

Color naming reveals our ability to distinguish between a colored background and colored light

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Objects appear to have much the same color under quite diverse illumination. This phenomenon, which is known as color constancy, can only be achieved by considering the color of surrounding surfaces. However, considering surrounding surfaces will yield errors if the chromaticity in such surfaces arises from the surface reflectance rather than from the illumination. Does the visual system treat chromaticity in the direct surrounding differently when it is evident that such chromaticity arises from the illumination than when it is evident that it arises from the surrounding surface reflectance? To investigate this, we briefly presented target patches on a simulation of a colorful ball rotating slowly under a lamp. Target patches were shown on differently colored surfaces, both under the lamp and in the shade. When naming the target patches' colors, surrounding colors had a larger influence on the named color when the simulated illumination was different than when the simulated reflectance of the surrounding surface of the ball was different. When matching the color rather than naming it, this distinction was only evident if the matching stimulus encouraged people to match the appropriate contrast. We propose that matching can reveal the sensed color, whereas naming reveals the interpretation in terms of surface reflectance.

Keywords: color appearance, color constancy, color vision, natural images, illumination, surface properties

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Introduction

Color constancy refers to the ability to judge spectral properties of a surface's reflectance from the light that the surface reflects toward our eyes (for a recent review, see Foster, 2011). The snag is that the amount of light of each wavelength that the surface reflects toward our eyes is the product of the surface's reflectance at that wavelength and the amount of light of that wavelength illuminating it. Thus, without somehow accounting for the illumination, it is impossible to derive the reflectance from the light reaching the eye. In natural scenes, knowledge about likely illuminations, specular highlights, shadows, mutual illuminations, the range of colors, and the correlation between color and luminance may all provide information about the illumination (e.g., Bloj, Kersten, & Hurlbert, 1999; Brainard et al., 2006; Golz & MacLeod, 2002; Granzier, Brenner, Cornelissen, & Smeets, 2005; Lee, 1986; Yang & Maloney, 2001; Yang & Shevell, 2003). Since the illumination in such scenes is seldom uniform,

the ordering of the image in terms of distances and orientations also needs to be considered when judging the illumination (Bloj et al., 1999; Boyaci, Doerschner, & Maloney, 2004; Boyaci, Doerschner, Snyder, & Maloney, 2006; Delahunt & Brainard, 2004; Kraft, Maloney, & Brainard, 2002; Lotto & Purves, 2002; Schirillo & Shevell, 2000; but see de Almeida, Fiadeiro, & Nascimento, 2010).

When there is little information about the illumination, as in simple simulations of a colorful plane under uniform illumination, people can interpret the scene in different ways when they are instructed to do so (Arend & Reeves, 1986), although not all people do so to the same extent (Cornelissen & Brenner, 1995). One way to interpret the finding that instructions can influence people's color judgments is that the instructions influence the extent to which differences in the average chromaticity within the scene are attributed to either differences in the illumination or differences in the reflectance of the surfaces surrounding the surface that is to be matched. If so, then everyone should be able to distinguish between the two sources of chromaticity if the scenes are not ambiguous.

The goal of the first experiment of the present study was to test whether this is the case.

Slightly contrary to what one may expect from the arguments given above, the results of a recent study suggested that people are unable to differentiate between illumination and reflectance when matching a real target's color by manipulating an isolated reference surface's chromaticity (Granzier, Brenner, & Smeets, 2009c). The goal of the second and third experiments was, therefore, to examine whether the way in which the color judgments are made influences the results.

Experiment 1

For our first goal, we wanted to construct a scene within which it is completely clear whether differences in the color of a target's immediate surrounding at different times are due to differences in illumination or to differences in the reflectance of the surrounding surface. To do so, we simulated a rotating colorful ball under non-uniform illumination (see Figure 1). Rotating the ball makes it relatively easy to distinguish between the two sources of surrounding color (for a review of cues that could contribute to this distinction, see Kingdom, 2008). We used a color-naming task because we know that color naming can give good color constancy both for simulated scenes (Troost & de Weert, 1991) and under natural circumstances (Granzier, Brenner, & Smeets, 2009a).

Methods

Seven subjects with normal color vision, including one of the authors, each took part in one 45-min session. All subjects except the author were naive as to the purpose of the experiment. The stimuli were presented on a Sony GDM-FW900 Trinitron monitor (48 cm × 31 cm; 1096 × 686 pixels; 160 Hz; 8 bits per gun). The monitor was calibrated with a Minolta CS-100A Chroma Meter. Subjects sat 70 cm from the screen and viewed the stimulus with both eyes. The room was dark except for the light from the screen.

The task

The color-naming task was similar to that used by Olkkonen, Hansen, and Gegenfurtner (2009). Subjects were shown a small target on the surface of a simulated rotating ball and a list of eight color names (Figure 1). The names were presented more or less in the corresponding color to help subjects find the right color name and to provide a fixed range of chromaticity within view. Subjects used a computer mouse to indicate whether the target's color was purple [0.34, 0.18, 26.0 cd/m²], red [0.62, 0.35, 20.9 cd/m²], orange [0.51, 0.43, 37.4 cd/m²],

yellow [0.41, 0.50, 75.6 cd/m²], green [0.28, 0.59, 55.8 cd/m²], turquoise [0.21, 0.34, 61.0 cd/m²], blue [0.14, 0.06, 6.2 cd/m²], or gray [0.32, 0.34, 24.2 cd/m²] (the values are the CIE_{xyY} coordinates of the colors in which the color names were written). The selected color was shown in a larger, bold font. Moving the mouse away from or toward the body moved the selected color upward or downward in the list. Subjects indicated that the appropriate color was selected by pressing the mouse button. They could correct their choices (until the next target appeared) by pressing the button again. Immediately before the session, the subjects were allowed to practice until they were confident that they understood the task and procedure. When they indicated that this was the case, the session started.

The simulated ball

The simulated ball had four differently colored surfaces, a diameter of 15 cm, and was floating in the air directly in front of the subject. The simulation was appropriate for a viewing position between the two eyes. The ball rotated at about 19°/s around an axis in the frontal plane that extended from the upper left to the lower right (see Figure 1A). New images were presented at about 10 Hz, with a rotation of 1.8° between consecutive images.

The ball's four surfaces differed in how much they reflect of the light that stimulates each cone. A bluish surface reflects 90% of the light that stimulates l- and m-cones and all the light that stimulates s-cones. A yellowish surface reflects 90% of the light that stimulates l- and m-cones and 70% of the light that stimulates s-cones. A reddish surface reflects 93% of the light that stimulates l-cones, 87% of the light that stimulates m-cones, and 80% of the light that stimulates s-cones. A greenish surface reflects 87% of the light that stimulates l-cones, 93% of the light that stimulates m-cones, and 80% of light that stimulates s-cones. Targets only appeared on the yellowish and bluish surfaces.

The simulated illumination

The ball was illuminated by 12 cd/m² of simulated ambient illumination from an overcast sky (standard illuminant C; CIE_{xy} = [0.31006, 0.31616]) and 7 cd/m² of simulated illumination by a distant tungsten lamp (standard illuminant A; CIE_{xy} = [0.44757, 0.40745]). The light from the simulated lamp originated 30° to the right of and closer than straight above the ball. The light emitted from each point of the screen (*S*) was based on the following equation:

$$S = RI_{\text{ambient}} + RI_{\text{lamp}}\cos(\alpha) + 0.5I_{\text{lamp}}\cos^{80}(\beta), \quad (1)$$

where *I* represents the intensity of the light source, *R* represents the surface's reflectance at that point, and the

