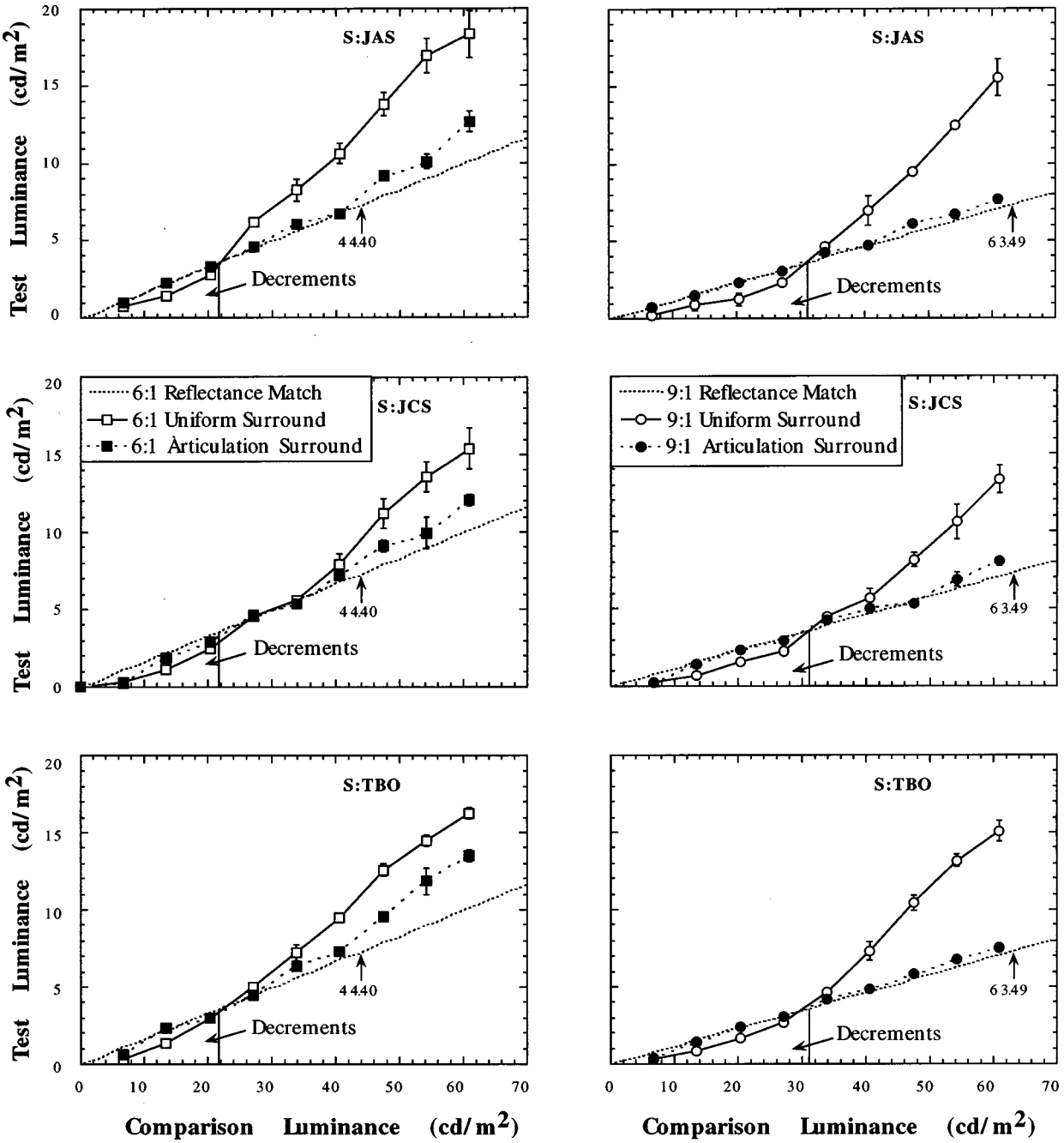

Fig. 1. Lightness matches for 6:1 and 9:1 uniform (open squares and circles, respectively) and articulation surrounds (filled squares and circles, respectively) for three observers.

