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The effect of illumination on gray color

Osvaldo Da Pos,* Linda Baratella, and Gabriele Sperandio

University of Padua, Italy

The present study explored the perceptual process of integration of luminance information in the production of the gray color of an object placed in an environment viewed from a window. The mean luminance of the object was varied for each mean luminance of the environment. Participants matched the gray color of the object with that of Munsell chips in a viewing box. The results show that the Munsell values so obtained are linear measures of gray color. The results support the possibility that the gray color of the object derives from an additive integration of the information about mean luminance of the object and about mean luminance of the environment, with the weights of this information varying with the mean luminances.

The gray color of an object and the illumination of the environment in which the object is placed seem to be produced at least in part by a common perceptual process (Bergström, 1977, 1994; Kozaki & Noguchi, 1976; Logvinenko & Menshikova, 1994; Rutherford & Brainard, 2002; Soranzo, Galmonte, & Agostini, 2009). This process is often studied using simple two-dimensional patterns. However, these patterns are not ecologically representative and may involve significant alterations in gray color due to local changes in the geometries of the patterns rather than to the process producing color and illumination (Bressan, 2006; Gilchrist, 2006; Kanizsa, 1979; Koffka, 1935). In the following experiment we undertook the study of the integration of luminance information in the production of the gray color and illumination of an object in a setting more ecologically representative than the settings typically reported in the literature.

Suppose standing in front of a window and seeing a gray object in the environment situated outside the window. Let L_O and L_E denote the mean luminance of this object and the mean luminance of this environment, respectively. If gray color and illumination depend on a single perceptual process, it seems plausible that both the gray color and the illumination of

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* We would wish to thank Norman H. Anderson and Sergio C. Masin for useful comments on earlier versions of this paper. Correspondence to Osvaldo Da Pos, Department of General Psychology, University of Padua, via Venezia 8, 35131 Padova, Italy. E-mail: osvaldo.dapos@unipd.it

the object result from the integration of quantitative information about L_O and about L_E. This quantitative information is a function F of L_E and of L_O, that is, $F(L_E)$ and $F(L_O)$, respectively. In this study, we focus only on the gray color of the object. In general, we propose that this color G is

$$G = w_1 \cdot F(L_E) + w_2 \cdot F(L_O) \quad (1)$$

with w_1 and w_2 weights. The following experiment was designed to test this model.

EXPERIMENT 1

Participants. The participants were four persons experienced in making psychophysical judgments. All of them had normal or corrected to normal vision and none used glasses.

Stimuli. Cylinders with width and height of 20 and 21 cm, respectively, were used as stimuli. Each cylinder was held up by a thin shaft in the middle of a table. The background of the cylinder was a fontoparallel two-dimensional achromatic poster showing a three-dimensional urban scene with surfaces varying from black to white. It was placed at a distance of 35 cm for the cylinder. Cylinders were presented individually or in pairs. A theatrical spot light, positioned laterally at a distance of 7 m, illuminated only the cylinders and the poster. The back of each cylinder was cut off to prevent the cylinder from casting a shadow on its neighbor cylinder. The table was black with black panels around it used to prevent light reflection.

Using achromatic filters placed in front of the theatrical spot light, the intensity of the projected light was set at 200, 600, or 2,200 lx. Each of these intensities generated a different mean luminance of the poster, L_E. For each intensity of the projected light, the mean luminance of the cylinder, L_O, was varied by covering the cylinder with uniform gray paper with reflectance of 0.04, 0.12, 0.15, 0.4, or 0.89.

The participant was situated at a distance of 2.80 m from the stimuli. At a distance of 1 m from the participant, a frontoparallel black panel with a rectangular 1 × 0.7 m window was placed between the participant and the stimuli. This panel allowed the participant to see only the poster and the cylinders in front of the poster. The cylinders looked as if they were suspended in midair. Changes in illumination level of the stimuli did not appreciably alter the color of the panel from the viewpoint of the participant. Behind the window, a translucent tent was used to hide the operations of changing of stimuli. The translucency of the tent allowed keeping a rather constant level of light adaptation of the participant's eyes when the participant was waiting for the next stimulus to be presented.