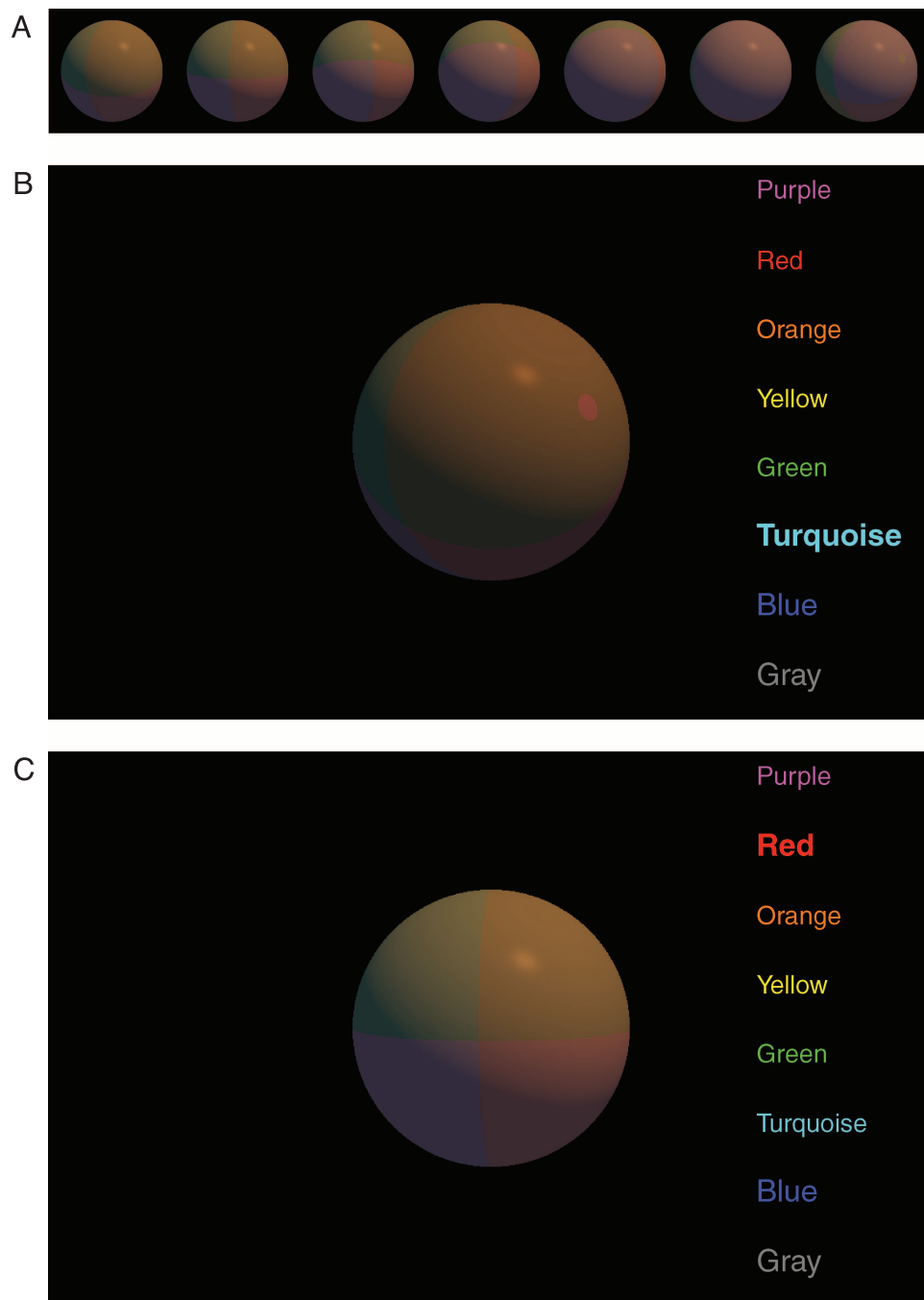


Figure 1. Stimulus of [Experiment 1](#). Subjects saw a four-colored ball rotating under a lamp (shown schematically in (A)). Targets either appeared in the shade at the lower left or at a position that was illuminated by the lamp at the upper right (as shown in (B)). (C) As the ball continued to rotate, the subject moved the computer mouse to highlight the term that best described the target's color. Panels (B) and (C) show the image as presented on the screen.

subscripts ambient and lamp specify the light source. The equation combines a Lambertian component (that depends on the angle α between the light rays from the lamp and the surface normal at the point in question) and a specular component (that depends on the angle β between the line of sight and the reflection of the lamp in the surface at that point and on the arbitrarily chosen exponent of 80 that

determines the width of the specular contribution). The arbitrarily chosen constant of 0.5 determines how shiny the surface appears (it determines the peak amplitude of the specular contribution in relation to the Lambertian contribution). We applied this equation to the light stimulating each of the three kinds of cones (for details, see Appendix A in Granzier, Brenner, & Smeets, [2009b](#)).

The targets

The 1.5-cm diameter circular targets (shape and dimensions on the simulated surface of the ball, not on the screen) were visible for 1 s. They were presented near the center of either the yellowish or bluish surface of the ball and moved with the ball. The presentations were timed so that halfway through the presentation the target was either 5.3 cm to the right of and 1.6 cm above the center of the image of the ball (under the lamp; [Figure 1B](#)) or 5.3 cm to the left of and 1.6 cm below the center of the image of the ball (in the shade). These positions and durations of presentation ensured that the target that was in the shade remained in the shade and that the illumination did not change much for the target under the lamp. A new target was presented every 5 s.

The colors of the targets formed a grid with distances of about 0.006 in CIE_{xy} color space. We confined the target's color to an area within an ellipse in this color space. The ellipse was centered at the coordinates of the light that would be reflected by a gray surface, so it was centered at the chromaticity of the local illumination. Consequently, the set of colors that were presented was different for the two positions on the ball. The ellipse was oriented along the $y = x$ line, because we mainly expected differences in that direction since the differences in the color of the illumination and in the color of the surface of the ball were in the blue–yellow direction. The target was about 11% brighter than the surface on which it was presented in order to make it clearly visible.

The color was determined separately for each pixel of the image of the ball. This was also so for the target area. In our analysis, we used the color at the center of the target halfway through the presentation to specify its color. These were the colors that formed the elliptically shaped grid. We determined the hypothetical reflectance of the target from these colors and the local illumination at that moment and used this reflectance for rendering the target.

Since the ball was continuously rotating and targets were presented each quarter cycle, the background surfaces and illuminations were presented in a fixed order. Targets were presented on one background surface in the shade, then on the same background surface under the lamp, then on the other background surface in the shade, on the other background surface under the lamp, on the initial surface in the shade, and so on. For each background surface and illumination, the targets were presented in random order. The background colors at the positions of the targets when no target was present were CIE_{xyY} = [0.380, 0.356, 16.61 cd/m²] for the blue surface under the lamp, CIE_{xyY} = [0.303, 0.301, 6.31 cd/m²] for the blue surface in the shade, CIE_{xyY} = [0.402, 0.393, 16.58 cd/m²] for the yellow surface under the lamp, and CIE_{xyY} = [0.325, 0.352, 6.29 cd/m²] for the yellow surface in the shade.

Analysis

For perfect performance, subjects must respond to the light reaching their eyes in accordance with the targets' simulated surface reflectance. The light emitted from the surface adjacent to the target was different for the two surfaces and two illuminations. The purpose of our analysis is to examine whether the extent to which people rely on the color of the immediately surrounding surface is affected by the distinction between this color being due to reflectance and this color being due to illumination.

We took all the targets' coordinates, converted them into values in the more perceptually uniform CIE_{u'v'} color space, and compared the named colors of sets with either the same background surface but different illumination, or the same illumination but differently colored background surfaces. Rather than using the naming data to estimate specific points, such as the neutral point or the borders between color categories, and quantifying how these points differed between the conditions, we directly examined how the relationship between the chromaticity of the light from the target and the name given to the target's color shifted. This was achieved by finding the shift in chromaticity of all the targets of one of the two sets (a uniform shift in CIE_{u'v'} color space) that minimizes the number of naming mismatches between the two sets (see [Figure 2](#)).

There is no naming mismatch for a certain target if the subject gave the nearest target of the other set the same name. If the nearest target of the other set was named differently, but the second nearest target of the other set was given the same name, there is a naming mismatch of one. If the second nearest target was also named differently, but the third nearest target was given the same name, there is a naming mismatch of two, and so on. Thus, the naming mismatch indicates the number of targets of the other set that were nearer in CIE_{u'v'} color space to the target in question than the nearest target of the other set that was given the same name. For instance, if the nearest shifted target to a target that was not shifted and was considered to be orange was also considered to be orange, there was no mismatch. If the nearest target was considered to be yellow, the second nearest to be red, the third nearest yellow again, and only the fourth nearest to be orange, the naming mismatch was three. We determined the shift that minimized the sum of the naming mismatches across all the targets. This method of quantifying the naming differences avoids some of the problems that have been raised in previous naming studies (Speigle & Brainard, 1996; Troost & de Weert, 1991). It is based on the assumption that a uniform shift in CIE_{u'v'} color space is a valid description of the changes in naming but is not very sensitive to modest deformations of the representation in color space as long as approximately the same range of colors is perceived, because most color borders radiate from the perceived neutral point.

