Suggesting that the illumination differs between two scenes does not enhance color constancy

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Abstract

Color constancy involves correctly attributing a bias in the color of the light reaching your eyes to the illumination, and therefore compensating for it when judging surface reflectance. But not all biases are caused by the illumination, and surface colors will be misjudged if a bias is incorrectly attributed to the illumination. Evidence from within a scene (highlights, shadows, gradients, mutual reflections etc) could help determine whether a bias is likely to be due to the illumination. To examine whether the human visual system considers such evidence we asked subjects to match two surfaces on differently colored textured backgrounds. When the backgrounds were visibly rendered on screens in an otherwise dark room, the influence of the difference in background color was modest, indicating that subjects did not attribute much of the difference in color to the illumination. When the simulation of a change in illumination was more realistic, the results were very similar. We conclude that the visual system does not seem to use a sophisticated analysis of the possible illumination in order to obtain color constancy.

Key words: ***Color Vision/Psychophysics, color constancy***

Introduction

The spectral distribution of the light reaching the eyes from an object of interest does not only depend on the object's surface reflectance, but also on the spectral distribution of the illumination (von Helmholtz, 1866). However, the apparent perceived color of the object is quite invariant to considerable changes in the spectral distribution of the illumination; a phenomenon known as color constancy (Land, 1959). One way to achieve color constancy is for the visual system to correctly assume that a bias in the spectral distribution of the light coming from the scene is the consequence of a bias in the spectral distribution of the illumination, and consequently to compensate for this bias (Helmholtz, 1866). However, if the visual system erroneously assumes that a bias in the spectral distribution of the light coming from the scene is the consequence of a bias in the spectral distribution of the illumination, and compensates for this bias, the object's color will be misjudged. This phenomenon is known as chromatic induction or simultaneous color contrast (see Walraven et al., 1987).

A reason to suspect that the visual system "knows" when to assume that the illumination is responsible for a bias in the spectral distribution of the light reaching the eyes is that the influence of the surface reflectances of the direct surrounding is weak in simple displays, in which it is evident that the surrounding surfaces have different reflectances (Troost & de Weert, 1991; Cornelissen & Brenner, 1995; Yang & Shevell, 2003; Lucassen & Walraven, 1996; Granzier, Brenner, Cornelissen, & Smeets, 2005), whereas it is large in experiments using more complex displays, in which pictorial depth cues suggest that the illumination rather than the reflectance of the background is different (e.g., Lotto & Purves, 2002) or when using real scenes (e.g., Kraft, Maloney & Brainard, 2002; Granzier et al., 2009a; Brainard, Brunt & Speigle, 1997; Brainard, 1998). A possible reason why only a small part of a simulated change in illumination is discounted when using virtual scenes is that the stimuli displayed on a CRT lack direct information about the illumination. The unexplained transition at the borders of the CRT (even if in peripheral vision; Murray et al., 2006) and the presentation of a single (patterned) surface makes subjects aware that they are judging emitted rather than reflected light. Results showing that the visual system discounts a larger part of a change in illumination in more complex displays are in line with evidence showing that the visual system uses various sources of information in the scene to determine whether the illumination causes the bias in the light reaching the eyes, such as the layout of the scene (Brenner, Granzier & Smeets, 2011; Kraft et al., 2002; Bloj et al., 1999), the presence of specular highlights (Yang & Maloney, 2001; Lee, 1986; Yang & Shevell, 2003; D'Zmura & Lennie, 1986), mutual illuminations (Drew & Funt, 1990; Bloj et al., 1999; Delahunt & Brainard, 2004b), shadows (Usui et al., 1996; D'Zmura, 1992), illuminant gradients (Brainard, Brunt & Speigle, 1997) and many additional cues (for a review see Maloney, 1999).

In the present study, we examine whether subjects discount a larger part of a difference in the overall chromaticity in the background if the experimental stimulus contains indications that it is correct to assume that the illumination is chromatically biased (see Hurlbert & Wolf, 2004; Lotto & Purves, 2000, 2002, 1999; Purves, Shimpy & Lotto, 1999, for related studies). We compared color matches for scenes that differed in the extent to which it was reasonable to assume that the difference in the average surface reflectance of the background was due to a difference in illumination.

