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Photometric, geometric, and perceptual factors in illumination-independent lightness constancy

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It has been shown that lightness constancy depends on the articulation of the visual field (Agostini & Galmonte, 1999). However, among researchers there is little agreement about the meaning of "articulation." Beyond the terminological heterogeneity, an important issue remains: What factors are relevant for the stability of surface color perception? Using stimuli with two fields of illumination, we explore this issue in three experiments. In Experiment 1, we manipulated the number of luminances, the number of reflectances, and the number of surfaces and their spatial relationships; in Experiment 2, we manipulated the luminance range; finally, in Experiment 3 we varied the number of surfaces crossed by the illumination edge. We found that there are two relevant factors in optimizing lightness constancy: (1) the lowest luminance in shadow and (2) the co-presence of patches of equal reflectance in both fields of illumination. The latter effect is larger if these patches strongly belong to each other. We interpret these findings within the albedo hypothesis.

Illumination-independent lightness constancy refers to the visual system's property of perceiving constant surface lightness in spite of large changes in illumination level. This phenomenon constitutes a problem for visual science, since visual objects are perceived by means of the light rays reflected from surfaces to the retina. In the achromatic domain, the intensity of the light rays is the product of the intensity of the incident light and the reflectance of surfaces. When the intensity of light falling on surfaces changes, the amount of light reaching the retina (i.e., the luminance) is correspondingly modified. We should expect, then, a different lightness for different conditions of illumination. However, this is not the case. Under many visual conditions, lightness undergoes very little variation even when the illumination is greatly changed.

This phenomenon has been extensively and systematically studied since the late 19th century. The most representative theories were developed by Helmholtz (1866/1924–1925) and Hering (1878). Helmholtz attributed lightness constancy to cognitive factors such as learning and judgment. He suggested that we learn to judge lightness in daylight illumination and then, when lighting conditions change, we unconsciously use what we have learned to maintain the value of lightness constant. Hering, in contrast, sought more tangible physiological mechanisms as the cause of lightness constancy, such as pupillary changes, adaptation, and lateral inhibition.

We can find influences of these two explanations in almost all the existing interpretations of lightness constancy. Many later authors, however, stressed relative rather than absolute luminance. Wallach (1948) was probably the best advocate of this point of view. He pointed out that the luminance ratio between neighboring regions remains the same even when the incoming light intensity changes. By means of an elegant experiment, he demonstrated that lightness can be predicted by calculating the ratio between the luminance of an object and that of the fields adjacent to it. For this reason, Wallach's (1948) view was dubbed the *luminance ratio principle*.

It should be noted, however, that when the visual scene is poorly articulated, the luminance ratio principle is not a good predictor of lightness. In other words, if there are few surfaces in the visual scene, their lightness cannot be exactly predicted from their luminance ratio. Previously, Katz (1911, 1935) devised an experimental technique to investigate lightness constancy systematically: He placed two Maxwell disks on a homogeneous achromatic background with a vertical screen between them. Light coming from one side fully illuminated one disk and was partially cut off from the other. The task was to adjust the illuminated disk to match the lightness of the other. Following Gilchrist and Annan (2002), we will call this procedure the *light/shadow method*. In such a simplified condition, Katz (1911, 1935) found that the two disks are perceived to be equal in lightness when the highly illuminated disk has been set at a lower reflectance value than the other

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disk. This demonstrated that the lightness constancy phenomenon does not appear in all conditions, or, in Katz's own words, ". . . we see that it would be false to conclude [. . .] that there is ideal color constancy" (1935, p. 82).

In a search for the factors that improve the degree of lightness constancy, Katz (1911, 1935) introduced variables such as subject's age, peripheral vision, presentation time, and also visual field articulation. In one variation of the light/shadow method, he replaced the homogeneous gray background behind the disks with a chart of 48 chips ranging from black to white. In this condition, lightness constancy increased in comparison with the condition with a homogeneous background. Katz (1911, 1935) referred to this phenomenon as *articulation*.

Following on Katz's (1911, 1935) findings, many other scientists found an interaction between illumination-independent lightness constancy and articulation. Using the Katz paradigm, Burzlaff (1931) found that the degree of lightness constancy depends on the number of gray samples present in the visual scene.

In 1935, Henneman performed a series of experiments on lightness constancy using a setting very similar to that of the light/shadow method introduced by Katz (1911, 1935). In these experiments, observers were asked to match the lightness of an illuminated disk (target) to that of a shadowed disk (standard). The standard, together with its background, had the highest reflectances in the scene (i.e., both white). Consequently, a target adjustment set to white would correspond to the "ideal" constancy, whereas departures from this value would correspond to proportional losses of constancy. Using this experimental setting, Henneman performed a number of different experiments on "field complexity," two of which are the most pertinent to the present research. In one of them, the author manipulated the number of additional medium-gray patches placed in the shadowed field; in the other, he manipulated the reflectance of those patches. Henneman found that, in comparison with the condition with no additional objects, the adjustments of the observers moved toward white—that is, toward the ideal constancy—when (1) the number of the additional patches was increased from one to three and (2) the reflectance difference between the additional objects and the standard was increased.

More recently, the cathode ray tube (CRT) technology has been used in psychophysical studies to investigate color constancy. Indeed, as Bruno (1994) pointed out, the impoverished degree of ecological validity of the CRT method is compensated for by its flexibility in controlling the spatial distribution of luminances.

Making use of CRT simulations, Arend and Goldstein (1987) found marked failures of lightness constancy when the experimental display was poorly articulated, whereas constancy was almost perfect when highly articulated Mondrian displays were used. Arend and Spehar (1993) found the same results and suggested that when the stimuli were too simple, observers asked to match lightness instead performed local brightness matches.

Some authors have underscored the importance of other factors. It has been shown, for example, that configural cues (see Agostini & Galmonte, 1999; Logvinenko, 2002; Schirillo & Shevell, 1997) and three-dimensional structure (see Gilchrist, 1977; Schirillo & Arend, 1995; Schirillo, Reeves, & Arend, 1990) influenced surface brightness and/or lightness even when the number of elements in the visual scene was kept constant.

The aim of the present research was to continue with Henneman's (1935) work. Actually, in his experiments on field complexity, he did not test the effects produced by the presence of additional objects having a reflectance higher than that of the standard (HR); furthermore, he placed these objects in the shadowed field only. In the present work, we attempt to fill these gaps. By simulating the light/shadow paradigm on a CRT monitor, we measured the effects of additional HR objects placed in one or the other field of illumination or in both fields simultaneously. In addition, we controlled the perceptual belongingness among the additional objects.