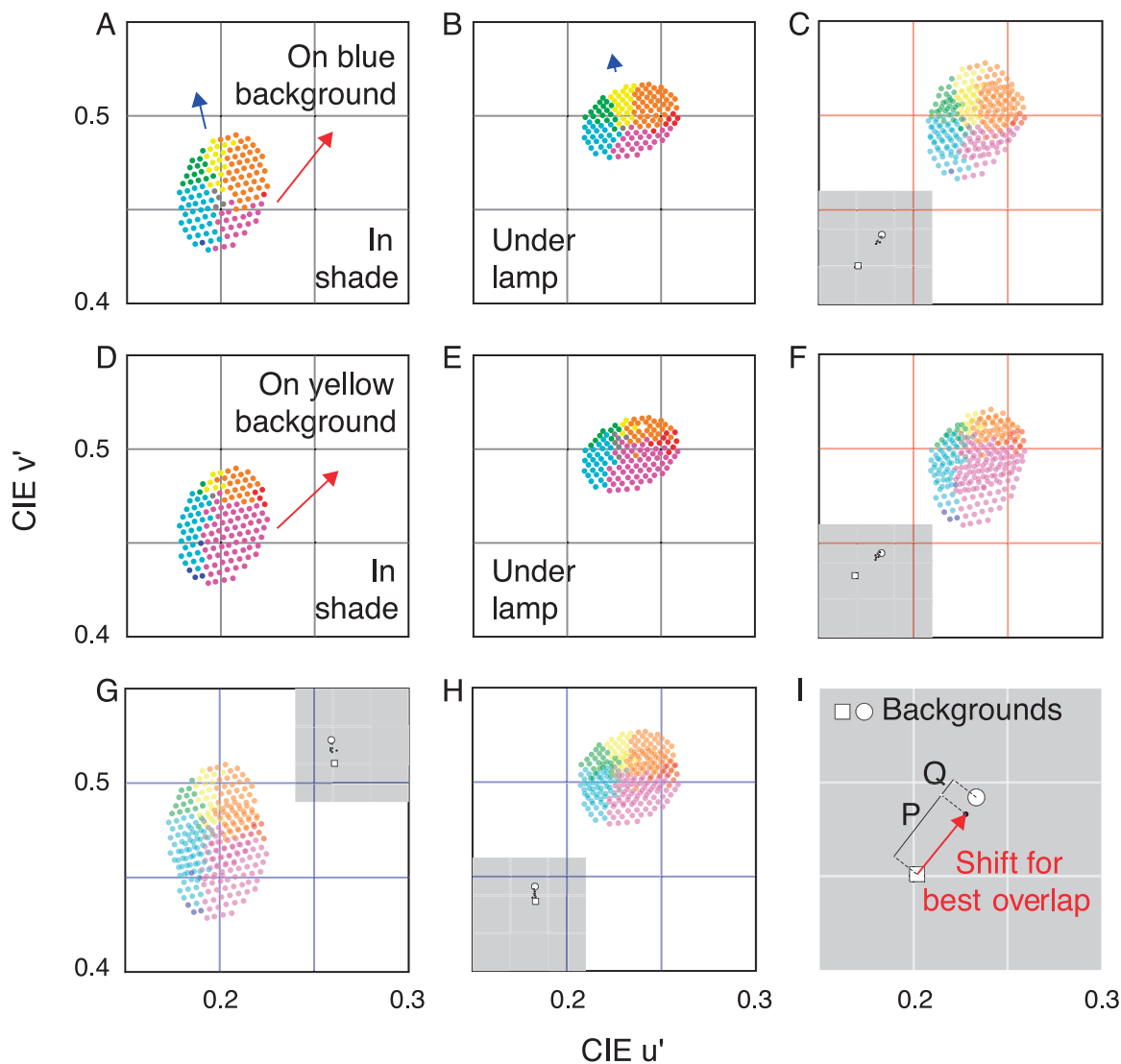


Figure 2. Analysis of the naming data. One subject's data in [Experiment 1](#), for targets on a blue background in the shade (A) or under the lamp (B) and targets on a yellow background in the shade (D) or under the lamp (E). Each dot's color indicates the named color for a target at the corresponding coordinates in CIE_{uv} color space. The red arrows in (A) and (D) indicate the shifts of the data for targets in the shade that give the best overlap with the data for targets under the lamp. The overlap after such shifts is shown in (C) and (F) for targets on the blue and yellow backgrounds, respectively. Similarly, the blue arrows in (A) and (B) indicate the shifts of the data for targets on the blue background that give the best overlap with the data for targets on the yellow background. The overlap after such shifts is shown in (G) and (H) for targets in the shade and under the lamp, respectively. Panel (I) explains our measure for the influence of surrounding color. The arrow represents the optimal shift (its endpoint is marked by a black dot). The square and circle indicate the color of the background at the position of the target for the comparison in question. The proportion of the difference in the surrounding chromaticity that is attributed to the illumination is given by $P / (P + Q)$, where P is the part of the distance between the square and circle that is accounted for by the shift (the component of the arrow in that direction), and Q is the part that is not. The insets in (C), (F), (G), and (H) show the endpoints of the optimal shifts for all seven subjects.

To evaluate how much of the difference in the simulated illumination was (correctly) attributed to a difference in illumination, we compared targets on the same background surface under different illumination (under the lamp or in the shade; the first two rows in [Figure 2](#)). The extent to which the named color shifted in accordance

with the illumination was quantified by dividing the shift that was needed to align the two sets of points (as explained above) by the shift caused by the illumination. We only considered the shift in the predicted direction (although this was not a necessary precaution because the direction of the shift always closely matched the

prediction). For each subject, we averaged the above-mentioned ratio (the proportion of the difference in color caused by the simulated illumination that the subject attributed to a shift in illumination) across the two background surface colors (bluish and “yellow”).

To evaluate how much of the difference in the color of the simulated background surface was (incorrectly) attributed to a difference in illumination, we compared targets under the same illumination on different background surfaces (bluish or “yellow”; the first two columns in Figure 2). The extent to which the named color shifted in accordance with interpreting the difference in background color to be due to a difference in illumination was quantified by dividing the shift that was needed to align the two sets of points by the difference between the two background surface colors under that illumination. Again, we only considered the shift in the predicted direction (although again this was an irrelevant precaution). For each subject, we averaged the above-mentioned ratio (the proportion of the difference in the background surface color that the subject attributed to a shift in illumination) across the two positions (in the shade and under the lamp).

Statistics

The parameter of interest is the proportion of the difference in the local surrounding color that is attributed to the illumination and, in particular, whether this depends on whether the difference arises from simulating differences in illumination or from simulating differences in surrounding surface reflectance. We evaluated the consistency across subjects in attributing more of the difference in the surrounding color to the illumination when the difference was caused by a simulated difference in illumination than when it was caused by a simulated difference in background surface reflectance with a paired *t*-test.

Results

Subjects only failed to respond to 10 of the 3892 targets (one such omission can be seen near the center of the range in Figure 2A). They sometimes corrected their choice. Figures 2C, 2F, 2G, and 2H show that uniform shifts within the CIE_{u'v'} space capture the differences in color naming quite well. We estimated how sensitive the sum of naming mismatches is to the precise value of the shift by determining the largest deviation from the best fit (in any direction) for which our measure did not increase by more than 5 points. We did so for each subject and comparison. The median absolute deviation is 0.003.