Table 1. Luminances (cd/m^2) for Articulation Patches on Various Surround Ratios

Surround Ratio	Test Articulate A	Test Articulate B	Test Surround	Test Articulate C	Test Articulate D	Comparison Articulate A	Comparison Articulate B	Comparison Surround	Comparison Articulate C	Comparison Articulate D
Experiment 2										
Uniform Surround										
8:1			1.52					12.75		
11:1			1.52					17.34		
17:1			1.52					26.01		
Articulated Surround										
8:1	0.74	1.06	1.52	2.17	3.11	6.24	8.92	12.75	18.23	26.07
11:1	0.74	1.06	1.52	2.17	3.11	8.48	12.13	17.34	24.80	35.45
17:1	0.74	1.06	1.52	2.17	3.11	12.72	18.19	26.01	37.19	53.19

= 3.63 cd/m^2, comparison surround = 21.72 cd/m^2), 9:1 (test surround = 3:63 cd/m^2, comparison surround = 31.05 cd/m^2), or 12:1 (test surround = 3.63 cd/m^2, comparison surround = 40.40 cd/m^2) (see Table 1 of Ref. 1, uniform surrounds 6:1, 9:1, and 12:1). Intermixed with the three uniform-surround conditions were three articulation-surround conditions. Two of the articulation patches on each surround were decrements, one by 1.43% and the other by 2.86%. The other two articulation patches on each surround were increments, one by 1.43% and the other by 2.86%. Thus the space-average luminances for each surround were identical in the uniform and the articulation surround conditions [see Fig. 1(b) of Ref. 1 and Table 1 of this paper, articulation surrounds 6:1, 9:1, and 12:1].

Figure 1 shows highly similar data from three observers; the dotted lines are theoretical equal local contrast-ratio matches (i.e., a reflectance match denoting perfect lightness constancy). With uniform surrounds, observers increased the lightness (i.e., the luminance) of the test patch high above a local contrast-ratio match as the luminance of an incremental comparison patch increased. With decrements, they decreased the lightness (i.e., the luminance) of the test patch below a local contrast ratio match (6:1, open squares; 9:1, open circles; 12:1 follows the same pattern but to save space is not shown). This suggests that although observers were instructed to match the apparent reflectance of the test and comparison patches, they actually made lightness matches that were insensitive to local contrast ratios.

However, with articulation surrounds, observers demonstrated near-perfect lightness constancy until the luminance of the highest articulation patch was reached. For 6:1 this was at 44.40 cd/m^2 and for 9:1 it was at 63.49 cd/m^2. Above these articulation upper limits, constancy broke down in the same fashion as with uniform surrounds (6:1, filled squares; 9:1, filled circles).

B. Experiment 2: Articulation-Maximum-Limits Constancy Range

To verify that lightness judgments would remain constant for patches within the gray-scale range of the articulation patches and deviate when the test and comparison patches exceeded the upper luminance boundary of the most-luminous articulation patch, we generated the following stimuli. The new luminance ratios between surrounds were 8:1, 11:1, or 17:1 and were either simple uniform surrounds or articulation surrounds (see Table 1). The purpose of introducing stimuli with a dimmer test surround and a larger surround luminance ratio was to have stimuli whose highest articulation-patch luminance intensities were lower than those previously used. This arrangement reveals more clearly what occurs at intensities above the highest articulation-patch luminances. Thus the 8:1 articulation surround's most-luminous articulation was 26.07 cd/m^2, for 11:1 it was 35.45 cd/m^2, and for 17:1 it was 53.19 cd/m^2. As before, observers made lightness judgments on both uniform and articulation surrounds.

Figures 2–4 show lightness matches made on 8:1, 11:1, and 17:1 uniform and articulation surrounds for three observers. A mark on the ordinate designates the highest articulation luminance for a given surround ratio. While lightness matches made with a uniform surround deviate from theoretical lightness constancy soon after they become increments, those made with an articulation surround remain constant until the highest articulation luminance is reached and only subsequently deviate in the direction of uniform-surround lightness matches.

