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

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Abstract

It has been shown that lightness constancy depends on the articulation of the visual field (Agostini and Galmonte, 1999). However, amongst 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? In the present research we explore this issue.

In three experiments, by using stimuli with two fields of illumination, we manipulated the following factors: In the first experiment we varied the number of luminances, the number of reflectances, and the number of surfaces and their spatial relationship; in the second experiment we varied the luminance range; and finally, in the third experiment, we changed the number of surfaces crossed by the illumination edge. We found that there are two relevant factors to optimize lightness constancy: i) The lowest luminance in shadow, and ii) The co-presence of equal reflectance patches in both fields of illumination; this effect is bigger if these patches strongly belong to each other. We interpret these findings within the albedo hypothesis.

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Illumination-independent lightness constancy refers to the property of the visual system to perceive constant surface lightness in spite of large changes in the 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 changing the intensity of light falling on surfaces, the amount of light reaching the retina (i.e. the luminance) is correspondingly modified. We should expect**,** then, a different lightness for each different condition of illumination. However, this is not the case. Under many visual conditions, lightness undergoes very little variation even when the illumination is largely changed.

This phenomenon has been extensively and systematically studied starting from the second half of the 19th century. The most representative theories were developed by Helmholtz and Hering. Helmholtz (1866) 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 lightning conditions change, we unconsciously use what we have learned to maintain the value of lightness constant. Hering (1878), instead, 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. Successively, however, many authors stressed more the relative rather than the absolute luminance. Wallach (1948) was probably the most representative scientist of this point of view. He underlined 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 is predictable by calculating the ratio between the luminance of an object and the luminance of the fields adjacent to it. For this reason Wallach's 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 can not be exactly predicted by their luminance ratio. Previously, Katz (1911, 1935) devised an experimental technique to systematically investigate lightness constancy: He placed two Maxwell disks on a homogeneous achromatic background with a vertical screen placed between them. Light coming from one side fully illuminated one disk and it was partially cut off from the other. The task was to adjust the illuminated disk to equate the lightness of the other. According to Gilchrist and Annan (2002) we will call this procedure the "light/shadow method". In such a simplified condition, Katz found that the two disks are perceived to be equal in lightness when the highly illuminated disk has been set on a lower reflectance value compared to the other. The author demonstrated, therefore, that the lightness constancy phenomenon doesn't appear in all conditions or, by using his own words: "…we see that it would be false to conclude […] that there is ideal colour constancy" (1935, p. 82).

Looking for the factors that improve the degree of lightness constancy, Katz introduced some variables, such as subject's age, peripheral vision, presentation time, etc.; among those variables he included also visual field articulation. In one variation of the light/shadow method, he replaced the homogenous gray background behind the disks with a chart of 48 gray chips ranging from black to white. In this condition, lightness constancy increased compared to the condition with a homogeneous background. Referring to this condition, Katz spoke for the first time of articulation.

Following on Katz's 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 presents in the visual scene.

In 1935, Henneman performed a series of experiments on lightness constancy using a setting very similar to the light/shadow method introduced by Katz. 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, was the highest reflectances in the scene (i.e. both white). Consequently, a target adjustment set to white would correspond to “ideal” constancy, while 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". Amongst these experiments, two are the most pertinent for the present research. In one of them, the author manipulated the number of additional medium gray patches placed in the shadowed field; while in the other experiment he manipulated the reflectance of these patches. Compared to the condition without any additional objects, Henneman found that the adjustments of the observers moved toward white, that is, toward the ideal constancy when i) The number of the additional patches was increased from one to three, and ii) The reflectance difference between the additional objects and standard, was increased.

More recently, psychophysical studies take advantage of the CRT technology to investigate color constancy. Indeed, as pointed out by Bruno (1994), the impoverished degree of ecological validity of the CRT method is compensated by the flexibility in controlling the spatial distribution of luminances.

Benefiting from CRT simulations, Arend and Goldstein (1987) found marked failures of lightness constancy when the experimental display was poorly articulated while 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 are too simple, observers asked to match lightness performed instead, local brightness matches.

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

The aim of the present research was to continue with Henneman’s work. Actually, in his experiments on field complexity, the author did not test the effects produced by the presence of additional objects having a reflectance higher than that of the standard;

furthermore, he placed these objects in the shadowed field only. In the present work we tried to fill these gaps.