A 51 × 25 × 45 cm viewing box was used to measure the gray color of the cylinders. The box had one hole in the middle of one wall. A scuba diving mask was fit in this hole such that the face of the participant could be placed in the mask and the participant could see inside the box without being affected by the illumination of the experimental room. Hidden from view, a fluorescent tube (18 W, D65 simulator) illuminated the inside of the box with constant illumination level of 435 lx. Each of the internal walls of this box was painted black. When the participant was looking inside the box, the participant saw a white 25 × 50 cm board with reflectance of 0.89 located on a frontoparallel plane at 35 cm from the eyes. On this board, thirty-seven 20 × 50 mm rectangular Munsell chips with Munsell value varying in steps of 0.5 from 1 to 9.5 were staggered in four parallel horizontal rows with Munsell values increasing from right to left.

Procedure. There were five sessions each of which took place in one of five consecutive days. In each session, for each of the three possible illumination levels, each cylinder was presented individually or paired with one of the other four cylinders. Thus, each participant observed each single cylinder a total of 25 times for each of the three illumination levels. Orders of illumination levels, cylinders, and positions of cylinders were random.

On each trial, the participant was asked to look at the cylinder and then look inside the viewing box and select the Munsell chip with the gray color most similar to that of the cylinder. For each cylinder, the participant could repeat this comparison as many times as needed.

RESULTS

Figure 1 shows the mean Munsell value matched to the gray of a cylinder as a function of the reflectance of the cylinder for each illumination level. The curves fitting the data points are least-squares logarithmic curves. It may be seen that the fit of these curves is rather good in agreement with previous general findings (Judd & Wyszeski, 1963).

The results in Figure 1 support the general model expressed by Equation 1. The mean Munsell value, a measure of the gray color of the cylinder, increased both with the mean luminance of the cylinder and with the mean luminance of the background.

A 3 (illumination level) × 5 (reflectance) analysis of variance showed that the effects of illumination level and reflectance and the interaction were significant [$F(4,12) = 263$, $p < .0005$, $F(2,6) = 27.8$, $p < .0005$, and $F(8,24) = 5.6$, $p < .005$, respectively]. This analysis was also made for each participant. The effects of illumination level and reflectance and the interaction were significant at the 0.005 level for each participant.

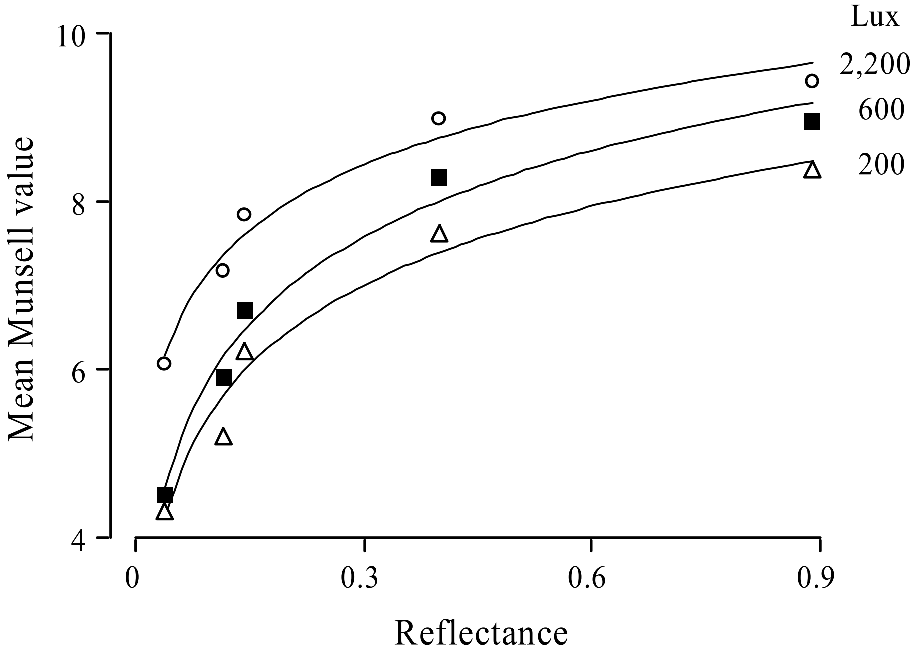

Figure 1: Results of Experiment 1. Mean Munsell value matched to the gray color of cylinders as a function of the reflectance of cylinders illuminated at three different illumination intensities. The data points are fit by least squares logarithmic curves.