C. Experiment 3: Mondrians Derived from Articulation Surrounds

The size and placement of the four articulation patches within each surround in experiment 2 allows for multiples of those patches to be generated and used to fill in each surround to ultimately produce a Mondrian configuration. From stimuli that originally had four articulation patches per surround [see Fig. 1(b) of Ref. 1], two versions of eight articulation patches per surround were generated at 9:1 and 17:1 surround contrast ratios (see Figs. 2(a) and 2(b) of Ref. 1]. A 16-articulation-patch stimulus was then generated by doubling the 8 articulation patches at 9:1 and 17:1 surround contrast ratios (see Fig. 3(a) of Ref. 1]. Two identical Mondrians were also generated [see Fig. 3(b) of Ref. 1]. Notice that with all of the above stimuli the local space-average luminance is

the same as in the uniform-surround condition. Just as important, the patches directly surrounding the test and comparison patches remained constant, thus preserving the local test/surround and comparison/surround contrast ratios.

Interestingly, as the number of articulation patches increases, *brightness* judgments increasingly shift toward ratio matches (see Fig. 8 of Ref. 1). This suggests that increasing the number of articulation patches increases the inference that the global surround luminance edge is due to a change in illumination [compare Figs. 1(b), 2(a), 3(a), and 3(b) in Ref. 1]. *Lightness* judgments, however,

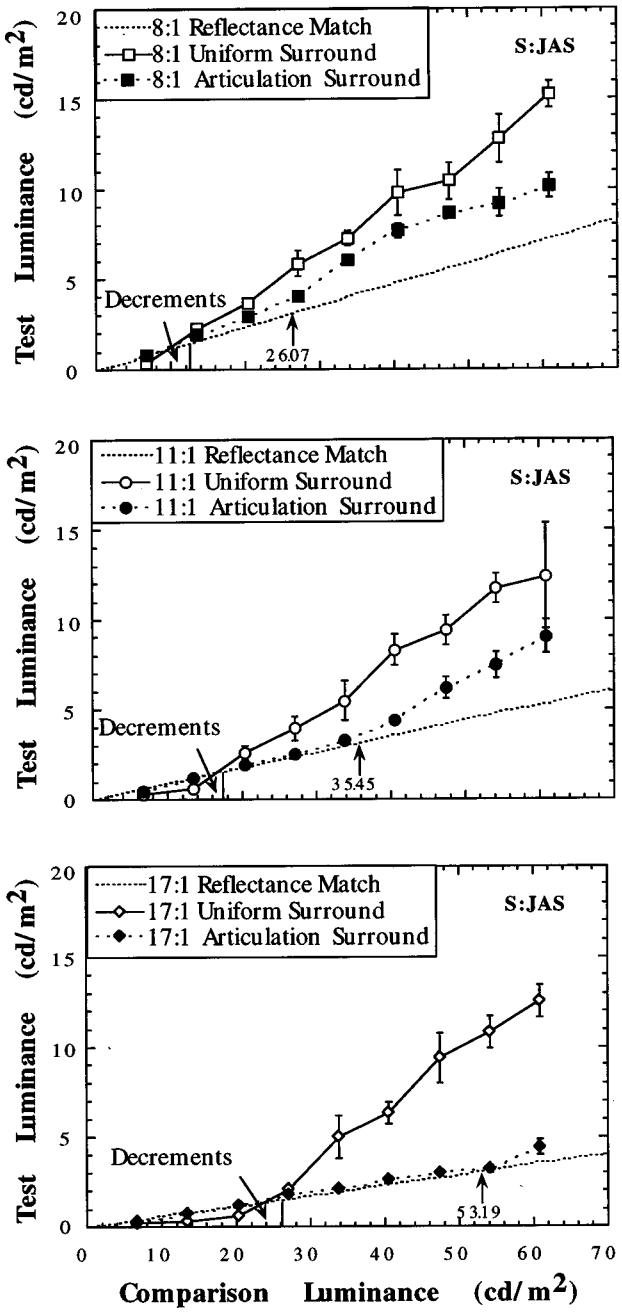

Fig. 2. Lightness matches for 8:1, 11:1, and 17:1 uniform (open squares, circles, and diamonds, respectively) and articulation surrounds (filled squares, circles, and diamonds, respectively) for observer JAS.