By simulating the light/shadow paradigm on a CRT monitor, we measured the effects of additional objects having reflectance higher than that of the standard which could have been placed either in one or the other field of illumination, or in both fields simultaneously. In addition, we controlled the perceptual belonginess among the additional objects.

EXPERIMENT 1

Method

Observers. 12 volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naïve as the regard to the experimental design.

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

Figure 1 about here

A rectangle was drawn also on the right side of the screen; its luminance was equal to 7.98 cd/m^2. At this point, the screen was divided in 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 (referred as "inner" and "outer" background) under two different levels of illumination. We will, then, name the left side of the screen the "light field" and the right side the "shadow field". Finally, two squares (1° x 1° visual angle each) were placed in the middle of the two inner backgrounds: The Square on the left was the target; while that on the right was the standard. The luminance of the standard was 3.98 cd/m^2.

In order to get a comparison term we had also a control condition that was 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, the reflectance, and the position of additional patches (1.5° x 1.5° visual angle) placed always in the inner background of the basic configuration.

In the interest of clarity, we arranged the experimental configurations in three collections of stimuli on the basis of the variables that have been manipulated.

1st collection of stimuli: From (a) to (h). In the stimuli of the first collection the additional patches lay either in light or in shadow. In display (a) and (b), there was only one additional patch in shadow. In display (a), the added patch (2.22 cd/m^2) had a lower reflectance (LR) compared to that of the standard, while in display (b), the added patch (7.03 cd/m^2) had a higher reflectance (HR) compared to that of the standard. The luminance difference in logarithmic units between the standard and the LR patch was the same as that one between the HR patch and the standard (i.e., 0.25). 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 then that of the LR patch in display (a), while in display (d), the luminance of the added patch (70.3 cd/m^2) was 10 times higher then that of the HR patch in display (b).

Displays from (e) to (h) were similar to displays from (a) to (d), except that in each display there were two additional patches, instead than one. This second additional patch was placed 2° of visual angle below the other patch, and shared with it the same size and luminance.

2nd collection of stimuli: From (i) to (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, while the one in light was 22.2 cd/m^2. Having the two patches the same luminance ratio of the two fields of illumination, they simulated equal reflectance. Therefore, there was only one reflectance more compared to the basic condition. The same holds in display (j) with a different luminance of the patches (7.03 cd/m^2 shadow and 70.3 cd/m^2 light). In display (k), instead, the luminance of both the additional patches was 2.22 cd/m^2. In this way we added only one luminance to the basic condition, but we simulated two different reflectances. Display (l) was equal to display (k), but the luminance of both the additional patches was 7.03 cd/m^2.

3rd collection of stimuli: (m) and (n). In both the 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 compared to the basic condition.

In display (m) the patches with the same simulated reflectance were separated on the horizontal axis, whether in display in display (n) they were adjacent. In this way, we manipulated the strength of perceptual organization between the additional patches simulating the same reflectance but lying in different field of illumination. We used the Gestalt factors of proximity in display (m), and good continuation in display (n).

Summarizing, there were altogether 16 stimuli: 14 experimental conditions plus the basic and the control configurations.

Procedure. Observers viewed the stimuli, presented in random order, in a darkened room from 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. Pressing another button signaled that a satisfactory match was 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 observers to make the target patch "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, so they provided 64 adjustments. Each display was left on the screen as long as needed to produce the match. The whole session lasted about half an hour.

Results

Figure 2 about here

Mean ratings are expressed as the difference, in logarithmic units, between the experimental configurations and the basic condition, that served as baseline. The basic condition holds a constancy value[1] of 0.62 in an interval ranging from 0 (luminance match) to

[1] This is a measure of the goodness of constancy. The formulae is the subsequent:
log.(*ESP*/*LS*)/log.(*Ratio*)
Were:
ESP = equivalent subjective point.
LS = Luminance of the standard.
Ratio = luminance ratio between the high and low illuminated field (that was equal to 10 in our conditions).
See Agostini, Soranzo, Galmonte (1999) for details.

1 (ratio match), while the control condition showed a value of 0.32. These data suggest that, although the impoverished degree of ecological validity of the CRT method, the simulation of two fields of illumination was satisfactory.