Figure 3 shows the influence of the surrounding color, both when differences in surrounding color should matter

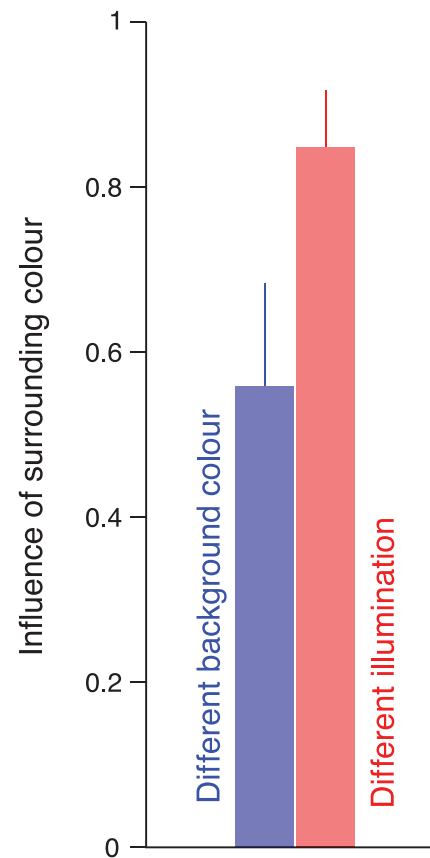


Figure 3. Influences of surrounding color in Experiment 1. Proportion of the difference in the surrounding color that was attributed to differences in illumination when it was appropriate to do so because the differences were due to differences in simulated illumination (pink bar) and when it was not appropriate to do so because they were due to differences between the simulated background colors (blue bar). Averages of 7 subjects' values with 95% confidence intervals.

because they are due to differences in simulated illumination (pink bar) and when such differences should not matter because they are due to differences in simulated background surface reflectance (blue bar). Previous studies on color constancy have generally only considered the former condition. Our stimulus allows us to also consider differences in surrounding color that are unambiguously *not* due to the illumination. This experiment also differs from conventional studies on color constancy in that the illumination of the scene does not change; the illumination of the relevant part of the ball changes because the ball rotates. Under these conditions, performance is far from perfect (a value for the influence of surrounding color of *zero* for a different simulated background surface reflectance and of *one* for a different simulated illumination), but we can clearly see that the simulated cause of the difference in the chromaticity in the target's immediate surrounding has a strong influence on

the judged color (an average difference in the expected direction of 0.29; $t_6 = 7.5$; $p < 0.001$).

Discussion

In simulated scenes, the extent to which chromaticity nearby a surface of interest is attributed to the illumination can be influenced both by giving explicit instructions without changing the image (e.g., Arend & Reeves, 1986) and by presenting information about the illumination within the image (e.g., by adding highlights: Yang & Maloney, 2001). The influence of the surrounding color is also known to depend on the luminance contrast (e.g., Brenner, Granzier, & Smeets, 2007; Gordon & Shapley, 2006), the overall range of chromaticity (e.g., Barnes, Wei, & Shevell, 1999; Brenner, Ruis, Herraiz, Cornelissen, & Smeets, 2003), the correlation between luminance and chromaticity (e.g., Golz & MacLeod, 2002; Granzier et al., 2005), and eye movements in combination with adaptation (Cornelissen & Brenner, 1995). In real scenes, there is normally enough information to identify the source of the color in the immediate surrounding of the surface of interest reasonably well (Brainard, 1998; Granzier et al., 2009a), although even in real scenes the true origin of color in the surrounding is not always completely unambiguous to the observer (Granzier et al., 2009b; Kraft & Brainard, 1999). Our study compares how differences in surrounding color as a result of simulated illumination and as a result of the simulated surrounding surface reflectance are interpreted in a simulated scene in which the origin of such differences is unambiguous to the observer.

Apart from the ambiguity that arises from only having access to the product of reflectance and illumination, there is normally also ambiguity due to the fact that the human visual system codes colors in terms of the stimulation of three types of cones. It is theoretically impossible to perceptually distinguish between the many spectral distributions of illumination and reflectance that give rise to the same cone stimulation. Thus, although one can accurately simulate a real surface, the subject cannot know the true underlying spectral distribution. However, in practice, most spectral distributions in natural scenes are quite smooth (Nascimento, Foster, & Amano, 2005), so one obtains quite good approximations from calculations based on cone excitation (Foster & Nascimento, 1994; Nascimento & Foster, 1997). Moreover, despite the ambiguity at each position and time, for the colored surfaces of the ball in our study, the interaction between illumination and surface reflectance is evident from the gradients across the surface and the changes when the ball rotates (assuming that the surfaces have simple reflectance properties that do not change as the ball rotates). The presence of the simulated specularities, which does not move when the ball rotates, is probably

also helpful in distinguishing between illumination and surface reflectance (Yang & Maloney, 2001; Yang & Shevell, 2003).

Experiment 2

Recent evidence suggests that when people manipulate the color of an isolated field by moving a computer mouse they are unable to consider it in terms of surface reflectance (Granzier et al., 2009c). Now that we have developed a method to demonstrate that people respond differently to the color in a background if it appears to arise from illumination than if it appears to arise from surface reflectance, we can examine whether this difference is absent when the task is to match the target with an isolated field rather than to name its color. In addition, in order to check that it is really disambiguating the image in terms of illumination and surface reflectance that matters, and not some subtle aspect of the analysis or of the simulation of the target and its direct surrounding, we ran a control session in which only the region near the target was shown.

Methods

The second experiment consisted of three sessions. One session was identical to the first experiment, except that the targets did not move with the ball. Instead, they appeared either 5.3 cm to the right of and 1.6 cm above the center of the image of the ball, or 5.3 cm to the left of and 1.6 cm below the center of the image of the ball (these positions are the target positions halfway through the presentations in Experiment 1). The targets remained at these positions for 1 s as the ball rotated. The reason for using static targets is that it allows us to present the same targets and their direct surroundings without having to shift and deform the images in accordance with the changes that occur when the ball rotates. We wanted to avoid such shifts and deformations because they could contribute to distinguishing between the surrounding color being due to the illumination and the surrounding color being due to the surrounding surface reflectance.

In the second session, the task and simulation were the same, but only the part of the ball that was within 1.5 cm of the border of the target, or of where the target will next appear, was visible (Figure 4A). Thus, subjects saw a section of the ball's surface with a diameter of 4.5 cm (in the simulation; alternating between sections under the lamp and in the shade) for 4 s, after which the target appeared at the center of this section and remained visible for 1 s. As soon as the target disappeared, its surrounding did too, and the other section was shown for 4 s, and so on.

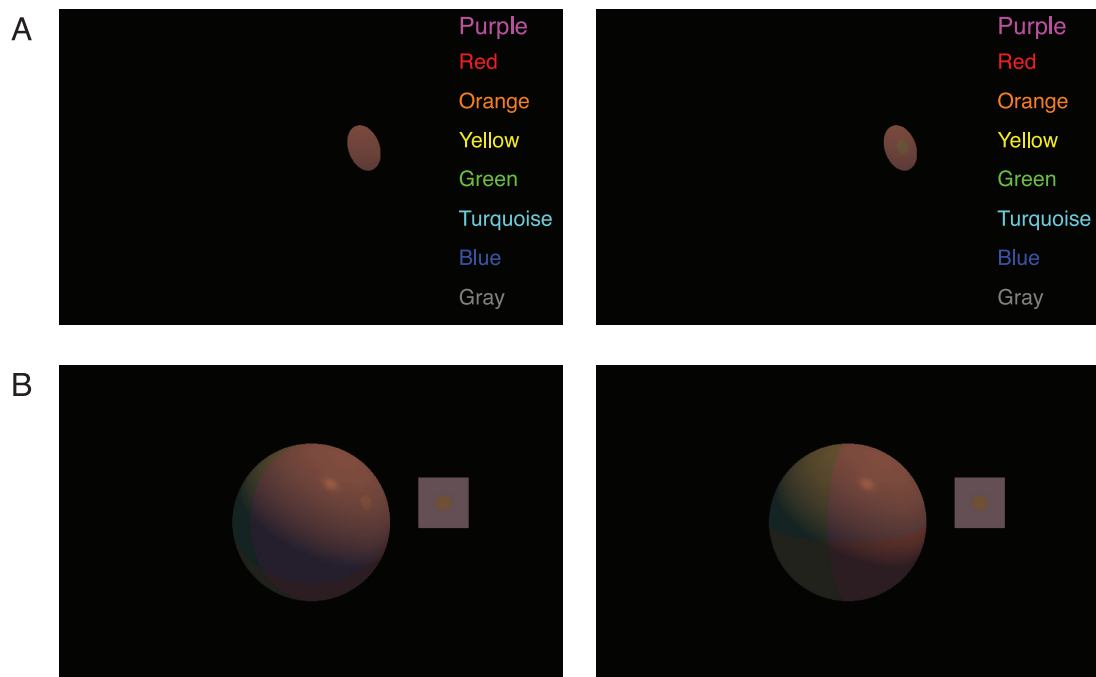


Figure 4. Stimuli of the second and third sessions of [Experiment 2](#) (for a stimulus of the first session, see [Figure 1](#)). (A) In the second session, only the part of the ball directly adjacent to the target was visible. The visible region switched between the two possible target positions when the target disappeared. (B) In the third session, the task was to match the target in an adjacent region. This region was on the right, at the same height as the target, when the target was on the right—as shown—and jumped to the left and lower as soon as the target appeared on the left.