EXPERIMENT 2

The significant interaction of illumination level and reflectance found in Experiment 1 indicates that the weights w_1 and w_2 of the model expressed by Equation 1 varied with L_E and L_O. However, it is also possible that this interaction was caused by nonlinearity in the Munsell scale. In fact, the Munsell value published in the Munsell atlas (Munsell, 1915) was obtained in conditions of presentation of Munsell chips that differed from the conditions of presentation of these chips used in Experiment 1. Also, the specific spatial arrangement of the Munsell chips used in Experiment 1 may have caused differential changes in the gray color of the chips in different parts of the Munsell scale depending on the position of chips in the array (Cataliotti & Gilchrist, 1995; Zavagno, Annan, & Caputo, 2004).

There is evidence that the rating method produces linear measures of sensory properties (Anderson, 1982, 1996). In this experiment, this method was used to determine whether the present Munsell scale was linear. The experiment tested whether the ratings of the gray color of Munsell chips were linearly related to the Munsell values published in the Munsell atlas.

Participants. The participants were 20 undergraduates with normal or corrected to normal vision. None of them used glasses. They did not participate in Experiment 1.

Stimuli. The stimuli were ten Munsell chips varying in Munsell value in steps of 1 from 0.5 to 9.5. These chips were used in Experiment 1. They were placed in the same viewing box with the same viewing conditions as those of Experiment 1. Two modes of presentation of chips were used: either the entire array of chips was presented or each chip was presented individually. Independently of the mode of presentation, the Munsell chips presented inside the viewing box in Experiment 2 preserved the same position they had in this same box in Experiment 1.

Procedure. Participants were asked to rate the gray color of Munsell chips using integers from 1 to 100. Two anchors were used. One was a 3 × 3 cm rectangle of black velvet with reflectance practically equal to zero placed on the right bottom corner of the box, which defined the rating of 1, and the other was a 3 × 3 cm rectangle of white magnesium sulfate with reflectance equal to 1.00 placed on the left bottom corner of the box, which defined the rating of 100. Half the participants first rated the individual Munsell chips and then rated the Munsell chips in the entire array of chips. For the other half this order was reversed. When the entire array of chips was presented, the participant rated each single chip in the order indicated by the experimenter by means of a stick inserted in the box through a small opening. The order of presentation of the Munsell chips was random.

RESULTS

Figure 2 shows the mean rated gray of each Munsell chip as a function of the Munsell value of the chip when the chip was in the array of chips and when it was presented individually.

The results in the left diagram are for the Munsell chips with an arrangement similar to that of the Munsell chips used in Experiment 1. They confirm that the Munsell values published in the Munsell atlas constitute a linear scale of gray color when the Munsell chips are used in conditions of presentation similar to those of Experiment 1.