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

In the graphs of figure 2 the dashed line, labeled *ratio match*, refers to the value obtained by subtracting, in log. units, the luminance that it would have been registered if the observers would have performed a perfect ratio match (i.e. 39.8 cd/m^2) and the average luminance actually registered in the basic condition. Similarly, the dashed line, labeled *luminance match*, refers to the value obtained by subtracting, in log. units, the luminance that it would have been registered as if the observers would have performed a perfect luminance match (i.e. 3.98 cd/m^2) and the average luminance actually observed in the basic condition.

1st collection of stimuli: From (a) to (h). In the collection of stimuli from (a) to (h) we distinguished three variables. They are listed, together with their levels, in the following table.

Table 1 about here

Figure 2a plots the results relative to the first collection of stimuli. A repeated measure ANOVA reveals a significant main effect for both the position and the luminance value [$F_{(1,11)} = 16.43$; $p. < 0.05$ and $F_{(1,11)} = 6.88$; $p. < 0.05$ respectively]. The interaction between the two factors is also significant [$F_{(1,11)} = 22.74$; $p. < 0.05$]. The main effect of the number of surfaces is not statistically significant as well as the interaction between this factor and the other two. The graph shows that in the light/shadow display the degree of lightness constancy increases only adding one or two LR patches in the shadowed field.

2nd collection of stimuli: From (i) to (l). In collection of stimuli from (i) to (l) there were two variables:

Table 2 about here

Figure 2b shows the results of the second collection of stimuli. A repeated measure ANOVA indicates that when the luminances added to the basic condition are two, lightness constancy significantly increases compared to the conditions where the added luminance is only one [$F_{(1,11)} = 15.31$; $p. < 0.05$]. The main effect of the luminance in shadow variable is also statistically significant [$F_{(1,11)} = 16.63$; $p. < 0.05$]. The interaction between the two variables is not significant.

Figure 2b also illustrates that in condition (i), where there are two luminances and the luminance in shadow is lower than that of the standard, lightness constancy improves compared to the basic condition [$t_{(11)} = 2.64$; $p.< 0.05$].

There is a significant difference also between condition (j) and (l) which differs only for the luminance of the patch in light [two vs. one; $t_{(11)} = 3.14$; $p. < 0.05$].

There is no difference between display (l) and the basic condition.

Therefore, adding LR patches in shadow, by its self, is sufficient to improve lightness constancy independently from the presence of patches in light. Additionally, compared to the first collection of stimuli, lightness constancy increases also when a HR patch is added in shadow, but only if there is, at the same time, another patch in light sharing the same reflectance.

3rd collection of stimuli: (m) and (n). In collection of stimuli (m) and (n) there was one variable:

Table 3 about here

Figure 2c shows the results of the third collection of stimuli. A t test shows a statistically significant effect of perceptual organization [$t_{(11)} = 2.5$; $p. < 0.05$]. Compared to the basic condition**;** the graph shows an enhancement of lightness constancy for both the conditions. Furthermore, these date suggest that the constancy increases even more if the patches sharing the same reflectance (see results of the 2nd collection of stimuli) strongly belong to each other.

Discussion

In this experiment, we extended Henneman's research (see introduction) including a number of conditions in which the standard patch was not the highest reflectance within the light/shadow display.

Lightness constancy has been systematically studied by manipulating:

a) The number and the reflectance of the additional patches, placed either in light or in shadow, and

b) The luminance ratio and the perceptual organization of the additional patches placed simultaneously in both fields of illumination.

Starting from the basic condition, in the first collection of stimuli we manipulated the number (one or two), the position (light or shadow) and the reflectance (higher reflectance – HR- or lower reflectance – LR - than that of the standard) of the additional patches. The results indicate that lightness constancy improves, compared to the basic condition, when the added patches are placed in shadow, and their reflectance is lower than that of the standard. Adding patches in light (independently whether they were HR or LR), instead, does not affect the lightness of the standard. Also the number of the additional patches placed in shadow does not play any role. In fact, increasing the number of the LR patches from one to two does not make any difference on lightness constancy.