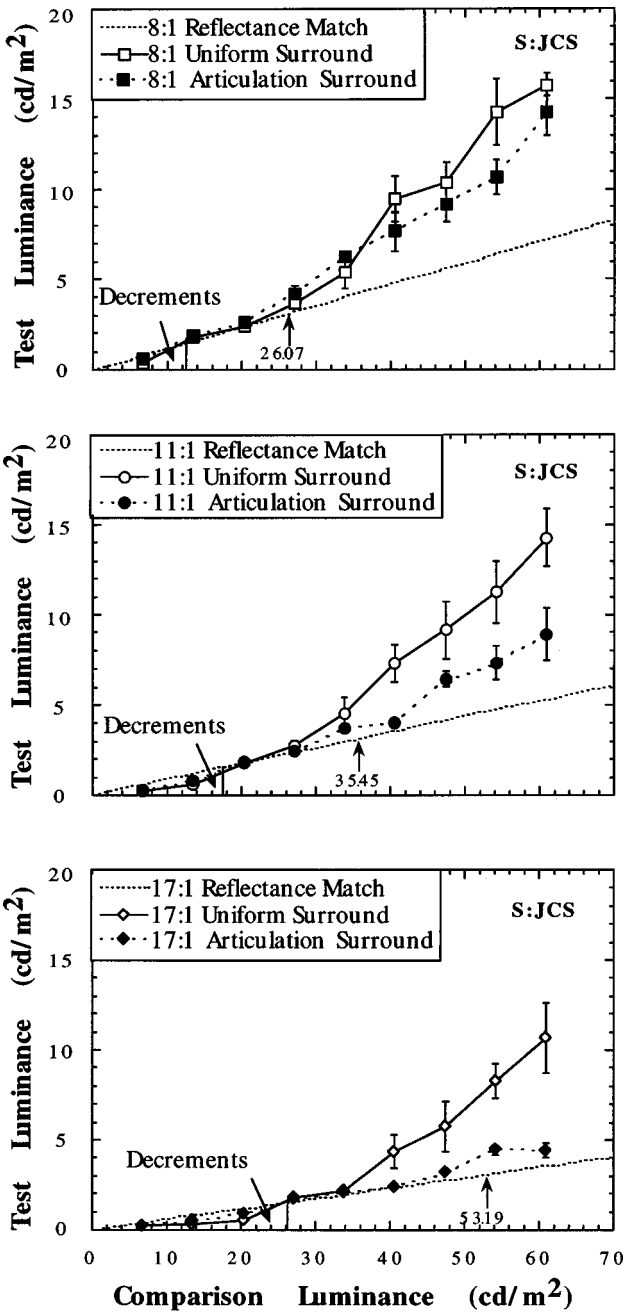

Fig. 3. Same as Fig. 2, for observer JCS.

do not require a multitude of articulation patches in order to reach lightness constancy. Figure 5 shows observers' lightness settings for a 9:1 surround ratio on uniform surrounds, 4-articulation-patch surrounds, or 20-articulation-patch Mondrian surrounds (to save space, similar results for a 17:1 surround ratio are not presented). Lightness constancy is near perfect with only four articulation patches and is unaffected by the addition of more articulation patches (for 9:1, compare filled squares with dot-within-circle patches).

This result is striking in that with four articulation patches the inferred illumination edge between surrounds is not as readily apparent as with Mondrians [in Ref. 1 compare Fig. 1(b) with Fig. 3(c)]. Thus the conscious perception of an illumination gradient is not required for

making lightness judgments that match local contrast ratios. However, as shown in Fig. 6, the variability in making lightness matches with a Mondrian is markedly less than with only four articulation-patch stimuli. Figure 6 replots the standard errors for lightness judgments made with the 9:1 uniform and articulation surrounds (taken from Figs. 2–4). In this case, articulation reduces the variability in observers' lightness judgments [compare uniform surrounds (open circles) with articulation surrounds (filled circles)]. This result suggests that by providing several examples of local contrast, articulation patches establish a gray scale against which lightness judgments are made. Increasing the number of patches without increasing the number of gray levels, from 4 articulations per surround to 20 articulations per surround