EXPERIMENT 1

Method

Observers. Twelve volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naive with regard to the experimental design.

Apparatus and Stimuli. The stimuli were all generated by a computer with a Pentium processor and were presented on a carefully calibrated 18-in. 523X Daewoo monitor (944 × 648 pixels). The basic configuration (see Figure 1C) represents a simulation of the light/shadow display and was constructed as follows. First, the screen of the monitor was vertically divided in two halves having different luminances (56 cd/m^2 for the left side and 5.6 cd/m^2 for the right side). Each half of the screen subtended 10º × 14º of visual angle. A rectangle (6.17º × 7.20º of visual angle) having a luminance equal to 79.8 cd/m^2 was then positioned on the left half of the screen.

A rectangle was also drawn on the right side of the screen; its luminance was equal to 7.98 cd/m^2. At this point, the screen was divided into four areas. The luminance ratio between the two areas on the left and the corresponding areas on the right was 10:1. Under these stimulation conditions, the edge dividing the two halves of the screen is perceived as an illumination edge and, therefore, the four areas are perceived as two surfaces (inner background and outer background) under two different levels of illumination. Thus, we will call the left side of the screen the "light field" and the right side the "shadowed field." Finally, a square (1º × 1º of visual angle) was placed in the middle of each of the two inner backgrounds: The square on the left was the target, whereas that on the right was the standard. The luminance of the standard was 3.98 cd/m^2.

To get a comparison term, we also designed a control condition consisting of a display eliciting background-independent lightness constancy, where the outer background had a single luminance equal to the geometric mean of the two halves of the outer background of the basic configuration—that is, 17.7 cd/m^2 (see Figure 1C, control condition).

In this experiment, we manipulated the number, reflectance, and position of additional patches (1.5º × 1.5º of visual angle) always placed in the inner background of the basic display.

In the interest of clarity, the experimental configurations are presented in three collections of stimuli on the basis of the variables manipulated.

First collection of stimuli: Displays A–H. In the stimuli of the first collection, the additional patches lay either in light or in shadow. In Displays A and B, there was only one additional patch in shadow. In Display A, the added patch had a lower reflectance than the standard

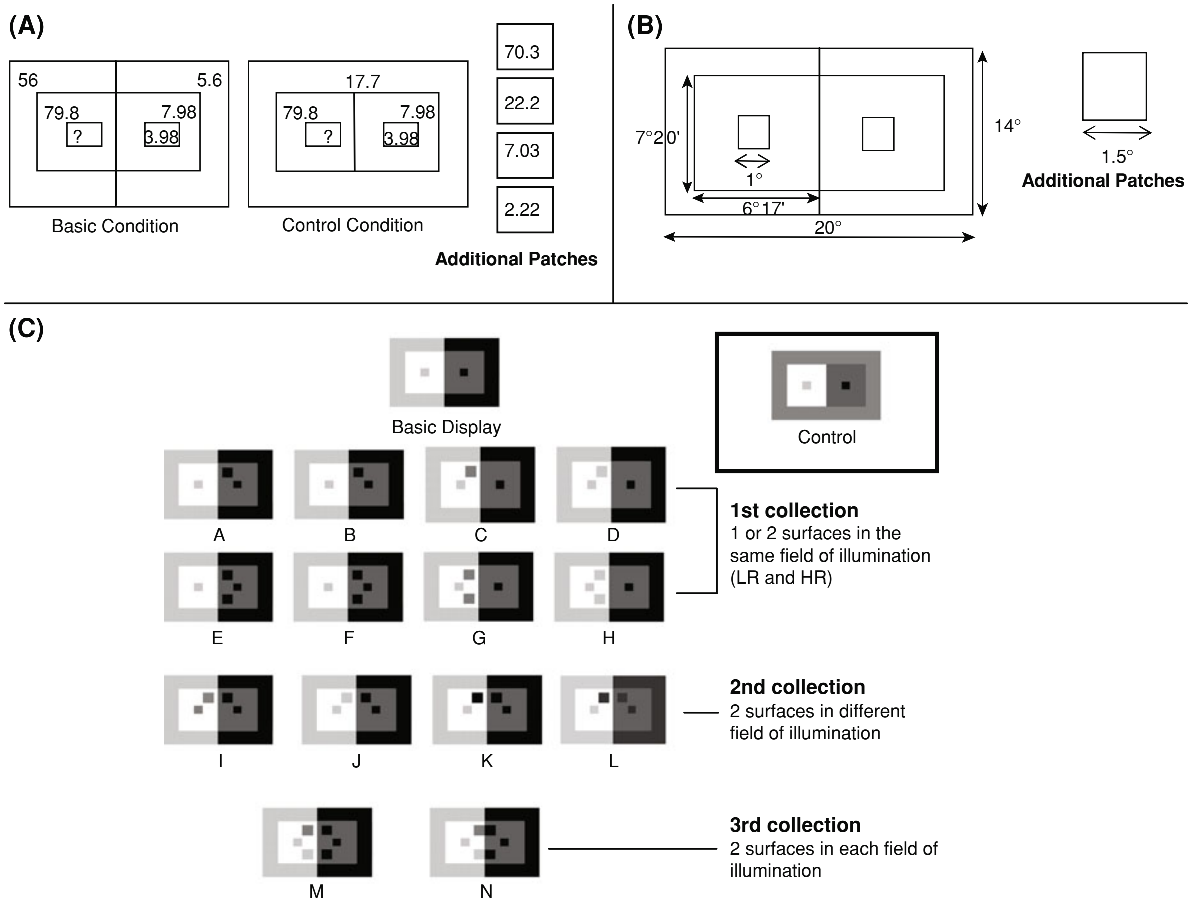

Figure 1. (A) Luminance (in cd/m^2) of the stimuli of Experiment 1. (B) Size (in degrees of visual angle) of the stimuli of Experiment 1. (C) Experimental displays of Experiment 1. Displays are arranged in three collections on the basis of the variables manipulated (see text for details). HR, patches with higher reflectance than the standard; LR, patches with lower reflectance than the standard.

(LR; 2.22 cd/m^2), whereas in Display B the added patch had HR (7.03 cd/m^2). The luminance difference in logarithmic units between the standard and the LR patch was the same as that between the HR patch and the standard (i.e., 0.25 cd/m^2). In Displays C and D, there was only one additional patch in light. In Display C, the luminance of the added patch (22.2 cd/m^2) was 10 times higher than that of the LR patch in Display A, whereas in Display D the luminance of the added patch (70.3 cd/m^2) was 10 times higher than that of the HR patch in Display B.