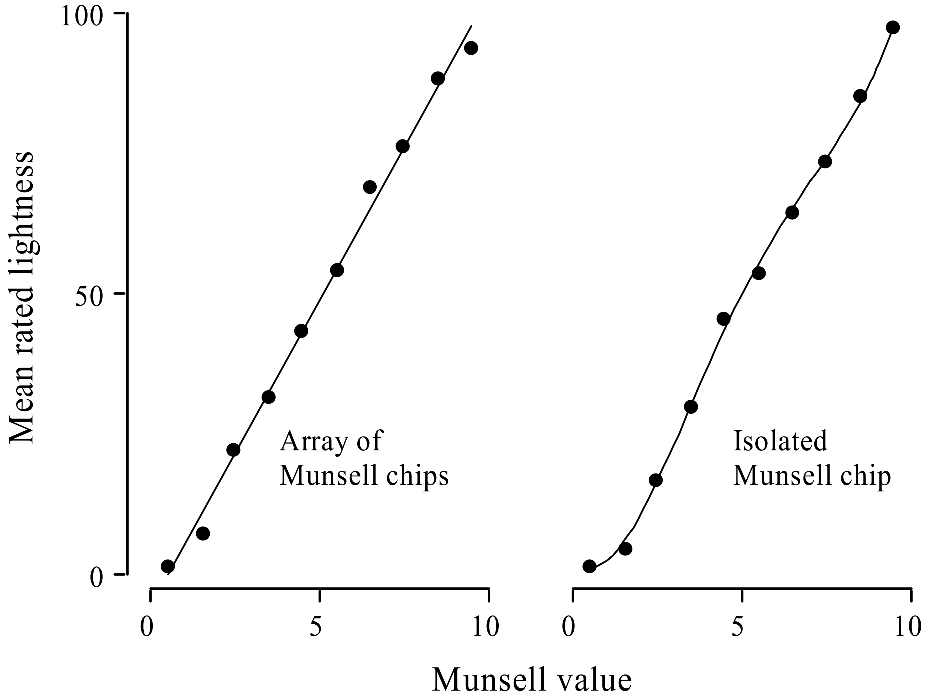

Figure 2: Results of Experiment 2. Mean rated lightness of Munsell chips as a function of Munsell value of chip when the chip was in an array of chips or was isolated on a white background. Data points are fitted by least squares curves. The curve in the right diagram is a fourth-degree polynomial.

The results in the right diagram are for Munsell chips presented individually. They reveal a very small effect of the horizontal position of the Munsell chip. This effect could depend on the variation in amount of light stimulation of the periphery of the retinas occurring when the eyes pointed at a central, left, or right part of the white board in the viewing box.

The linear trend was significant for the data in the left and right diagrams. The quartic trend was significant only for the data in the right diagram [$F(1,19) = 21.3$, $p < .0005$]. No other trend was significant. The left and right curves fitting the data points in Figure 2 are a least-squares straight line and a fourth-degree polynomial, respectively.

CONCLUSION

The results of the present study support the possibility that the gray color of an object placed in a variegated environment is determined by a perceptual process that additively integrates information about mean luminance of the object and information about mean luminance of the environment. This conclusion agrees with the idea that object color and illumination are produced by a common perceptual process. The results of Experiment 2 support linearity of the Munsell scale used in Experiment 1. This linearity supports the possibility that the non-parallelism of factorial curves obtained in the present study was due to the variation of integration weights with the mean luminance of the object and of the environment.

Allred & Brainard (2007) have recently found that the degree of constancy of the gray color of an object increases with the geometric complexity of the variegated environment in which the object is placed. The present results confirm that constancy of gray color fails when a variegated environment is geometrically rather complex. The results of this study additionally show that, for a fixed complexity of the environment, there is a systematic failure of constancy of gray color specifically related to the intensity of the light illuminating the environment. Given a fixed reflectance of an object, the gray color of the object becomes progressively lighter as the illumination becomes progressively stronger.

One of the best known and widely accepted theories of achromatic color is Wallach's (1948) theory which says that the gray color of an object is determined by the luminance ratio between the object and its background, such that equal luminance ratios correspond to equal gray colors. In the field of applications, the well known and widely used Retinex theory (Land & McCann, 1971) is based on the same relational principle of Wallach's theory. Jacobsen and Gilchrist (1984) consider the luminance ratio principle to be valid within a large range of luminances (1:1,000,000). However, according to them, it should be integrated with the principle that the highest luminance in the scene is identified as white. For a similar model, see Bressan (2006). According to these models, gray color and illumination are independent since changes in the intensity of illumination do not affect gray colors, including white, because luminance ratios remain unchanged when illumination changes. However, Da Pos and Cardi (2003) have recently shown that the highest luminance in the field does not always appear white, since it was found that at low levels of illumination the highest luminance appeared decidedly gray. The present results further show that Wallach's luminance ratio principle is inadequate to predict gray colors. This principle states that G is a function F of the ratio between the mean luminance of the object and the mean luminance of the background environment. That is,

$$G = F\left(\frac{L_O}{L_E}\right). \qquad (2)$$

Since the ratio L_O/L_E is the reflectance of the object, Equation 2 predicts that the factorial curves in Figure 1 should be superimposed one on the other. However, as one can see, these curves are widely separated from one another. Instead, our results support a process of information integration in which the gray color of an object in a scene is proportional to a weighted average with differential weighting of the luminance information about the object and about the background scene in which the object is situated.

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