Methods

The idea was to compare color judgments, and in particular the extent to which local biases in chromaticity are attributed to a difference in illumination, in two situations that differ markedly in the extent to which it is reasonable to assume that one is looking at similar scenes under different illumination. The task was to match two surfaces presented on similar backgrounds on two CRT screens. On some trials both surfaces and their backgrounds were under the same simulated illumination and on other trials the simulated illumination was different on the two screens. The two situations were tested in separate sessions. In one session the screens were simply placed side by side, facing the subject, in a dark room (*aligned screens*). In the other session (*simulated lamp*) the two screens were placed behind a curtain, and were only visible through windows in the curtain, making it more reasonable to consider the dark surrounding to belong to a space with a different illumination (see Schirillo & Shevell, 2000). Moreover, one of the screens was rotated away from the frontal plane, making it more likely that it was illuminated differently. Finally, the simulated illumination of the slanted screen was not uniform. There was a visible lampshade at a position that was consistent with the gradients on the screen, making it look compellingly as if the scene was illuminated by this additional lamp (see Figure 1).

Subjects

Twelve subjects were tested in each session. All had normal color vision as tested with Ishihara color plates (Ishihara, 1969). Since we had to change the set-up between the two kinds of sessions we presented them in a fixed order: first the *aligned screens* and then the *simulated lamp*. Six subjects, including one of the authors, participated in both kinds of sessions (on different days). An additional twelve subjects (including the other authors) each took part in only one session (six in each). Since there were no evident differences in performance in the *simulated lamp* session between subjects who had done the *aligned screens* session first and ones who had not, we distinguish between these groups for the statistical evaluation but plot the overall averages for each session. All subjects except the authors were naïve as to the purpose of the experiment.

The set-up

A *matching disk* and its background were presented on one screen (a Sony GDM – F520 Trinitron monitor; 40 cm X 30 cm; 1600 X 1200 pixels; 85 Hz; 8 bits per gun). A *reference disk* and a similar background were presented on a second screen (a Sony GDM-FW900 Trinitron monitor; 48 cm x 31 cm; 1920 x 1200 pixels; 90 hz; 8 bits per gun). Subjects sat 220 cm from the screens with their chins and foreheads supported. The room was dark except for the light from the screens. The walls of the room were painted matt black and the table that the screens were on was covered with black cloth. The right edge of the image on the left screen and the left edge of the image on the right screen were about 40 cm apart. The reference disk was always presented on the left and the matching disk was always presented on the right.

The sessions

In the *aligned screens* session the images were aligned in the frontal plane (see figure 1). The table and the walls of the room were clearly visible in the light from the screens. In the *simulated lamp* session, the screen on the left (with the reference disk) was slanted by 30°, so that its left edge was further from the subject. Its right edge was in the plane of the other screen. A curtain with two (more or less) rectangular windows was placed 175 cm from the subject, so that only the images on the screens were visible through the windows. We placed the curtain in such a manner that as much of the image was visible as possible, but since we wanted to ensure that subjects did not see the edges of the images on the screens, and due to the slanted orientation of the left screen, the retinal images were of course smaller in this situation. The angular size of the image was reduced by about 11% for the match and by about 36% for the reference (excluding the part covered by the visible lampshade). Increasing the angle between the screen and the line of sight also increased the horizontal spatial frequencies of the disk and tiles on the retina (by about 25%, depending on the position on the screen), because we simulated the same pattern on the screen.

The matching disk and its background

The matching disk had a radius of 3 cm (about 0.8°). Moving a computer mouse changed its color (mouse coordinates were mapped to the part of the two-dimensional 1931 CIE_{xy} color space that could be rendered on the screen). Pressing the 'up' or 'down' arrow key of the computer keyboard increased or decreased the matching disk's luminance. Subjects indicated that they were content with a set value by pressing the mouse button. Once they did so, a new stimulus appeared on the reference screen and the hue and luminance of the matching disk were set to random values from within the range that could be set.