Displays E–H were similar to Displays A–D except that in each of them there were two additional patches instead of one. The second additional patch was placed 2º of visual angle below the first additional patch and shared with it the same size and luminance.

Second collection of stimuli: Displays I–L. In each display of the second collection, there were two additional patches: one in light and the other in shadow. In Display I, the luminance of the additional patch in shadow was 2.22 cd/m^2, whereas that in light was 22.2 cd/m^2. Since the two patches were at the same luminance ratio as the two fields of illumination, they simulated equal reflectance. Therefore, there was only one reflectance more than in the basic display. The same holds true of Display J, but with different patch luminances (7.03 cd/m^2 in shadow and 70.3 cd/m^2 in light). In Display K, in contrast, the luminance of both additional patches was 2.22 cd/m^2. In this way, we added only one luminance to the basic display but simulated two different reflectances. Display L was equal to Display K, but the luminance of both its additional patches was 7.03 cd/m^2.

Third collection of stimuli: Displays M and N. In both displays of the third collection, there were four additional patches: two in light (22.2 and 70.3 cd/m^2) and two in shadow (2.22 and 7.03 cd/m^2). Therefore, there were two reflectances more than there were in the basic display.

In Display M, the patches with the same simulated reflectance were separated on the horizontal axis, whereas in Display N they were adjacent. In this way, we manipulated the strength of the perceptual organization between the additional patches simulating the same reflectance but lying in different fields of illumination. We used the gestalt factors of proximity in Display M and good continuation in Display N.

To summarize, there was a total of 16 displays: 14 experimental displays plus the basic and control displays.

Procedure. The observers viewed the stimuli, presented in random order, in a darkened room at a distance of 80 cm from the monitor. They were instructed to match the lightness of the target patch on the left side (illuminated field) to the corresponding standard patch on the right side (shadowed field) using the plus and minus keys of the keyboard. By pressing another button, they signaled that a satisfactory match had been achieved; at that point, the target luminance was recorded and the next trial began. The luminance of the target was set to a random value at the beginning of each trial. In order to achieve a lightness match, we asked the observers to make the target patch to "look as if it were cut from the same piece of paper as the standard." The observers performed four matches for each of the 16 stimuli, for a total of 64. Each display was left on the screen as long as was needed for the observer to produce the match. The whole session lasted about half an hour.

Results

Mean ratings are expressed as the difference, in log units, between the experimental displays and the basic condition, which served as the baseline. The basic display holds a constancy value[1] of .62 in an interval ranging from 0 (luminance match) to 1 (ratio match), whereas the control display showed a value of .32. These data suggest that, despite the impoverished degree of ecological validity of the CRT method, the simulation of two fields of illumination was satisfactory.

We compared the observers' lightness matches separately for the three collections of stimuli.

In the graphs of Figure 2, the dashed lines labeled *ratio match* refer to the value obtained by subtracting, in log units, the luminance that would have been recorded if the observers had performed a perfect ratio match (i.e., 39.8 cd/m^2) from the average luminance actually recorded in the basic display. Similarly, the dashed lines labeled *luminance match* refer to the value obtained by subtracting, in log units, the luminance that would have been recorded if the observers had performed a perfect luminance match (i.e., 3.98 cd/m^2) from the average luminance actually observed in the basic display.

First collection of stimuli: Displays A–H. In the collection of Displays A–H, we distinguished three variables. They are listed, together with their levels, in Table 1.

Figure 2A plots the results relative to the first collection of stimuli. A repeated measures ANOVA revealed a significant main effect for both position and luminance values [$F(1,11) = 16.43$, $p < .05$ and $F(1,11) = 6.88$, $p < .05$, respectively]. The interaction between the two factors was also significant [$F(1,11) = 22.74$, $p < .05$]. Neither the main effect of the number of surfaces nor the interaction between it and the other two factors was statistically significant. The graph shows that, in the light/shadow display, the degree of lightness constancy increases only when one or two LR patches are added in the shadowed field.

Second collection of stimuli: Displays I–L. In the collection of Displays I–L, there were two variables, which are listed, together with their levels, in Table 2. Figure 2B shows the results of this collection. A repeated measures ANOVA indicates that when two luminances are added to the basic display, lightness constancy significantly increases in comparison with the displays in which only one luminance is added [$F(1,11) = 15.31$, $p < .05$]. The main effect of the variable of luminance in shadow was also statistically significant [$F(1,11) = 16.63$, $p <$

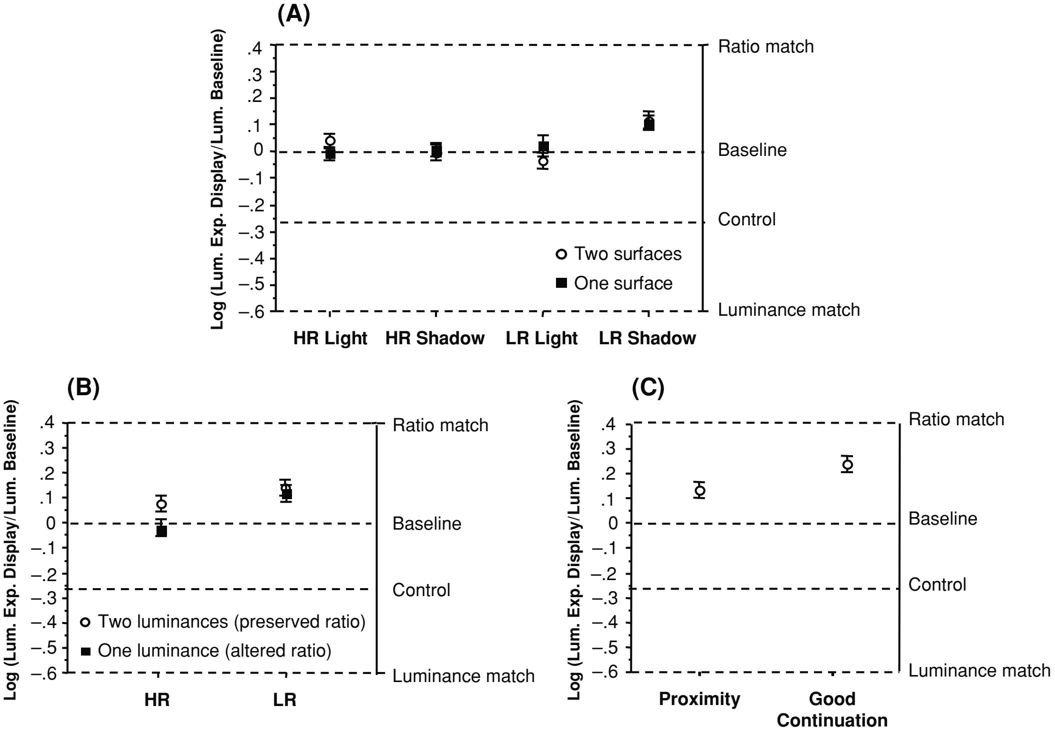

Figure 2. Experiment 1: Results of (A) the first collection of stimuli (Displays A–H), (B) the second collection of stimuli (Displays I–L), and (C) the third collection of stimuli (Displays M and N) of Experiment 1. HR, patches with higher reflectance than the standard; LR, patches with lower reflectance than the standard. Bars indicate standard errors.