In the third session, the ball was identical to that in the first session. The target was similar to those of the first session, but it was always a simulation of a gray surface. It was identical to the target at the center of the ellipse of targets in the naming task. A gray target reflects all colors of light to the same extent, so its color on the screen was that of the illumination at that position. As soon as a target appeared, a similar 1.5-cm diameter matching disk on a gray ($CIE_{xy} = 0.333, 0.333$) square with sides of 4.8 cm appeared too ([Figure 4B](#)). This matching disk and the gray square remained visible for 5 s, until the next target appeared on the ball. Subjects could change the color of the matching disk within the square by moving the computer mouse (lateral and sagittal movements were linked to the x and y coordinates of CIE_{xy} color space) and could increase and decrease the luminance of the gray square by pressing the “down” and “up” keys on the keyboard. Their task was to match the target in the square to that on the ball in both color and luminance. We changed the luminance contrast by manipulating the luminance of the gray square rather than that of the matching disk on that square so that the matching disk would always have the same luminance as the target.

Of course, subjects could not match the color and luminance within the 5-s viewing time in the third session. To allow subjects to make satisfactory settings without changing the frequency with which targets were presented or the ball rotated, the computer stored the current setting

as soon as the next reference target appeared and replaced it when that reference target reappeared 15 s later. Thus, subjects were intermittently working on 4 different settings. Once they were content with any of the settings, they pressed the mouse button and the values for that setting were stored and replaced by random values (the luminance was not changed because we were primarily interested in the set color; we only allowed subjects to set the luminance in order to ensure that they would find the best possible match). When the target was in the shade, the matching disk was 12.6 cm to the left of and 1.9 cm below the center of the ball. When the target was under the lamp, the matching disk was 12.6 cm to the right of and 1.9 cm above the center of the ball. Subjects made settings for 45 min.

Subjects and procedure

The same seven subjects who had taken part in [Experiment 1](#), and two additional subjects who were not aware of the hypotheses, performed the three sessions on separate days in different orders. Each kind of session was the first, second, and third for three of the subjects. Immediately before each session, the subjects were allowed to practice until they were confident that they understood the task and procedure. When they indicated that this was the case, the session started. Before performing the matching task, seven of the eight naive subjects

were given a piece of paper with an approximate rendition of the central part of the CIE_{xy} color space to help them navigate with the mouse.

Analysis

The data of the naming task were analyzed in the same manner as in the first experiment. For the matching task, we first took all of a subject's settings for each of the four conditions (under the lamp or in the shade; on the bluish or yellowish surface) and determined the median set values of CIE_{u'} and CIE_{v'} (and the intra-quartile ranges). To evaluate how much of the difference in the simulated illumination was correctly attributed to a difference in illumination, we compared targets on the same background surface under different illumination (Figures 5A–5C). Since we always simulated the same target surface reflectance (that of a gray surface), correctly attributing the difference between the target and background colors on the screen to a difference in illumination will result in identical matches at both locations (on each background). The extent to which the matches were the same under both kinds of illumination indicates the extent to which the difference in the local color is attributed to a difference in illumination. Dividing the sum of the differences between the median matched colors and the corresponding true colors (in the predicted directions) by the difference between the colors of the backgrounds gives us the extent to which subjects attributed the difference to the illumination. For each subject, we averaged this value across the two background surface colors (blue and yellow).

To evaluate how much of the difference in the color of the simulated background surface was incorrectly attributed to a difference in illumination, we compared targets under the same illumination on different background surfaces (Figures 5D–5F). Since varying the background surface does not influence the light from the target surface, the extent to which the set color depended on the surrounding surface indicates the extent to which the difference in the local color is attributed to a difference in illumination. Dividing the difference (in the predicted direction) between pairs of median matched colors by the difference between the colors of the backgrounds (under the prevailing illumination) gives the extent to which subjects attribute the difference to illumination. For each subject, we averaged this value across the two positions (in the shade and under the lamp).

Statistics

The main parameter of interest is the proportion of differences in the local surrounding color that is attributed to the illumination and, in particular, whether this depends on whether the differences arise from simulations of changes in illumination or from simulations of changes in surface reflectance. To evaluate this, we performed a repeated measures analysis of variance on the proportion

of the difference in color that is attributed to the illumination, with factors simulated cause (*different surface color* or *different illumination*) and session (*naming with ball*, *naming with patch*, and *matching with ball*). For each of the three sessions, we also used paired *t*-tests to evaluate whether the proportion of the difference that is attributed to the illumination was larger when different illumination was simulated than when different background surfaces were simulated. All tests were conducted on the basis of the subjects' average values for each session and simulated cause (which were determined in the manner described above).

Results

Subjects failed to respond on 40 of the 5004 trials in the *naming with ball* session and on 38 of the 5004 trials in the *naming with patch* session. In the *matching* session, they made an average of 31 settings (range: 10–92) for each of the four combinations of surface color and illumination. The pink bars in Figure 6 show how much of the difference that is due to the simulated illumination is correctly attributed as such. The blue bars show the extent to which a difference in the surrounding color is incorrectly attributed to the illumination rather than to the surrounding surface reflectance. Identical values for the two kinds of bars indicate that subjects do not distinguish between the two causes for the surrounding color. This is the case when the task is to match the target's color and when only the directly adjacent area of the surrounding is visible. When the whole ball is visible and the task is to name the target's color, the pink bars are higher, as they were for similar conditions in Experiment 1.

There are considerable differences in the extent to which subjects attributed the differences on the screen to illumination, but the general pattern is similar for all subjects. Analysis of variance only revealed a significant interaction between cause and session ($p < 0.0001$). For the *naming with ball* session, more of the difference was attributed to illumination when a difference in illumination was simulated (mean difference of 0.27; $t_8 = 5.7$; $p < 0.001$). This was not the case for the other two sessions ($t_8 = -2.3$; $p = 0.98$ for the *naming with patch* session; $t_8 = 0.85$; $p = 0.2$ for the *matching with ball* session). When setting the luminance in the matching session, subjects set an average contrast of 1%, which is clearly less than that of the reference target on the ball.

Discussion

The results for the *naming with ball* session replicate the findings of the first experiment. This is not too surprising because the only difference is that the target was static on the screen in the second experiment, whereas