In the second collection of stimuli we manipulated the luminances of two additional patches placed one in light and the other in shadow**,** respectively. The results suggest that lightness constancy is enhanced, compared to the basic condition, when the two added patches share the same reflectance. This effect occurs independently from the reflectance value of the patches. On the contrary, if the added patches share the same luminance, lightness constancy improved, compared to the basic condition, only when the reflectance of the patch in shadow is lower than that of the standard. Therefore, it seems that the number of reflectances (but not luminances) is not a critical factor for lightness constancy improvement while lightness constancy is affected from the number of equal reflectances placed in both fields of illumination. It should be noted that these reflectances share the same luminance ratio between the fields of illumination. Therefore, we submit that lightness constancy improves when the added patches lie in both the 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 contemporaneously present in both fields of illumination.

Compared to the basic condition, we found that lightness constancy significantly improved in both the conditions. Furthermore, in condition (n) lightness constancy was significantly higher than those observed in all the conditions of this experiment. It is plausible to assume that the strength of belongingness between the patches was higher in display (n), where the four patches are perceived as two unitary objects, than in condition (m). From the second collection of stimuli we observed that lightness constancy improves when surfaces having the same reflectance are placed in both fields of illumination, but from the third collection of stimuli, we can further add to this observation, that lightness constancy is even better if these surfaces strongly belong to each other.

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Summarizing, two main factors seem to be relevant to optimize lightness constancy in a light/shadow display when the standard patch had a lower reflectance compared to that of the background:

1. The presence of LR patches in shadow;
2. The co-presence of equal reflectance patches in both fields of illumination. This effect is bigger if these surfaces strongly belong to each other.

The following two experiments are aimed to further investigating these two factors.

EXPERIMENT 2

In the second experiment the effect of the LR patches in shadow was further investigated. Actually, in the first experiment, the additional LR patches besides having a lower reflectance value than that of the standard, they were also the lowest luminance in shadow. In this way, two factors varied at the same time: The range of luminances and the lowest luminance in shadow. Figure 3 shows graphically the problem.

Figure 3 about here

As can be observed from the figure, display (a) differs from the basic condition for both the lowest luminance (that was 0.35 instead of 0.6, in log. units) and for the luminance range (that was 0.55 instead of 0.3).

Therefore, in this experiment, we controlled for these two factors.

Method

Observers. 12 volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naïve as the 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 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 the second experiment.

Figure 4 about here

The two basic configurations were both light/shadow type displays. The first one was a copy of the basic configuration of the first experiment, while the second one differs from the previous for the fact that the luminances of each area were lowered by a factor of 1.5. Therefore, the two basic configurations shared the same luminance ratio between the two fields of illumination (10 to 1) and the same luminance range in shadow (0.4 log. units). They differed only for the absolute luminance values. We name "high luminance" (HL) the first basic condition and "low luminance" (LL) the second one.

In the first experimental display there was, in the shadowed field of the HL basic condition, one patch having a luminance value of 2.22 cd/m^2. Therefore, this display was equal to the display (a) of the first experiment.

In the second experimental display there was, in the shadowed field of the LL basic condition, one patch having a luminance value of 1.48 cd/m^2. Therefore, these two experimental conditions shared the same luminance range in shadow (0.55 log. units), but they differed for the lowest luminance that was 2.22 cd/m^2 (plus symbol on figure 4b) for the first experimental condition and 1.48 cd/m^2 for the second one (minus symbol on figure 4b).

In the third experimental display there was in the shadowed field of HL basic condition, one patch having a luminance value of 1.48 cd/m^2. In this way, we had a larger luminance range (0.85 log. units – Large Range) compared to that of the other two displays (0.55 log. units, Small Range), but the lowest luminance was the same as that of the second experimental display (marked with the minus symbol).

Summarizing, the first two experimental conditions shared the same relative luminance range (Small Range) and differed for the absolute luminance (plus vs. minus). In the third experimental condition, the lowest luminance in the shadowed field was the same as in the second experimental condition (minus) but the luminance range was larger (Large Range).

In total, there were 5 stimuli: 3 experimental conditions plus 2 basic configurations.

Procedure. The procedure was the same as in the first experiment. Observers performed 6 matches for each one of the 5 stimuli. The whole session lasted about 20 minutes.

Results

Mean ratings are expressed as the difference, in logarithmic units, between the experimental displays and the comparable basic condition. Thus, for each observer, the luminance value that she or he assigned to the HL basic condition was subtracted from the luminance values that she or he assigned to both the first and the third experimental conditions; while the luminance value that she or he assigned to the LL basic condition was subtracted from the luminance that she or he assigned to the second experimental condition. Figure 4c reports the results of the second experiment.