Table 1
Variables and Levels of the First Collection of Stimuli

Variable	Levels (Displays)
Number of surfaces	One (A, B, C, D)
	Two (E, F, G, H)
Position	In shadow (A, B, E, F)
	In light (C, D, G, H)
Reflectance	LR patch (A, C, E, G)
	HR patch (B, D, F, H)

Note—For explanations of the displays, see Figure 1C, first collection. LR, lower reflectance than the standard; HR, higher reflectance than the standard.

Table 2
Variables and Levels of the Second Collection of Stimuli

Variable	Levels (Displays)
Number of luminances	Two (I, J)
	One (K, L)
Luminance in shadow	HL (J, L)
	LL (I, K)

Note—For explanations of the displays, see Figure 1C, second collection. HL, higher luminance than the standard; LL, lower luminance than the standard.

.05]. The interaction between the two variables was not significant.

Furthermore, in Display I, in which there are two luminances and the luminance in shadow is lower than that of the standard, lightness constancy improves in comparison with the basic display [$t(11) = 2.64, p < .05$].

There was also a significant difference between Displays J and L, which differ only in the luminance of the patch in light [two vs. one; $t(11) = 3.14, p < .05$].

There is no difference between Display L and the basic display.

Therefore, adding LR patches in shadow is sufficient to improve lightness constancy independently of the presence of patches in light. In addition, in comparison with the first collection of stimuli, lightness constancy also increases when an HR patch is added in shadow, but only if another patch sharing the same reflectance is simultaneously present in light.

Third collection of stimuli: Displays M and N. In the collection of Displays M and N, there was only variable, which is listed, together with its levels, in Table 3. Figure 2C shows the results of this collection. A *t* test shows a statistically significant effect of perceptual organization [$t(11) = 2.5, p < .05$]. In comparison with the basic display, the graph shows an enhancement of lightness constancy for both experimental displays. Furthermore, these data suggest that the constancy increases even more if the patches sharing the same reflectance (see results of the second collection of stimuli) strongly belong to each other.

Discussion

In this experiment, we extended Henneman's (1935) research to a number of conditions in which the standard patch did not have the highest reflectance within the light/shadow display. Lightness constancy was systematically studied by manipulating (1) the number and reflectance of the additional patches placed either in light or in shadow and (2) the luminance ratio and perceptual organization of the additional patches placed simultaneously in both fields of illumination.

Starting with the basic condition, in the first collection of stimuli we manipulated the number (one vs. two), position (in light vs. in shadow), and reflectance (HR vs. LR) of the additional patches. The results indicate that lightness constancy improved, in comparison with the basic display, when the added patches were placed in shadow and their reflectance was lower than that of the standard. In contrast, adding patches in light (independently of whether they were HR or LR) did not affect the perceived lightness of the standard. Also, the number of additional patches placed in shadow did not play any role. In fact, increasing the number of LR patches from one to two did not make any difference in lightness constancy.

In the second collection of stimuli, we manipulated the luminances of two additional patches, one placed in light and the other in shadow. The results suggest that lightness constancy was enhanced, in comparison with the basic display, when the two added patches shared the same reflectance. This effect occurred independently of the reflectance value of the patches. If, instead, the added patches shared the same luminance, lightness constancy improved over that of the basic display only when the reflectance of the patch in shadow was lower than that of the standard. Therefore, it seems that the number of reflectances (but not the number of luminances) was not a critical factor for lightness constancy improvement, whereas lightness constancy was affected by the number of patches of equal reflectances placed in both fields of illumination. It should be noted that these reflectances shared the same luminance ratio between the fields of illumination. Therefore, we submit that lightness constancy improves when the added patches lie in both fields of illumination and share the same luminance ratio as that between the two fields.

Finally, in the third collection of stimuli we manipulated the perceptual organization between patches sharing the same reflectance and simultaneously present in both fields of illumination. We found that lightness constancy significantly improved in both experimental displays in comparison with the basic display. Furthermore, in Display N lightness constancy was significantly higher than in all the other displays of this experiment. It is plausible that the strength of belongingness between the patches was higher in Display N, where the four patches were

Table 3
Variables and Levels of the Third Collection of Stimuli

Variable	Levels (Displays)
Perceptual organization	Proximity (M)
	Good continuation (N)

Note—For explanations of the displays, see Figure 1C, third collection.

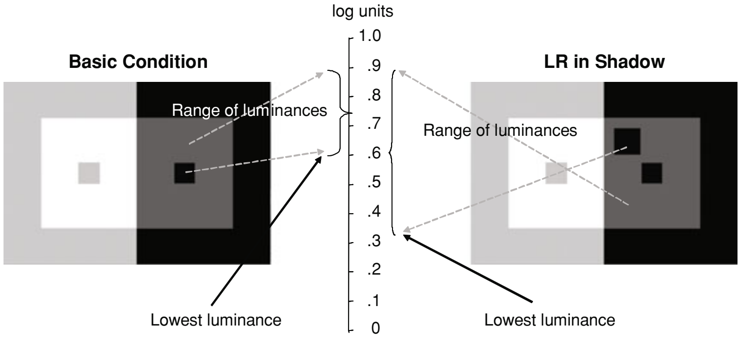

Figure 3. Range of luminances and lowest luminance (in cd/m^2) in the shadowed field of the basic display (left) and Display A (right) of Experiment 1.

perceived as two unitary objects, than in Display M. From the second collection of stimuli, we observed that lightness constancy improved when surfaces having the same reflectance were placed in both fields of illumination; however, from the third collection of stimuli, we can further add to this observation that lightness constancy was even better if these surfaces strongly belonged to each other.

To summarize, two main factors seem to be relevant to optimizing lightness constancy in a light/shadow display when the standard patch had a lower reflectance than the background: (1) the presence of LR patches in shadow and (2) the co-presence of equal-reflectance patches in both fields of illumination. This effect is larger when these surfaces strongly belonged to each other.