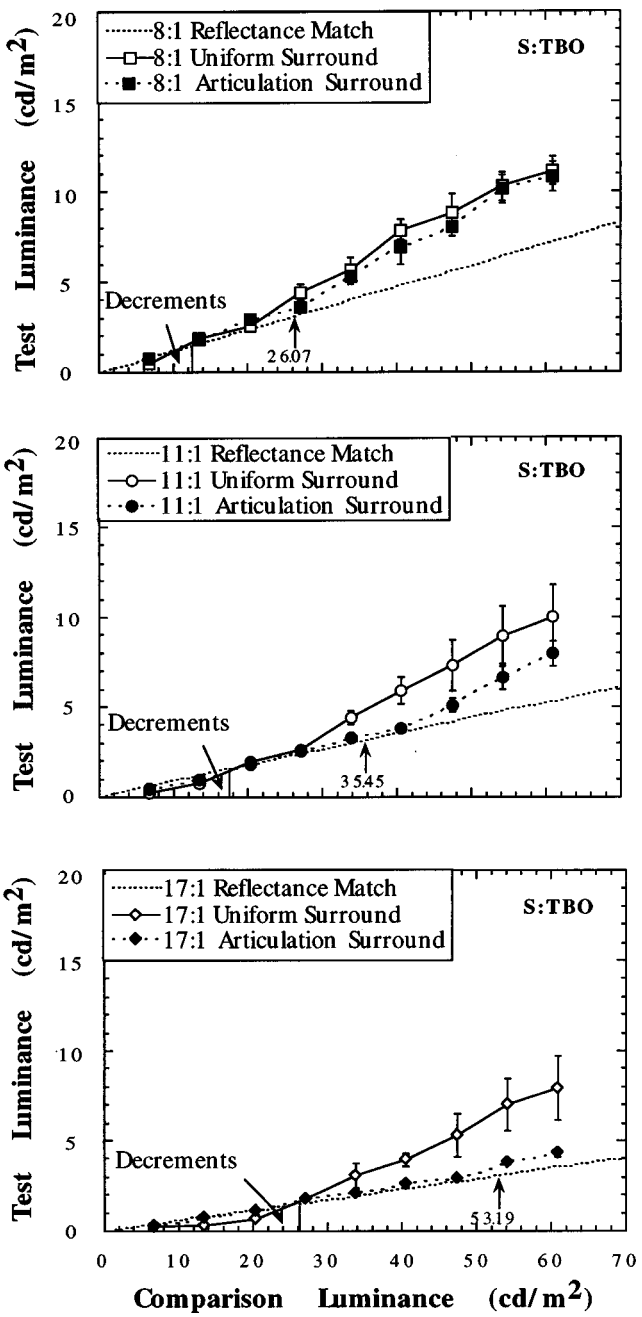

Fig. 4. Same as Fig. 2, for observer TBO.