A repeated measure ANOVA reveals a statistically significant difference among the conditions [$F_{(4,11)} = 29.28$ p. < 0.01]. A last square means analysis reveals a significant difference (with a p value lower than 0.01) between the first and second experimental conditions as well as that between the first and the third conditions. The difference between the second and third experimental conditions, instead, is not significant. Therefore, we find a difference only between the conditions that differ for the lowest luminance but not between those conditions that differ for the luminance range only.

Discussion

This experiment was run in order to understand whether lightness constancy is more influenced by the lowest luminance or by the range of luminances. Under our experimental conditions, we found that the improvement of lightness constancy due to the presence of a LR patch in shadow is due to the lowest luminance and not to the luminance range.

EXPERIMENT 3

In the third experiment we further investigate the role of perceptual grouping on lightness constancy. In the first experiment, the highest degree of constancy was found for display (n) of the third collection of stimuli. In this condition, the equal reflectance patches belong strongly to each other because they were adjacent. Actually, one can argue that the four patches were perceived by the observers as two elongated patches crossed by an illumination edge. Therefore, two conditions (n) and (m) of the first experiment differed for two variables: 1) Adjacency among grouped patches [“adjacency” display (n), “no adjacency” display (m)], and 2) illumination edge crossing grouped patches [“crossing” display (n), “no crossing” display (m)]. Furthermore, in both displays there were, at the same time, patches having higher reflectance and patches having lower reflectance compared to that of the standard.

In the present experiment we manipulated three factors: Adjacency among grouped patches (2 levels – adjacent, no adjacent), degree of rotation of the squares forming the grouped patches (2 levels – 0°, 45°), grouped patches reflectance (3 levels – High Reflectance: HR, Low Reflectance: LR, High/Low Reflectance: H/LR).

Therefore, this experiment should answer to 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. 13 volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naïve as the regard to the experimental design. None of them had participated in the previous experiments.

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 5 about here

The basic configuration was the same as the basic configuration of the first experiment. We had four experimental conditions. In each experimental condition 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. Conditions 1 and 2 were the same as conditions (m) and (n) of the first experiment, respectively. Conditions 3 and 4 were similar as conditions 1 and 2, but the additional patches were 45 degrees rotated.

In this way, in conditions 1 and 3, there were no adjacency and the illumination edge was not crossing the grouped patches. In condition 2 and 4, the grouped patches were both adjacent and crossed by the illumination edge, but the amount of illumination edge crossing them was different: Along one side of the squares for condition 2, and only at one point of the 45 degrees rotated squares for condition 4.

We had three levels of the grouped patches reflectance variable:

High reflectance (HR). The four additional patches had a reflectance value higher than that of the standard (7.03 cd/m^2 for the patches in shadow, and 70.3 cd/m^2 for those in light).

Low reflectance (LR). The four additional patches had a reflectance value lower than that of the standard (2.22 cd/m^2 for the patches in shadow, and 22.2 cd/m^2 for the patches in light).

High and Low reflectance (H/LR). Two additional patches had higher reflectance, and two had lower reflectance than that of 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 conditions of the H/LR reflectance variable.

In sum there were 13 stimuli: 12 experimental conditions plus the basic configuration.

Procedure. The procedure was the same as in the previous experiments. Observers performed 4 matches for each of the 13 stimuli. The whole session lasted about 20 minutes.

Results

Figure 5b reports the results of the third experiment. Mean ratings are expressed as the difference, in logarithmic units, between the experimental configurations and the basic condition.

A repeated ANOVA measure reveals a significant main effect for “adjacency” and “reflectance” [$F_{(1,12)} = 17.6$; $p. < 0.005$, and $F_{(2,12)} = 9.03$; $p. < 0.005$ respectively]. The “degree of rotation”, instead, is not significant and neither are the interactions among the variables. A last square means analysis doesn’t reveal a significant difference between condition 2 and 4 and between conditions 1 and 3; while the comparisons among displays with or without adjacency are all statistically significant with a p value lower than 0.05.

Regarding the grouped patches reflectance, we find a significant difference between LR vs. HR and between H/LR vs. HR [$t_{(12)} = 3.69$ p. < 0.001 and $t_{(12)} = 4.1$ p. < 0.001, respectively]. The difference between LR vs. H/LR is not significant.