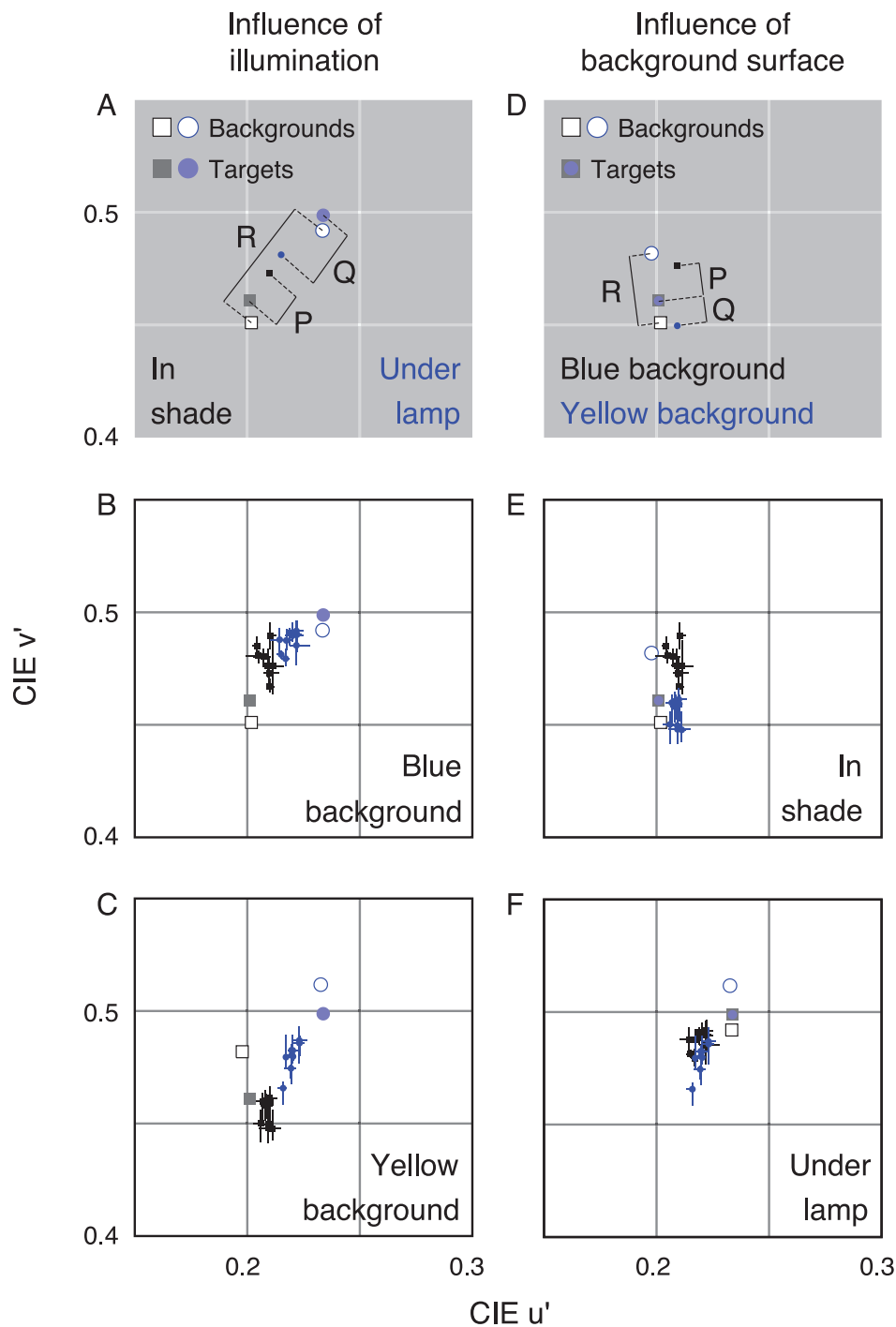


Figure 5. Analysis of the matching data. Panels (A) and (D) show one subject’s data to explain our measure for the influence of surrounding color. Panels (B), (C), (E), and (F) show the nine individual subjects’ median matched values (with intra-quartile ranges) for Experiment 2. Each value (small points with error bars) is shown twice, once to show the influence of the illumination for a given background surface (B, C) and once to show the influence of the background surface for a given illumination (E, F). The white (open) symbols indicate the relevant background colors. The shaded symbols indicate the colors of the “gray” targets that are being matched (or equivalently, the color of the illumination, so the two symbols are superimposed in (B), (E), and (F)). The proportion of the difference in the surrounding chromaticity that is attributed to the illumination is given by $(P + Q) / R$, where R is the distance between the colors of the backgrounds (at the position of the target), and P and Q are the deviations of the matched color from the color that was being matched (expressed as components in the direction of the difference between the colors of the backgrounds).

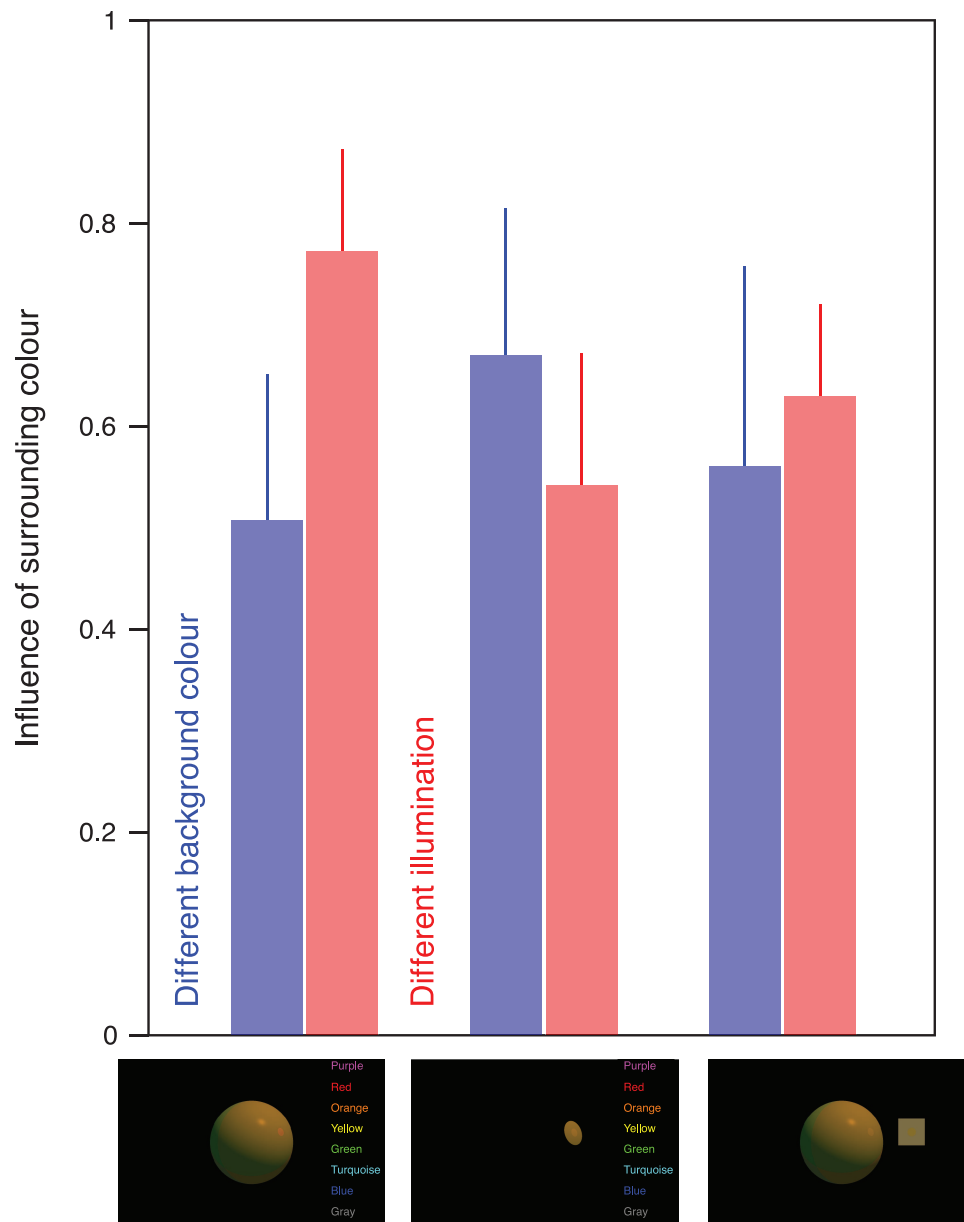


Figure 6. Influence of surrounding color in [Experiment 2](#). Proportion of the difference in the surrounding color that was attributed to differences in illumination when it was appropriate to do so because the differences were due to differences in simulated illumination (pink bars) and when it was not appropriate to do so because they were due to differences between the simulated background colors (blue bars). Averages of 9 subjects' values with 95% confidence intervals. From left to right, the pairs of bars represent the naming session in which the whole ball was visible, the naming session in which only the patch near the target was visible, and the matching session.

it moved with the surface of the ball in the first one. A target that does not shift when the ball rotates moves across the ball's surface, which is more consistent with light projected onto the ball than with a patch of the ball's surface, so one may have expected a smaller effect. However, the fact that the targets appeared and disappeared abruptly in both experiments is also inconsistent with a patch of the ball's surface having different spectral reflectance. Thus, perhaps the effect would have been larger for a more realistic simulation. However, the effect of the simulated cause of the difference in chromaticity was evident.