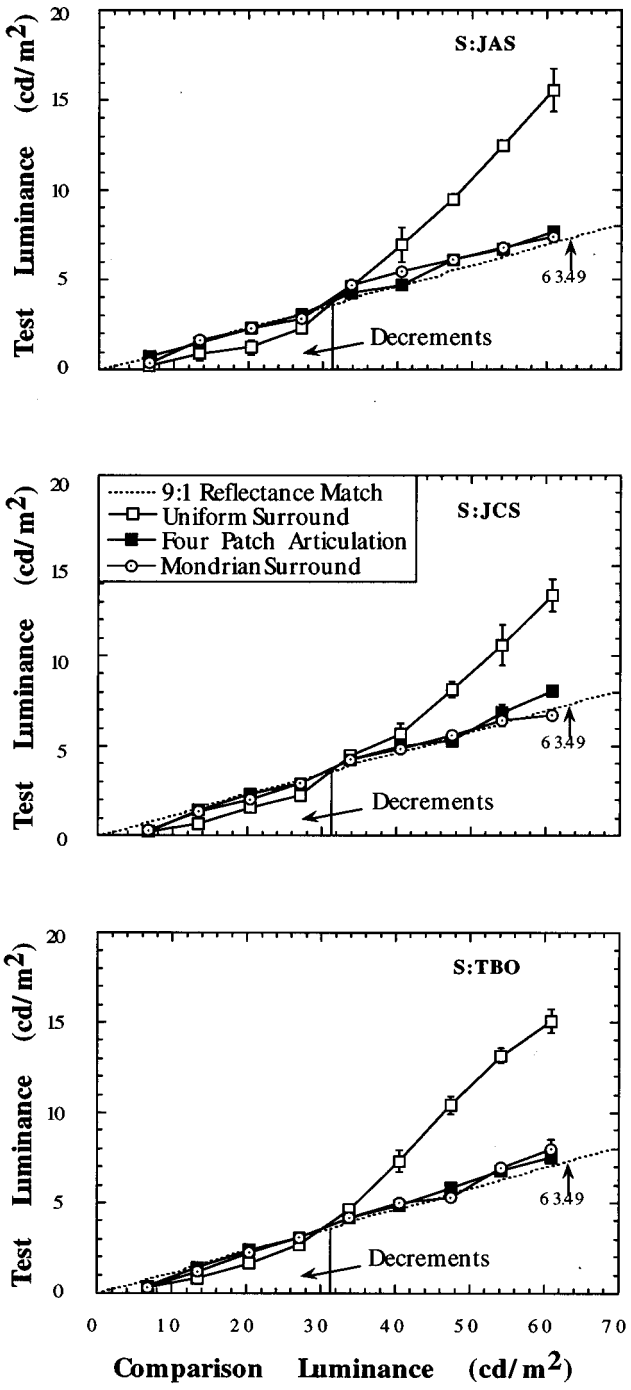

Fig. 5. Lightness matches for a 9:1 uniform (open squares), 4-articulation-patch (filled squares), and 20-articulation-patch (i.e., Mondrian) (dot-within-circle) surrounds for three observers.

[i.e., Mondrians (open squares), taken from Fig. 5] reduces observers' variability in making lightness judgments even further. Thus, although the computation of an illumination gradient does not require adding variation in the gray scale, it does, as in the case of Mondrians, enhance observers' confidence in making lightness judgments. It is as if lightness judgments were based on local ratios, and having several other local contrast ratios available of different amplitudes significantly improves one's judgment. Making these local ratios redundant, as with a Mondrian [see Fig. 3(c) of Ref. 1], produces addi-

tional ratios. That is, each articulation patch is now surrounded by several other articulation patches and not just by the uniform surround. This configuration increases variation in the surround's local contrast without altering the range of the gray scale.

4. DISCUSSION

In the phenomenological literature, Arend and Goldstein[2] make a crucial distinction between lightness and brightness. The current study suggests that articulation can be used to demonstrate that both lightness and brightness judgments rely on an inference being made regarding the prevailing level of illumination. As Fig. 7 demonstrates, for 9:1 and 17:1 surround ratios, lightness and brightness judgments of identical stimuli are different. Yet articulation appears to increase the inference that the surround luminance is due to an illumination gradient in both cases. That is, with brightness judgments, observers set the test luminance lower with an articulation surround than with a uniform surround, suggesting that the test luminance appears brighter as a result of an increase in the inferred illumination gradient (see Schirillo Ref. 1). With lightness judgments, the increase in the inferred illumination gradient with articulation makes it easier to determine and discount the global luminance edge ratio. This process works only if the comparison patch is dimmer than the comparison surround's lightest articulation patch. Thus the whitest surface within a segmented region of a scene may set the illumination gradient, as Cataliotti and Gilchrist suggest.[15] Moreover, the effect of articulation is prominent with increments but is quite small for decrements, where brightness and lightness matches are similar.