Discussion

In the present experiment we need to clarify if the high degree of constancy, registered in display (n) of the first experiment, was due to the strength of belongingness between the equal reflectance patches, or to the amount of illumination edge crossing the grouped patches.

We find that lightness constancy improves when the grouped patches are adjacent, independently from 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 run to test the grouped patches' reflectance. Being that the highest degree of constancy is achieved in conditions LR and H/LR, 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 the added patches is lower than that of the standard. Furthermore, it should be noted that there is no difference between conditions LR and H/LR. Given that the number of reflectances in the H/LR condition is larger than that in the LR one, it seems that, under our experimental conditions, the number of different reflectances in the scene is not a crucial factor to improve lightness constancy.

GENERAL DISCUSSION

The aim of the present work was to carry forward the findings of Henneman (1935), by benefit of the CRT method[2]. We have found that when the reflectance of the standard is

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

lower than that of the background, two factors seems to be relevant to optimize illumination-independent lightness constancy in a light/shadow display:

1. One or more patches in the shadowed field which must be the lowest luminance within the field;

2. At least two patches having the same reflectance, one placed in the illuminated 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 will discuss the two factors separately.

The LR patch(es) in shadow

The increase of constancy observed when the added patch is the lowest luminance in the shadowed field is particularly important since, until now, most of the relevant literature (Land & McCann, 1971; Wallach, 1976; Horn, 1977; Li and Gilchrist, 1994; Gilchrist at all., 1999) 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 is predictable by the "Highest Luminance Rule" stating that the highest luminance in a scene is perceived as "white" and serves as anchor for the lightness of the other surfaces.

Our results show that in a visual scene where there are two fields of illumination, the lowest luminance in the low illuminated field serves the visual system as a reference to assign the lightness of the surfaces in that field. Furthermore, from the second experiment it emerges 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 more influenced by the lowest luminance rather than the range of luminances. Actually, looking at the second experiment, the first condition shares the same luminance range as the second one, but they differ for the lowest luminance in shadow. We find that the degree of lightness constancy is significantly higher in the second condition, where the lowest luminance in shadow was lower. Furthermore, the second condition shares the same lowest

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luminance as the third one, but they differ for the range of luminances. From this comparison no significant difference in the degree of lightness constancy emerges. It seems, therefore, that the LR patch in shadow improves lightness constancy independently from the expansion of the luminance range.

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

Since Henneman did not test the effects of "field objects" having a reflectance value higher than that of the standard, 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 explain why the lowest luminance in shadow has a so strong effect on the lightness of the others surfaces in shadow.

One could claim that when there are two frames of illuminations the lowest luminance in shadow serves as an anchor for the other surfaces. This would suggest, in opposition to the highest luminance rule, also 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 starting point of our interpretation is the observation that errors in lightness constancy are systematic: If equal in 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 lower the difference. In agreement with this evidence, Helson (1943), using a light/shadow paradigm, found that the degree of constancy improves when the reflectance of

[3] Albedo is synonymous of reflectance.

the standard was reduced. The discovery that low reflectance patches hold better constancy than high reflectance ones, is securely 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, the standard. Therefore, in order to explain this effect, some additional hypothesis 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 LR patch could be that of reducing the apparent illumination level in those regions. On this basis, the albedo hypothesis (Kozaki, 1965; Oyama, 1968; Beck, 1972; Kozaki & Noguchi, 1976; Noguchi & Kozaki, 1985; Logvinenko & Menshikova, 1994, Agostini & Galmonte, 1997) states that a reduction of the amount of luminance that the visual system attributes to the illumination produces a correspondent improvement in the amount of luminance attributed to the reflectance. This would explain way one surface in shadow tends to appear lighter when a LR patch is added.

However, from other studies (as, for example, Kozaki, 1973, Oyama, 1968; and Beck, 1972) it emerged that also the highest luminance or the range of luminances could be a stimulus correlate of the perceived illumination. Nevertheless, from our results it emerged that the LR in shadow affects the shadowed surface lightness even when the highest luminance is kept constant. Furthermore, from the second experiment, it came out that this effect does not depend from 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 surface lightness of the shaded surfaces by enhancing the apparent illumination level of the shadow 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 the lowest luminance are used by the visual system in two different ways: The first is used to gain both the surface lightness and the apparent illumination in light, while the second is used to gain the apparent illumination in shadow.