That the interpretation of the scene is responsible for the difference between how much of the surrounding color is attributed to the illumination rather than some subtle detail of the local contrast or of analyzing the data in terms of shifts in coordinates in $CIE_{u'v'}$ color space is evident from the results of the naming session in which only the patch of the ball near the target was visible. For that session, there was no effect of the distinction between illumination and surrounding surface reflectance, which is what we expected because we had removed almost all information for making such a distinction.

The main finding of the second experiment is that subjects did not *match* the targets' colors differently when confronted with different causes of surrounding chromaticity, although the rotating ball was fully visible so the distinction between illumination and surface reflectance should have been easy to make. We used an unconventional matching task with four alternating targets. Subjects did not report any difficulty in determining which target they were matching at each instant, although it was obviously more cumbersome to make matches in this manner. Importantly, the failure to differentiate between the two sources of surrounding color in our matching task cannot be explained by subjects confusing the targets when making their matches, because the two targets are physically identical when the background is different, but they are physically different when the illumination differs. If subjects had been confused about which target to match, they would have tended to make the same settings for all targets. Doing so would lead to different interpretations in terms of the influence of surrounding color for the two causes: reducing the influence for simulated changes in background surface (because the targets are physically the same) and increasing the influence for simulated differences in illumination (because the physical colors are different and considering the surrounding color helps compensate for this difference).

Experiment 3

The results of the matching task of [Experiment 2](#) are consistent with the idea that people do not distinguish between surface reflectance and illumination when they match a target by moving a computer mouse to change the color of an isolated field (Granzier et al., 2009c). We propose that the reason for this is that a matching task allows one to equate certain aspects of the stimulus. A naming task forces one to interpret (categorize) the relevant part of the stimulus. If this is true, then we may expect people's performance in the matching task to depend on the circumstances. We know that people can be enticed to match either the light from the surface of interest or its contrast with the surrounding surfaces by varying the contrasts involved (Brenner et al., 2007). We propose that instructing people to make different kinds of matches probably also encourages people to match one or the other.

In experiments in which people compare targets within identical scenes under different illumination, matching contrasts between corresponding surfaces will give rise to a high degree of color constancy. If only a certain surface is known to have the same reflectance in both scenes, one could match the contrast with that surface. However, if the scenes are completely different, matching contrasts will only give rise to color constancy in as far as the

chromaticity in the surfaces that are used for matching contrasts is caused by a difference in illumination. In the third experiment, we examined whether people match the contrast with identified regions when given the opportunity to do so. For this, we repeated the matching task of [Experiment 2](#) but replaced the gray background of the matching field with a simulation of a surface with the same four reflectances as the surface of the ball, under the same illumination. We compared this with a condition with a background of four more saturated colors.

Methods

The third experiment consisted of two sessions that were both identical to the matching session of [Experiment 2](#) except for some details of the matching field ([Figure 7](#)). In one session, the background of the matching field was divided into four squares, each with the same simulated reflectance as one of the four parts of the ball and illuminated in the same way as the ball. As a consequence, the luminance of the matching field's background was now also the same for all targets. The CIE_{xyY} coordinates of the four squares were [0.38, 0.38, 11.8 cd/m²], [0.39,

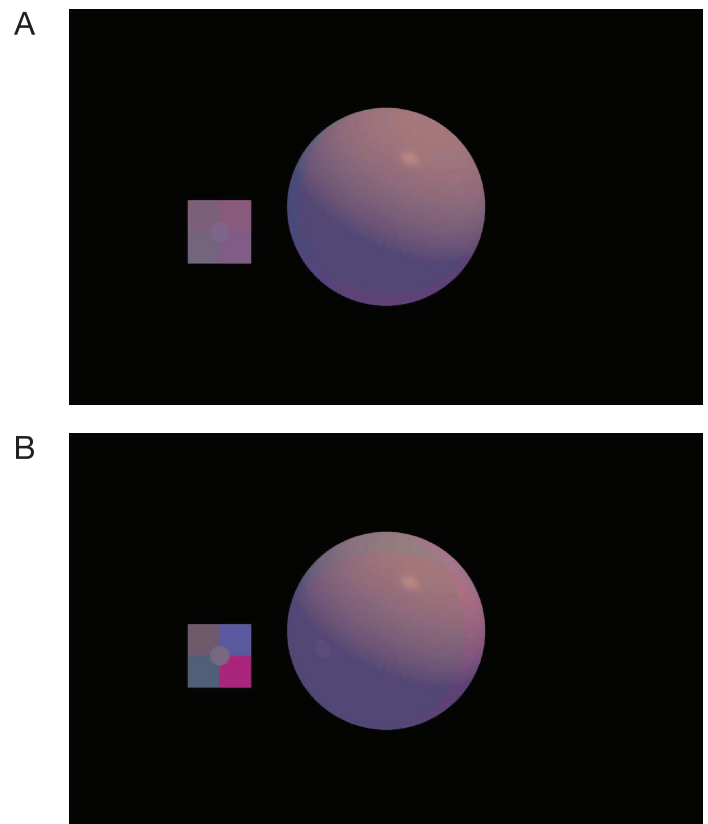


Figure 7. Stimuli of [Experiment 3](#). (A) The background of the matching region consisted of four surfaces with the same simulated reflectance as the surfaces of the ball. (B) The background consisted of four surfaces with more saturated colors. Other details as for the third session of [Experiment 2](#).

0.36, 11.9 cd/m²], [0.35, 0.38, 11.7 cd/m²], and [0.36, 0.34, 11.8 cd/m²]. The matching field's luminance was the same as it would be if the field were set to perfectly match the target in terms of reflectance, and the subject had to set its chromaticity by moving the computer mouse. In the second session, the task was the same and the background of the matching field was also divided into four squares, but the colors of the squares were more saturated. Their CIE_{xyY} coordinates were [0.50, 0.30, 9.4 cd/m²], [0.25, 0.25, 9.6 cd/m²], [0.30, 0.40, 9.3 cd/m²], and [0.40, 0.43, 9.5 cd/m²]. In this session, subjects could also adjust the luminance of the matching field. Note that in [Experiment 3](#) the matching field and its background were identical for all targets, apart from the position that varied as in [Experiment 2](#) (in [Experiment 2](#), the luminance of the matching field was different for targets under the lamp and in the shade because the luminance always matched that of the target).

Six naive subjects took part in the experiment. They had all taken part in [Experiment 2](#). Three of them first made matches whereby the four simulated frontal surfaces surrounding the target had the same reflectance as the four surfaces of the ball. The other three first made matches for the more saturated background. A repeated measures analysis of variance on the proportion of the difference in color that is attributed to the illumination, with factors simulated cause (*different surface color* or *different illumination*) and session (*same surface reflectance* or *more saturated colors*), was used to examine whether the background matters. For each session, paired *t*-tests were used to evaluate whether the proportion of the surrounding color that is attributed to the illumination was significantly larger when different illumination was simulated than when different background surfaces were simulated.

Results

On average, subjects made 40 settings (range: 14–71) for each of the four combinations of surface color and illumination when the matching field's background had surfaces with the same reflectance as the ball and 44 settings (range: 10–83) for each of the four combinations when the matching field's background was more saturated. The mean intra-quartile ranges were 0.006 and 0.009 in CIE_{u'} and 0.008 and 0.008 in CIE_{v'}. The proportion of the difference in surrounding color that was attributed to the illumination ([Figure 8](#)) was significantly larger when different illumination was simulated than when different background surfaces were simulated ($p = 0.01$). It did not differ significantly between the two sessions, but there was a significant interaction between simulated cause and session ($p = 0.007$). The distinction between surface color and illumination was significant for the matched surface reflectance ($t_5 = 7.1$; $p = 0.0004$) but not for the more saturated background ($t_5 = 1.7$; $p = 0.07$).

Despite these differences, there was a strong correlation across subjects in the extent to which surrounding color influenced the matches in the two sessions ($r = 0.93$).

Discussion

The difference between the matching data in the two sessions confirms that people can match targets in different ways. The targets that were matched were identical in the two sessions, and the matching field and its surrounding were identical for all conditions within each session, and yet the influence of surrounding color did not depend to the same extent on its simulated origin in both sessions. Thus, we managed to make people match the target differently without instructing them to do so, simply by changing the background. The difference cannot simply be attributed to the saturation of the colors in the background of the matching field being lower when it appeared to have the same colors as the ball, because saturation was even lower (zero) in the matching task of [Experiment 2](#), whereas the results were more similar to those for the more saturated colors of this experiment.