The aim of the following two experiments is to further investigate these two factors.

EXPERIMENT 2

In Experiment 2, the effect of the LR patches in shadow was investigated further. In the previous experiment, in addition to having LR, the additional LR patches had the lowest luminance in shadow. Thus, two factors varied at the same time: The range of luminances and the lowest luminance in shadow. Figure 3 shows the problem graphically.

As can be observed from the figure, Display A differs from the basic display in both the lowest luminance (which was .35 instead of .6 log units) and the luminance range (which spanned .55 instead of .3 log units). Therefore, in this experiment we controlled for these two factors.

Method

Observers. Twelve volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naive with regard to the experimental design. None of them had participated in the previous experiment.

Apparatus and Stimuli. The apparatus was the same as in the first experiment. The size of the areas of the stimuli was the same as in the first experiment (see Figure 1B). Figure 4A shows the luminances of each area of the two basic configurations and the luminances of the additional patches. Figure 4B depicts the stimuli of Experiment 2.

The two basic displays were both light/shadow configurations. The first was identical to the basic display of Experiment 1, whereas the second differed from it in that the luminances of each area were lowered by a factor of 1.5. Therefore, the two basic displays had the same luminance ratio between the two fields of illumination (10:1) and the same luminance range in shadow (.4 log units). They differed only in the absolute luminance values. We describe the first basic display as having higher luminance than the standard (HL) and the second as having lower luminance than the standard (LL).

To create the first experimental display, to the shadowed field of the HL basic display, one patch having a luminance value of 2.22 cd/m^2 was added. Therefore, this display was equal to Display A of the first experiment.

To create the second experimental display, to the shadowed field of the LL basic display, one patch having a luminance value of 1.48 cd/m^2 was added. Therefore, the two experimental displays shared the same luminance range in shadow (.55 log units), but they differed for the lowest luminance, which was 2.22 cd/m^2 (plus symbol in Figure 4B) for the first experimental display and 1.48 cd/m^2 (minus symbol in Figure 4B) for the second.

In the third experimental display, to the shadowed field of the HL basic display, one patch having a luminance value of 1.48 cd/m^2 was added. Thus, we had a larger luminance range (.85 log units) than in the previous two displays (.55 log units), but the lowest luminance was the same as that of the second experimental display (minus symbol in Figure 4B).

To summarize, the first two experimental displays shared the same (small) relative luminance range and differed in absolute luminance (plus symbol vs. minus symbol in Figure 4B). In the third experimental display, the lowest luminance in the shadowed field was the same as that in the second experimental display (minus symbol in Figure 4B), but the luminance range was larger.

In total, there were five displays: three experimental displays plus two basic ones.

Procedure. The procedure was the same as in the first experiment. The observers performed six matches for each one of the five stimuli. The whole session lasted about 20 min.

Results

Mean ratings are expressed as the difference, in log units, between the experimental displays and the displays of the corresponding basic display. Thus, for each observer the luminance values that she or he assigned to the HL basic display were subtracted from the luminance values that she or he assigned to both the first and the third experimental displays; similarly, the luminance values

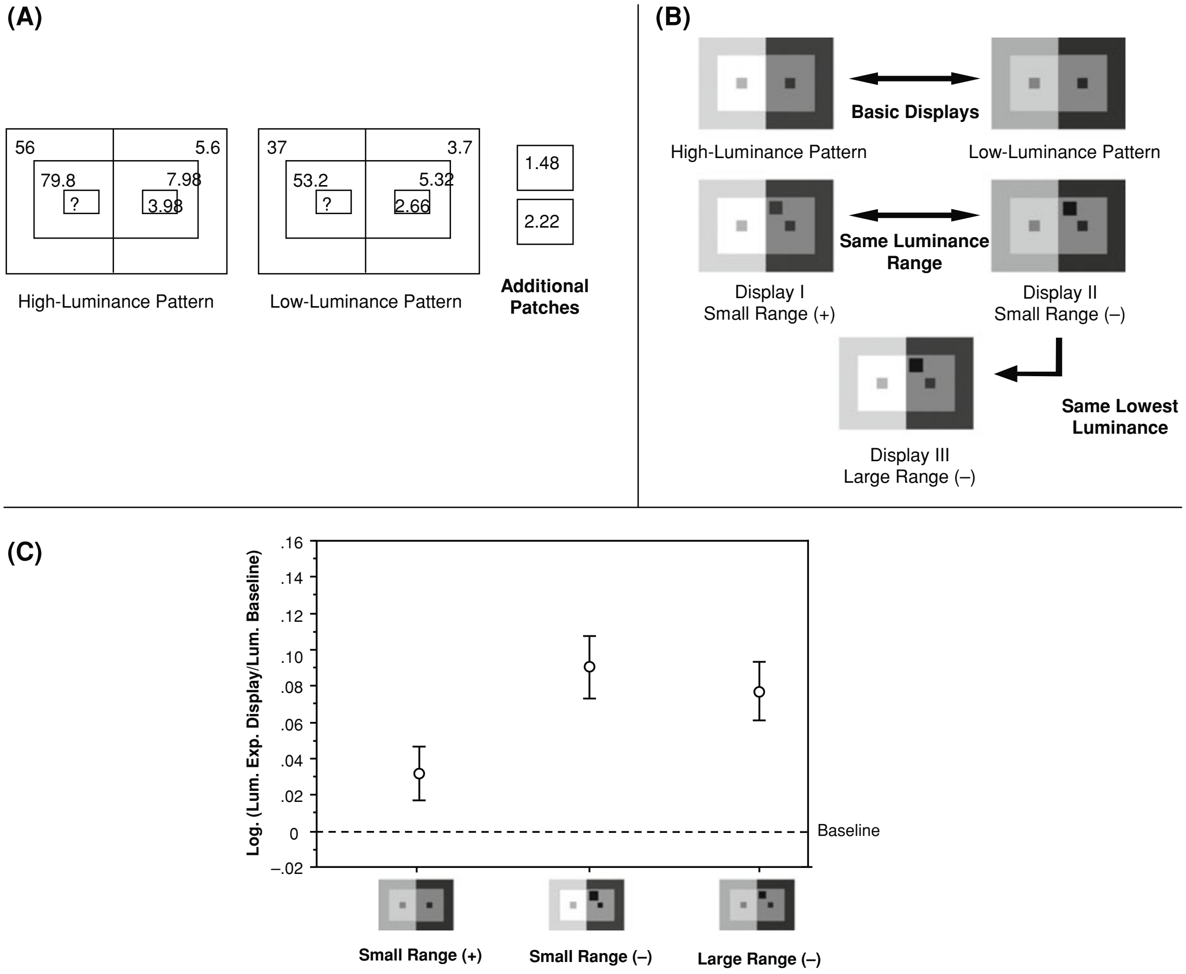

Figure 4. (A) Luminance (in cd/m^2) of the basic displays and the additional patches used in Experiment 2. (B) Experimental displays of Experiment 2. (C) Results of Experiment 2. Bars indicate standard errors.

that she or he assigned to the LL basic display were subtracted from the luminance values that she or he assigned to the second experimental display. Figure 4C reports the results of Experiment 2.