A last consideration must be made. In spite of the fact that in our conditions the lowest luminance was more effective than the luminance range in improving lightness constancy (see 2nd experiment), we do not exclude that even the luminance range plays some role in lightness perception. However, from our data it emerged that equal luminance ranges could give rise to different lightness assignment if they differ in the lowest luminance. In order to explain this data it should be noted that the lowest possible luminance holds a physical constraint that is the absence of light (zero luminance). In fact, while the same luminance range can be obtained with an infinite number of luminance couples, the lowest luminance can not be lower than zero. Therefore, we retain that the visual system evolved considering this physical constraint and used this limit as a point of reference for inferring the intensity of the illumination.

The entry of caves or of 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 the lowest luminance standing in light only. Indeed, in condition “k“ of the first experiment, the lowest luminance was present in both fields of illumination at the same time. Furthermore, in conditions “c” and “g” the additional patches had a lower reflectance (not 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 compared to the base line 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 actually testing this hypothesis.

Equal reflectance surfaces in both fields of illumination

The effect of equal reflectance surfaces in both fields of illumination is **a** quite surprising because, starting from the proposed of Katz (1911, 1935), the number of different reflectance**s** 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" (page 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 the first experiment in which there are two patches, one in light and the other in shadow. Having the two patches in display "l" the same luminance but standing in different illumination, they differ in their reflectance. Therefore, in that condition, there are two reflectances more in comparison to the basic condition (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 condition. In display "j", on the contrary, the whole number of reflectances was reduced compared to display "l" because the two patches had the same reflectance. In spite of this reduction in the number of reflectances, lightness constancy improves.

Therefore, in a light/shadow display, increasing the number of patches having different reflectance 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 equal reflecting patches is exactly the same as that occurring 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 couples of luminances leading to the same ratio*.

We propose that the number of different couples 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 with 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 luminance 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 luminance average ratio leads to better illumination estimation.

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

We interpret this result in agreement with our hypothesis that the number of different couples 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 of 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 stressed before, to the basic conditions we added only a few patches (four at most). We proposed that the whole number of different reflectances in the light/shadow display does not affect lightness constancy. It remains to be understood if this is a general assumption or if it depends on the number of added patches. We are actually comparing conditions in which the lowest reflectance and belonginess are kept constant, but the number of patches having different reflectances is increased. These experimental manipulations should help to better understand the relation between luminance range and the number of reflectances.

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VARIABLES	Levels
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	Low Reflectance patch (a, c, e, g)
	High Reflectance patch (b, d, f, h)

Table 1: Variables and levels of the first collection of stimuli.

VARIABLES	Levels
Number of luminances	Two (i, j)
	One (k, l)
Luminance in shadow	Higher then the standard (j, l)
	Lower then the standard (i, k)

Table 2: Variables and levels of the second collection of stimuli.

VARIABLES	Levels
Perceptual organization	Proximity (m)
	Good continuation (n)

Table 3: Variables and levels of the third collection of stimuli.

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FIGURE CAPTIONS

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Figure 1. a) Luminance of the stimuli of the 1st experiment (cd/m^2).

b) Size of the stimuli of the 1st experiment (degrees of visual angle).

c) Experimental displays of the 1st experiment. Displays are arranged in 3 collections on the basis of the variables that have been manipulated (see text for details).

Figure 2. a) The results of the 1st collection of stimuli (from display a. to h.) of the 1st experiment. Bars indicate standard errors.

b) The results of the 2nd collection of stimuli (from display i. to l.) of the 1st experiment. Bars indicate standard errors.

c) The results of the 3rd collection of stimuli (display m. and n.) of the 1st experiment. Bars indicate standard errors.

Figure 3. Comparison between the range of luminances in the shadowed field of the basic Condition and of display (a) of the first experiment.

Figure 4. a) Luminance of the basic conditions and of the additional patches used in the 2nd experiment (cd/m^2).

b) Experimental displays of the 2nd experiment.

c) The results of the 2nd experiment. Bars indicate standard errors.

Figure 5. a) Experimental displays of the 3rd experiment.

b) The results of the 3rd experiment. Bars indicate standard errors.

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