The background consisted of a tiled pattern of 40 by 30 squares, each with sides of 1 cm (about 0.3°). There were nine different kinds of squares. Their colors were equally spaced along a circle with radius 0.055 around the coordinates (0.310, 0.316) in 1931 CIE_{xy} color space. The squares had luminances of 3, 6 or 9 cd/m^2 (three each) with a fixed relationship between color and luminance (see pictures in Figure 1). The nine kinds of squares were arranged in a fixed pattern of 3 by 3 squares, and this pattern was repeated across the screen.

The reference disk and its background

The reference disk had the same dimensions as the matching disk and was presented on a similarly tiled background (48 by 30 tiles in the same regular 3 by 3 pattern that was described in the previous paragraph). The disk either had 1931 CIE_{xy} coordinates of (0.310, 0.316) and a luminance of 6.0 cd/m^2 (*dark target*) or CIE_{xy} coordinates of (0.351, 0.343) and a luminance of 9.2 cd/m^2 (*bright target*). On separate trials the colors of the reference disk's tiles were either identical to those of the matching disk, suggesting that the same tiles are presented under the same uniform illumination, or else they were simulations of the same tiles under a different illumination. The different simulated illumination could either produce gradients that are consistent with light from an additional reading lamp (*simulated lamp* session), or it could be uniform and therefore just as consistent with an additional ambient light source as with differently colored tiles under the same illumination (*aligned screens* session). The question is whether subjects will attribute more of the difference in color to the illumination in the *simulated lamp* session as a result of it being more evidently a simulation of a change in illumination.

Simulating illumination by an additional lamp

The simulated tungsten reading lamp (standard illuminant A) was 24 cm from the screen surface, and about 10 cm above its centre. The metal lampshade of a real reading lamp was clearly visible at the position of the simulated lamp, partially occluded by the edge of the window (see Figure 1). The subjects' eyes were about 12 cm higher than the centre of the screen. The influence of the simulated lamp on the light emitted from the screen was the sum of a lambertian component (that depends on the angle alfa between the light rays from the lamp and the surface normal) and a specular component (that depends on the angle Beta between the line of sight and the reflection of the lamp in the surface). The light emitted from each point of the screen (S) was based on the following equation:

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

where I represents the intensity of the light source, R represents the surface's reflectance, the subscripts *ambient* and *lamp* specify the light source, *'alpha'* and *'beta'* are the angles described above, 80 is an arbitrarily chosen exponent that determines the width of the specular contribution, and 0.5 is an arbitrarily chosen constant that determines the peak amplitude of the specular contribution (in relation to the lambertian contribution). Following what is known as 'von Kries scaling' (Von Kries, 1905; Brainard & Wandell, 1992; Lucassen & Walraven, 1993) we applied this equation to the light stimulating each of the three kinds of cones (rather than to every wavelength). I_{lamp} was zero for trials without light from the additional simulated lamp.

The values of R and I are not uniquely defined by the stimulus on the screen: the same value of S could arise from a bright surface in low light or a dark surface in bright light. However this is not a fundamental problem because the shift in color is mainly determined by the ratio of the two light sources ($I_{ambient}$ and I_{lamp}). The absolute value of R is only relevant in relation with the specular component, which is anyway given an arbitrary weight. To conform to the physical capabilities of the screen we simulated 12 cd/m^2 of ambient illumination by standard illuminant C (simulating an overcast sky) and 7cd/m^2 of additional illumination by a tungsten lamp (standard illuminant A). For simulating the scene with the additional lamp *on* we first converted the CIE$_{xyY}$ values of the light emitted by the various parts of the screens when the lamp was *off* (the values given in the previous section), and of the simulated illumination, into cone stimulation values (principles explained in Lucassen & Walraven, 1993; Pokorny & Smith, 1986; for details see Appendix A in Granzier, Brenner & Smeets, 2009b). We then used the equation given above (with I_{lamp}=0) to determine the extent to which light stimulating each of the three kinds of cones was reflected by the simulated surface, and finally used these values of R to determine each point of each tile's color when the additional simulated lamp was on.