A repeated measures ANOVA revealed a statistically significant difference among the displays [$F(4,11) = 29.28$, $p < .01$]. A least squares means analysis revealed a significant difference ($p < .01$) between the first and the second experimental displays as well as between the first and the third displays. The difference between the second and third experimental displays, on the other hand, was not significant. Therefore, we find a difference only between the displays that differ in lowest luminance but not between those that differ only in luminance range.

Discussion

This experiment was conducted to help us understand whether lightness constancy is influenced more by the lowest luminance or by the range of luminances. In our experimental displays, we found that the improvement of lightness constancy with the presence of an LR patch in shadow is due to the lowest luminance and not to the luminance range.

EXPERIMENT 3

In the third experiment, we further investigated the effect of perceptual grouping on lightness constancy. In Experiment 1, the highest degree of constancy was found for Display N of the third collection of stimuli. In this display, the patches of equal reflectance belonged strongly to each other because they were adjacent. Actually, one can argue that the observers perceived the four patches as two elongated patches crossed by an illumination edge. Therefore, two displays (M and N) of Experiment 1 differed for two variables: adjacency among grouped patches (adjacency [Display N] vs. no adjacency [Display M]) and (2) illumination edge crossing grouped patches (crossing

[Display N] vs. no crossing [Display M]). Furthermore, simultaneously present in both displays were HR patches and LR patches.

In the present experiment, we manipulated three factors: adjacency among grouped patches, degree of rotation of the squares forming the grouped patches (0º vs. 45º), and reflectance of grouped patches (HR vs. LR vs. higher/lower reflectance than the standard [H/LR]).

Therefore, this experiment should answer the following questions: (1) Is the high degree of lightness constancy found in Display N due to the strength of belongingness or to the amount of illumination edge crossing the grouped patches? (2) What is the role of the reflectance assigned to the patches?

Method

Observers. Thirteen volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naive with regard to the experimental design. None of them had participated in either of the previous experiments.

Apparatus and Stimuli. Both the apparatus and the size of the areas of the stimuli were the same as in Experiment 1 (see Figure 1B). The basic display was also the same as that of Experiment 1. In each of four experimental displays, there were four additional patches: two in light and two in shadow. For each patch in shadow, there was a corresponding patch in light having a luminance value 10 times higher. Displays 1 and 2 were the same as Displays M and N of Experiment 1, respectively. Displays 3 and 4 were similar to Displays 1 and 2, but the additional patches were rotated by 45º.

Thus, in Displays 1 and 3 there was no adjacency and the illumination edge did not cross the grouped patches. In Displays 2 and 4, the grouped patches were both adjacent and crossed by the illumination edge. However, the amount of illumination edge crossing them differed, and the crossing occurred along one side of the squares in Display 2 and at only one point of the 45º rotated squares in Display 4.

The grouped patches reflectance variable had three levels: (1) HR, in which all four of the additional patches HR (7.03 cd/m^2 for the patches in shadow and 70.3 cd/m^2 for those in light); LR, in which all four of the additional patches had LR (2.22 cd/m^2 for the patches in shadow and 22.2 cd/m^2 for the patches in light); and H/LR, in which two additional patches had higher reflectance and two had lower reflectance than the standard (7.03 and 2.22 cd/m^2 for the patches in shadow, and 70.3 and 22.2 for the patches in light). For the sake of brevity, Figure 5A depicts only the four displays of the H/LR reflectance variable.

In summary, there were 13 displays: 12 experimental displays plus the basic one.

Procedure. The procedure was the same as in the previous experiments. The observers performed four matches for each of the 13 stimuli. The whole session lasted about 20 min.

Results

Figure 5B reports the results of Experiment 3. Mean ratings are expressed as the difference, in log units, between the experimental displays and the basic displays.

A repeated measures ANOVA revealed significant main effects for adjacency and reflectance [$F(1,12) = 17.6$ and $F(2,12) = 9.03$, respectively, both $ps < .005$]. The degree of rotation, however, was not significant, and neither were the interactions among the variables. A least squares means analysis revealed no significant difference between Displays 2 and 4 or between Displays 1 and 3; the differences between displays with and without adjacency were all statistically significant (all $ps < .05$). Regarding the grouped patches' reflectance, we find a significant difference between LR and HR and between H/LR and HR [$t(12) = 3.69, p < .001$ and $t(12) = 4.1$, respectively, both $ps < .001$]. The difference between LR and H/LR was not significant.

Discussion

In the present experiment, we need to clarify if the high degree of constancy recorded in Display N of Experi-