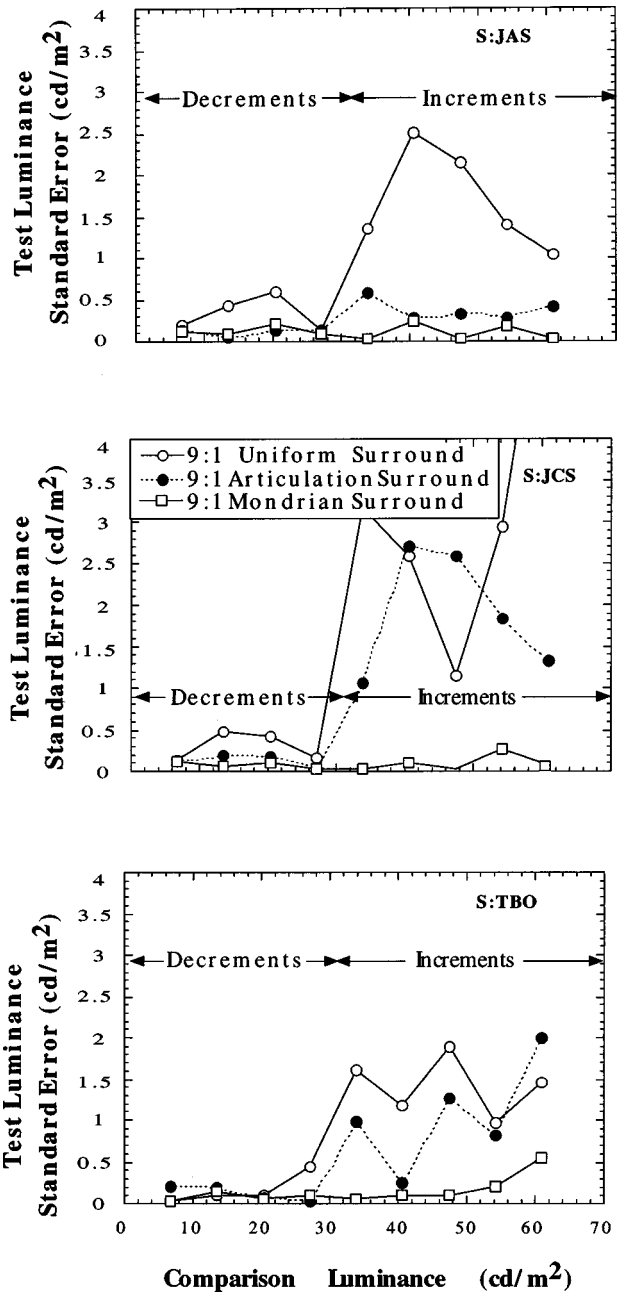

Fig. 6. Standard error of the mean of lightness matches made on 9:1 uniform (open circles), articulation (filled circles) and Mondrian (squares) surrounds for three observers.

Adding patches of varying luminance to a uniform surround while keeping the local space-average luminance constant alters lightness matches in a way that resembles what would happen if global contrast were made less ambiguous by the use of an extended luminance border between the test and the comparison surrounds to suggest an illumination edge.[5,13]

The largest luminance range used in this study was 72:1, obtained by using a 17:1 articulation surround ratio (see Table 1). This is slightly above the 60:1 luminance ratio often cited as the black-to-white (lightness) range possible under a single illuminant and may be the reason that two illuminants were perceived.[16–19] However, the pattern of these results was consistent with the smallest luminance range used (i.e., a 6:1 articulation-surround ratio resulting in 25:1 luminance range) (compare Figs. 2–4). Therefore, while articulation increased the luminance range, it is not likely that this accounts for the perception of two distinct illumination gradients.

Arend and Spehar[3] did not find that a random rearrangement of the grays in a Mondrian altered lightness matches. However, specific rearrangements of patches can affect their perceived lightnesses. Adelson[20] produced the perception of an increase in illumination in a region containing white surfaces and a decrease of illumination in a region containing black surfaces. This is a form of assimilation that is due to spatial grouping. With articulation, however, the additional patches are both increments and decrements relative to their surround. Therefore articulation is an excellent means of exploring the continuum between the argyle illusion[20] and random rearrangements of the gray scale.

The companion paper[1] suggests that surround articulation strengthens the inference that an illumination edge between surrounds is incorporated in making brightness judgments. Thus a test surround that has articulation appears to be under less illumination, or its comparison surround appears to be under more illumination, or both, compared with a uniform-surround condition. As demonstrated, this causes observers to increase the luminance of the test in making a brightness match to overcome the shadow that the test patch appeared to be under. Light-