It was easy to tell whether or not the surfaces behind the matching field had the same simulated reflectances as the four sections of the ball. When this was so, people presumably compared the contrast between the matching field and the appropriate part of the background to the contrast between the target and its direct surrounding. If people can identify the appropriate part of the background, matching these two contrasts will give rise to a distinction between the two causes of color in the surrounding, because the appropriate part changes when the target is presented on a different simulated surface but not when the illumination changes. If it is difficult to identify an appropriate part of the background, as it is when the colors surrounding the matching field are different from those on the ball, or if there is no choice at all because the matching field is surrounded by a uniform gray area, we expect the distinction between the two possible origins of chromaticity in the surrounding of the target on the ball to be more difficult or impossible to make. The results of the three matching sessions of [Experiments 2](#) and [3](#) support this view.

We cannot tell whether varying the colors surrounding the matching field only influenced the reference that was used for matching color contrast or whether it also influenced the extent to which subjects relied on color contrasts rather than local color at the target. The large variability across subjects in the influence of surrounding color suggests that people rely to very different extents on contrast when making matches. The strong correlation between the extent to which surrounding color influenced our subjects' matches in the two sessions of [Experiment 3](#) shows that they are consistent in doing so. One could try to influence the extent to which people rely on contrast through instructions (assuming that instructions influence

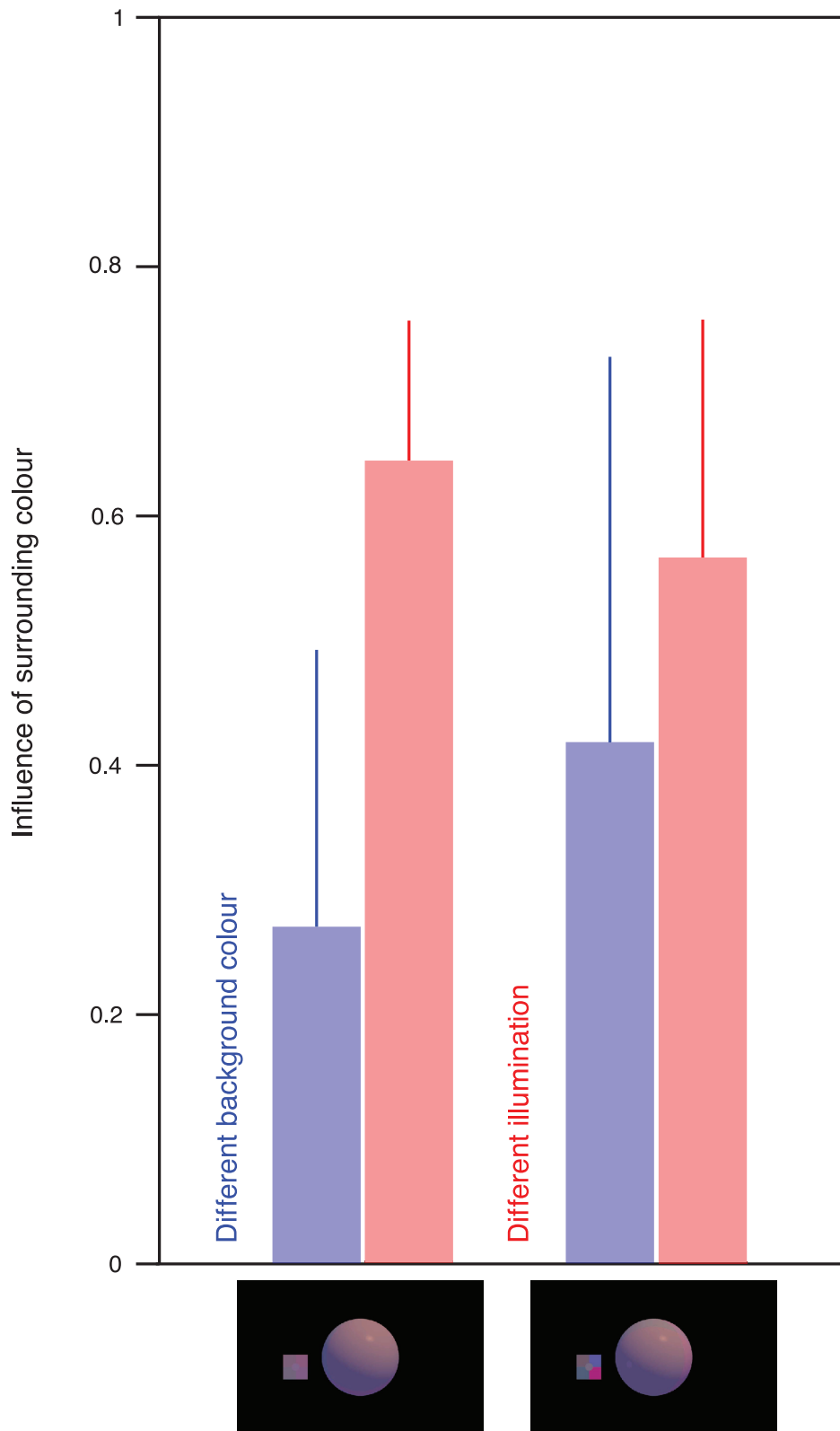


Figure 8. Influence of surrounding color in Experiment 3. Proportion of the difference in the surrounding color that was attributed to differences in illumination when it was appropriate to do so because the differences were due to differences in simulated illumination (pink bars) and when it was not appropriate to do so because they were due to differences between the simulated background colors (blue bars). Averages of 6 subjects' values with 95% confidence intervals. The left pair of bars represents the session in which the four sections of the background of the variable surface have the same simulated reflectance as the four sections of the ball. The right pair of bars represents the session in which the four sections of the background had more saturated colors.

color constancy by encouraging or discouraging people to rely on contrast). However, attempts to do so are not always successful. In the first study that examined the role of instructions (Arend & Reeves, 1986), the two authors were clearly influenced by the instructions, but a third, naive subject was not. In a later study (Cornelissen & Brenner, 1995), only two of the five subjects, one of whom was an author, was affected by the instructions to an extent that could not be accounted for by indirect effects of eye movements.

General discussion

In our experiments, we simulated a ball that was illuminated from above by a lamp as well as by ambient daylight. Target patches were shown on two differently colored surfaces, either directly under the lamp or in the shade of the ball. When naming the targets' colors, people treated a change in the surrounding chromaticity differently when it was a simulation of a difference in reflectance than when it was a simulation of a difference in illumination. This difference disappeared when only small parts of the ball were shown and when people were asked to match the color rather than to name it, unless the background of the matching field contained areas that were recognizably the same color as the ball. We conclude that the extent to which differences in the surrounding chromaticity are attributed to the illumination depends on how the scene is interpreted. We show that whether this is revealed in experimental studies depends on the task that is used to measure the perceived color.

We used a rotating ball to make it easy to distinguish between surface color and illumination (for an overview of relevant cues, see Kingdom, 2008). When the ball rotated, the edges of its differently colored surfaces moved, while the illumination did not. Moreover, the illumination varied smoothly, due to the smooth curvature of the surface, whereas the borders between surfaces with different reflectance were sharp. We can be sure that the subjects in our study made the critical distinction, because otherwise they would not have responded differently to biases in the reflectance of the surrounding surfaces than to biases in the color of the illumination.

When they had to match two surfaces' colors, our subjects did not necessarily respond differently to chromaticity arising from a bias in the surrounding surface reflectance than to chromaticity arising from a bias in the illumination. We argue that this is because they do not match a judged surface reflectance but match some aspects of the sensed chromaticity instead (Arend, 1993). The latter may be a combination of the sensed chromaticity of the target itself and the sensed contrast with (selected parts of) the surrounding (Brenner et al., 2007). Thus, we propose that matching allows subjects to reproduce the chromaticity of the light reaching the eye

from the target as modified by adaptation and various spatial contrasts, while naming reveals the interpretation of the chromaticity in the scene in terms of surfaces and their reflectances and illumination.

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