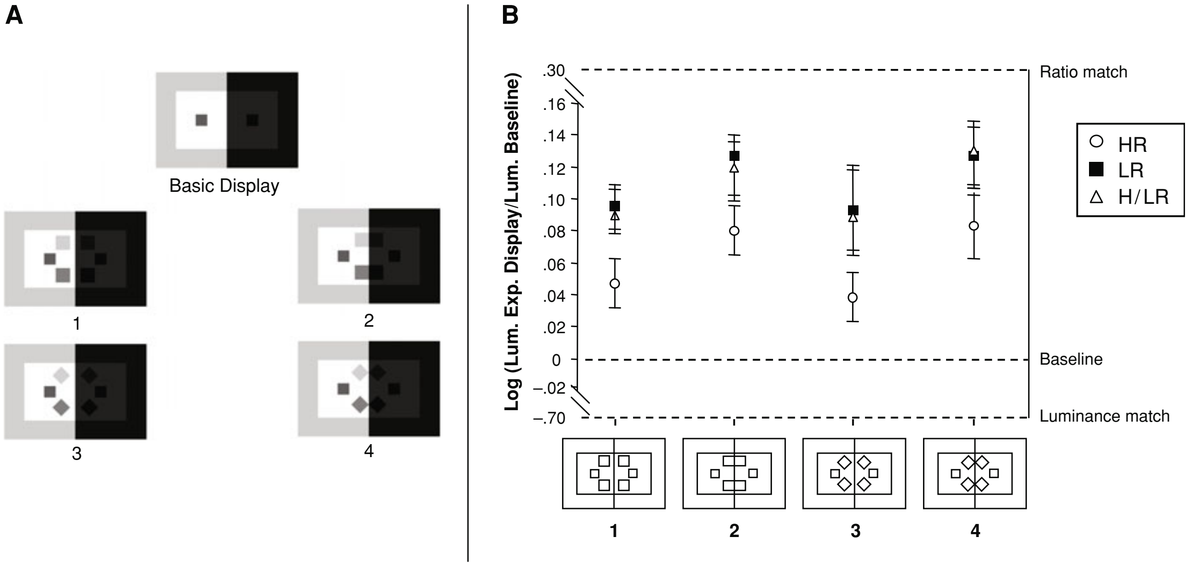

Figure 5. (A) Experimental displays of Experiment 3. (B) Results of Experiment 3. HR, all patches have higher reflectance than the standard; LR, all patches have lower reflectance than the standard; H/LR, two patches have HR and two patches have LR. Bars indicate standard errors.

ment 1 was due to the strength of belongingness between the equal reflectance patches or to the amount of illumination edge crossing the grouped patches.

We found that lightness constancy improved when the grouped patches were adjacent independent of the amount of illumination edge crossing them. Therefore, we suggest that the co-presence of equal reflectance patches in both fields of illumination affects lightness constancy more when the surfaces forming them strongly belong to each other.

Furthermore, the present experiment was conducted to test the grouped patches' reflectance. Since the highest degree of constancy is achieved in the LR and H/LR conditions, we conclude that the co-presence of equal-reflectance patches in both fields of illumination strongly improves lightness constancy if the reflectance of one or both of the added patches is lower than that of the standard. Furthermore, it should be noted that there is no statistically significant difference between the LR and H/LR conditions. Given that the number of reflectances in the H/LR condition is larger than that in the LR condition, it seems that, under our experimental conditions, the number of different reflectances in the scene is not a crucial factor for improving lightness constancy.

GENERAL DISCUSSION

The aim of the present work was to carry forward the findings of Henneman (1935) through the use of the CRT method.[2] We have found that when the reflectance of the standard is lower than that of the background, two factors seem to be relevant to optimizing illumination-independent lightness constancy in a light/shadow display: (1) one or more patches in the shadowed field, which must have the lowest luminance within the field; and (2) at least two patches having the same reflectance, one placed in the illuminated field and the other in the shadowed field. This effect is bigger if the surfaces having the same reflectance strongly belong to each other.

In the next two sections, we discuss the two factors separately.

LR Patch(es) in Shadow

The increase of constancy observed when the added patch has the lowest luminance in the shadowed field is particularly important since, until now, most of the relevant literature (Gilchrist et al., 1999; Horn, 1977; Land & McCann, 1971; Li & Gilchrist, 1999; Wallach, 1976) had focused only on the effects of the highest luminance as the most relevant factor in improving lightness constancy. According to these authors, the perceived lightness of a given surface can be predicted from the *highest luminance rule*, which states that the highest luminance in a scene is perceived as white and serves as an anchor for the lightness of the other surfaces.

Our results show that in a visual scene in which there are two fields of illumination, the lowest luminance in the low-illuminated field serves the visual system as a reference for assigning the lightness of the surfaces in that field. Furthermore, Experiment 2 shows that the effect on lightness of the lowest luminance in shadow is not due to the consequent expansion of the luminance range. Indeed, in that experiment it can be inferred that lightness constancy is influenced more by the lowest luminance than by the range of luminances. Actually, the first display of Experiment 2 shares the same luminance range as the second, but they differ in the lowest luminance in shadow. We find that the degree of lightness constancy is significantly higher in the second display, in which the lowest luminance in shadow was lower. Furthermore, the second display shares the same lowest luminance as the third, but they differ in range of luminance. From this comparison, no significant difference in the degree of lightness constancy is evident. It seems, therefore, that the LR patch in shadow improves lightness constancy independent of the expansion of the luminance range.

Similar results were found by Henneman (1935). Using a light/shadow display, he found that shifting the reflectance of what he called the "additional field objects" in shadow from gray to black improved lightness constancy. That is why, he pointed out, "the influence of these field objects is increased by strengthening the albedo[3] difference between them and the standard" (p. 53).

Since Henneman (1935) did not test the effects of HR field objects, we can now be more precise: In a light/shadow display, in which the reflectance of the standard is lower than that of the background, the influence of the field objects on standard lightness can be increased by lowering their reflectance.

It remains to be explained why the lowest luminance in shadow has such a strong effect on the lightness of the other surfaces in shadow. One could claim that when there are two frames of illumination the surface with the lowest luminance in shadow serves as an anchor for the other surfaces. This would also suggest, in opposition to the highest luminance rule, a lowest luminance rule stating that the lowest luminance in the shadowed field is perceived as black. However, this hypothesis can be rejected. Indeed, in our experiments, when the standard was the lowest luminance in shadow, this luminance was never matched with a luminance corresponding to black.

Therefore, we propose another explanation for this effect. The point of departure of our interpretation is the observation that errors in lightness constancy are systematic: At equal reflectance, shaded surfaces tend to appear darker than illuminated ones (Gilchrist et al., 1999). Furthermore, this difference depends on the surface reflectance: The lower the reflectance, the smaller the difference. In accordance with this evidence, Helson (1943), using a light/shadow paradigm, found that the degree of constancy improved when the reflectance of the standard was reduced. The discovery that LR patches hold better constancy than HR patches is surely an important cue for the understanding of lightness constancy, but it is not sufficient. Indeed, from our experiments it emerges that the LR patch improves the constancy of another surface—namely, the standard. Therefore, in order to explain this effect, additional hypotheses must be advanced. We propose that the LR patch in shadow could have an indirect effect on the lightness of the surfaces in shadow by inducing a change in the apparent illumination.

Assuming that errors in the illumination-independent lightness constancy are due to an overestimation of the illumination level of the shadowed regions, the effect of the LR patch could be that of reducing the apparent illumination level in those regions. On this basis, the albedo hypothesis (Agostini & Galmonte, 1997; Beck, 1972; Kozaki, 1965; Kozaki & Noguchi, 1976; Logvinenko & Menshikova, 1994; Noguchi & Kozaki, 1985; Oyama, 1968) states that a reduction of the amount of luminance that the visual system attributes to the illumination produces a corresponding improvement in the amount of luminance attributed to the reflectance. This would explain why one surface in shadow tends to appear lighter when an LR patch is added.