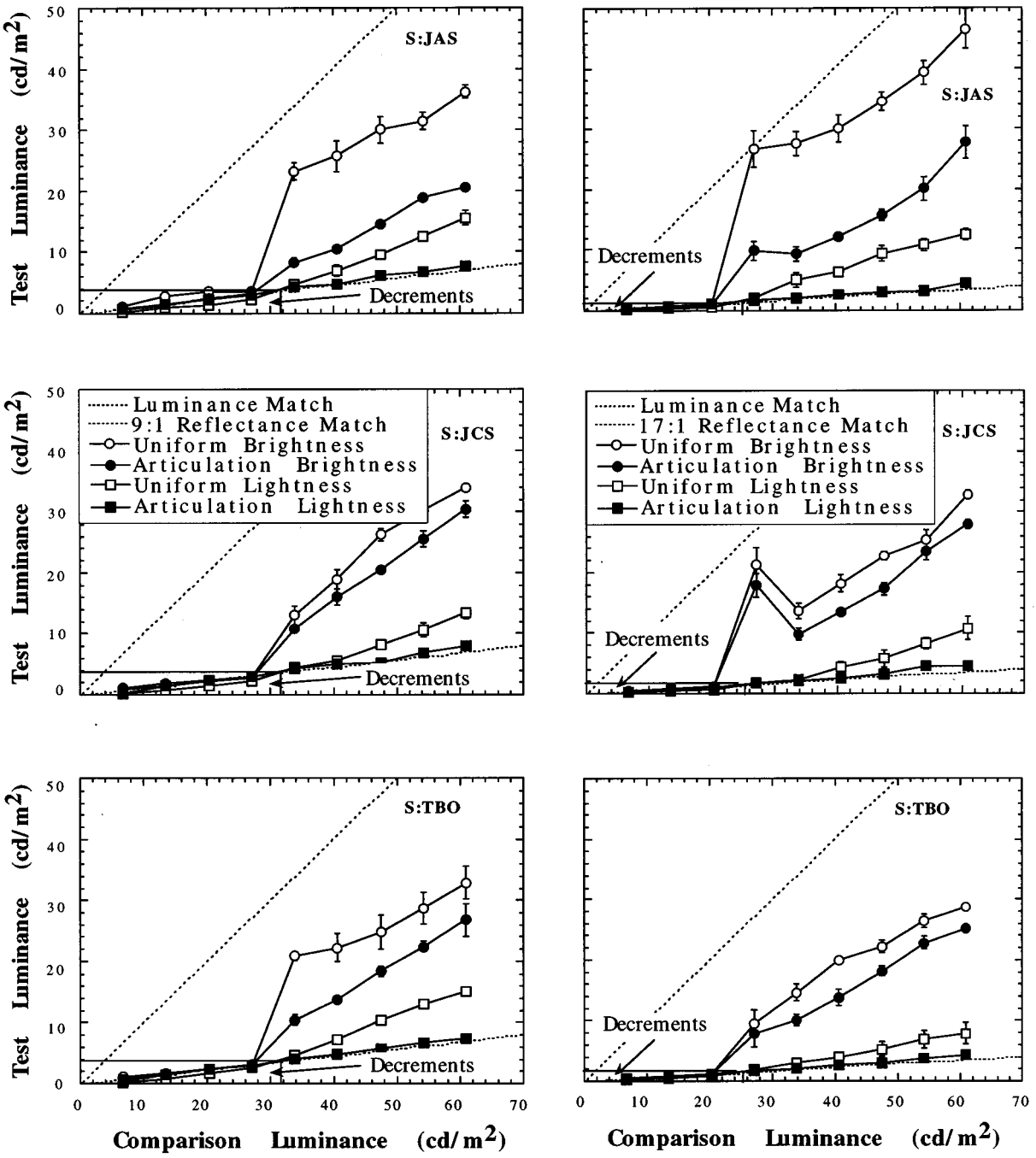

Fig. 7. Brightness matches are plotted for 9:1 and 17:1 uniform (open circles) and four-articulation-patch (filled circles) surrounds. Brightness data are taken from Figs. 4 and 8 of Ref. 1. Lightness matches are plotted for 9:1 and 17:1 uniform (open squares) and four-articulation-patch (filled squares) surrounds. Lightness data are replotted from Figs. 1–4. Data are for observers JAS, JCS, and TBO.

ness judgments made on these articulation and uniform surrounds support this hypothesis. Perfect lightness constancy is possible with articulation surrounds, suggesting that articulation provides an accurate inference of an illumination edge that is to be discounted.

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