However, from other studies (e.g., Beck, 1972; Kozaki, 1973; Oyama, 1968) it emerged that the highest luminance or the range of luminances could also be a stimulus correlate of the perceived illumination. Nevertheless, our results showed that the LR in shadow affects the shadowed surface lightness even when the highest luminance is kept constant. Furthermore, Experiment 2 shows that this effect does not depend on the luminance range in the shadowed field. Therefore, we suggest that, in a bipartite field of illumination, the LR in shadow may affect the apparent illumination of the shadowed field even when both the highest luminance and the range of luminances are kept constant.

Hence, we propose that the LR in shadow affects the lightness of the shaded surfaces by enhancing the apparent illumination level of the shadowed field: The lower the luminance of the LR, the lower the apparent illumination in that field and, consequently, the higher the lightness of the shaded surfaces.

According to our assumption, in achromatic scenes with two frames of illumination, the highest and lowest luminances are used by the visual system in two different ways: The former is used to gain both the surface lightness and the apparent illumination in light, whereas the latter is used to gain the apparent illumination in shadow.

A final consideration must be made. Despite the fact that in our displays the lowest luminance was more effective than the luminance range in improving lightness constancy (see Experiment 2), we cannot rule out the possibility that even the luminance range may play some role in lightness perception. However, our data showed that equal luminance ranges can give rise to different lightness assignments if they differ in lowest luminance. In order to explain this datum, it should be noted that the lowest possible luminance has a physical constraint—namely, the absence of light (zero luminance). In fact, although the same luminance range can be obtained with an infinite number of luminance pairs, the lowest luminance cannot be below zero. Therefore, we believe the visual system evolved with this physical constraint taken into account, and uses this limit as a point of reference for inferring the intensity of the illumination.

The entrances of caves and holes are good examples of regions in which the luminance could be zero. According to our hypothesis, the best illumination intensity estimation of a shadowed field, and consequently the best degree of lightness constancy, should be obtained in cases in which there is a region having zero luminance.

Further experiments, of course, are needed to better understand the role of the lowest luminance. For example, we did not test the effect of placing the lowest luminance in light only. Indeed, in Display K of Experiment 1, the lowest luminance was present in both fields of illumination at the same time. Furthermore, in Displays C and G the additional patches had a lower reflectance (but not a lower luminance) than the standard. According to our hypothesis, if in a bipartite field the lowest luminance is placed in light only, the apparent illumination of that field should be decreased in comparison with the baseline and, as a consequence, the degree of lightness constancy should decrease because a large amount of the target luminance will be attributed to its reflectance. We are currently testing this hypothesis.

Equal Reflectance Surfaces in Both Fields of Illumination

The effect of equal reflectance surfaces in both fields of illumination is quite surprising because, starting from the proposal of Katz (1911, 1935), the number of different reflectances has generally been considered an important factor for lightness constancy achievement. Gilchrist and Annan (2002), for example, remarked that ". . . with few exceptions, articulation was operationally defined as the number of patches of different reflectance within a field of illumination" (p. 143).

However, from our experiments it emerges that lightness constancy can be improved even by reducing the number of reflectances. Consider Displays L and J of Experiment 1, in which there are two patches, one in light and the other in shadow. Since the two patches in Display L have the same luminance but different illuminations, they differ in reflectance. Therefore, in that display there are two more reflectances than in the basic display (one for each field of illumination). Even though the number of reflectances was increased, the degree of lightness constancy was the same as that observed in the basic display. In Display J, on the other hand, the total number of reflectances was reduced in comparison with that of Display L because the two patches had the same reflectance. In spite of this reduction in the number of reflectances, lightness constancy improved.

Therefore, in a light/shadow display, increasing the number of patches having different reflectances does not necessarily improve lightness constancy. For example, it is possible to improve the level of constancy even with two patches having the same reflectance. This occurs when one patch is placed in light and the other in shadow.

In order to explain this surprising effect, it should be noted that the luminance ratio between these equally reflecting patches is exactly the same as that among the differently illuminated sides of the backgrounds. Therefore, when two patches sharing the same reflectance are placed one in light and the other in shadow, what is increased is *the number of different pairs of luminances leading to the same ratio*.

We propose that the number of different pairs of luminances leading to the same ratio is a cue used by the visual system to infer the illumination intensity. Thus, we suggest that the visual system detects the coincidence represented by the equal luminance ratios and uses this information to infer the illumination intensity.

When two patches are added, one in light and the other in shadow, and they share the same luminance ratio as the other surfaces, the average luminance ratio between the shadowed and lighted sides does not change. It seems that preserving the ratio between the average luminances of the two fields of illumination is an important cue for inferring the perceived illumination. Furthermore, increasing the number of luminances within each field of illumination without altering the average luminance ratio leads to better illumination estimation.

Another interesting consideration emerged from the third experiment. Strengthening belongingness between the equal reflectance patches improved lightness constancy. Furthermore, we ascertain that this effect is not due to the amount of illumination edge crossing the added patches.

We interpret this result according to our hypothesis that the number of different pairs of luminances leading to the same ratios is a crucial cue for the illumination estimation. Increasing the strength of belongingness between the patches having the same luminance ratio as the two fields of illumination should increase the strength of this cue. Indeed, as the level of belongingness between the added patches is increased, the visual system uses their luminance ratio all the more for estimating the illumination level.

Even this second factor has to be further investigated. As was stressed above, to the basic displays we added only a few patches (four at most). We proposed that the total number of different reflectances in the light/shadow display does not affect lightness constancy. It remains to be seen whether this is a general assumption or whether it depends on the number of added patches. We are currently comparing conditions in which the lowest reflectance and level of belongingness are kept constant but the number of patches having different reflectances is increased. These experimental manipulations should help us to better understand the relation between luminance range and number of reflectances.

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NOTES

1. This is a measure of the goodness of constancy. The formula is log(ESP/LS)/log(ratio), where ESP = equivalent subjective point, LS = luminance of the standard, and ratio = luminance ratio between the high- and low-illuminated fields (which equaled 10 in our conditions). See Agostini, Soranzo, and Galmonte (1999).

2. It should be mentioned that the use of the CRT method in lightness studies has pros and cons. The main advantage of this technique is its optimal flexibility in controlling the spatial distribution of luminances. On the other hand, its main limitation is the short luminance range that is reproducible on most CRT monitors.

3. *Albedo* is a synonym of *reflectance*.

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