An equivalent illumination for the aligned screens

For the session with the aligned screens the simulated illumination was always uniform. In terms of the equation, I_{lamp}=0 and $I_{ambient}$ had to be adjusted so that the overall illumination was in some way equivalent to that in the session with the simulated lamp. We chose an ambient illumination ($I_{ambient}$) that matched the light emitted from the screen at the centre of the reference disk in the session with the simulated lamp. The values of R were obviously the same in the two sessions, so although there was no illumination gradient or specularity in the *aligned screens* session, the average color and local color contrasts were similar in both sessions. Of course all these simulation issues are irrelevant for trials in which the additional lamp was off, because in that case the background colors were identical on both screens.

Procedure

On each session, subjects dark adapted for 5 minutes and then matched the color and luminance of the matching disk (on the right) to that of the reference disk (on the left) for 40 minutes. The number of matches was not fixed and subjects were not pressed to respond quickly, so some subjects made more settings than others. The trials within each session alternated between ones with and without light from the additional simulated lamp (or equivalent ambient luminance and chromaticity). We hoped that alternating between having the simulated lamp *on* and *off* would encourage subjects to consider the change to be due to the illumination because with the lamp off the two backgrounds were identical. The two kinds of reference disk (bright and dark) were presented in random order.

Analysis

The first step in the analysis was to determine the median set 1931 CIE$_{xyY}$ values for each subject (n=12), session (*additional lamp* or *aligned screens*), illumination (lamp *on* or *off*) and reference disk (*dark* or *bright*). We then confirmed that the differences between the *set* x and y values on trials with the lamp *on* and *off* (i.e. the vectors between corresponding disks and circles in the left part of Figure 2) were about in the direction of the expected difference for the simulated surface in question considering the shift in the illumination that is caused by turning on the simulated light (i.e. the vector between the crosses in the left part of Figure 2). Since this was clearly the case we divided the set difference by the difference that subjects would set if they attributed all the change in the background to a change in illumination. We also divided the difference in set luminance between trials with the lamp on and off by the difference that would be expected if subjects had attributed all the change in the background to a change in illumination. These values were calculated separately for each subject, session and reference disk.

Results

During the 40-minute sessions, subjects made between 48 and 126 settings. Subjects who made more settings tended to make more variable settings, but the median value was just as reliable because the larger number of settings compensates for the larger variability. Figure 2A shows the median settings in 1931 CIE$_{xy}$ color space for one subject for the dark reference disk in the *simulated lamp* session. Dividing the distance between the set coordinates by the distance between the 'correct' coordinates according to our simulation gives an estimate of the proportion of the difference in the tiles' color that the subject attributed to a difference in illumination. Figure 2B shows this estimate as well as an equivalent estimate for luminance for both reference disks (averaged across the 12 subjects). Our main interest is in a comparison of the two kinds of simulations: red and black bars represent the *aligned screens* and *simulated lamp* sessions, respectively.

It is evident that any difference between the two sessions is very small. The proportion of the difference attributed to the illumination was much larger for luminance than for color. It also appeared to be a bit larger for the dark reference disk. In accordance with the latter impression, an analysis of variance for color, considering only the twelve subjects who each took part in a single session, with session as a between-subject factor and target luminance as a within-subject factor, revealed a significant effect of target luminance ($p=0.02$), but not of session and no significant interaction. For luminance there was also only a significant effect of target luminance ($p<0.001$). A repeated measures analysis of variance with factors target and session for the other six subjects, who took part in both sessions, revealed no significant differences for judgments of color. For judgments of luminance we found a significant effect of target luminance ($p=0.007$) and a significant interaction between session and target luminance ($p=0.01$).

Discussion

The extent to which the color of the background influenced the perceived color of the reference disk was similar to that in many studies of chromatic induction (e.g. Cornelissen & Brenner, 1995; Granzier et al., 2005; Hurlbert & Wolf, 2004; Lucassen & Walraven, 1996; Troost & de Weert, 1991; Yang & Shevell, 2003). A slightly larger influence of the background color when the target surface is darker than the background has also been found before (Bauml, 2001; Delahunt & Brainard, 2004a). These results are consistent with a combination of mechanisms such as adaptation and contrast largely determining the perceived color (Cornelissen & Brenner, 1995; Hurlbert & Wolf, 2004).

The main result of the experiment is that subjects did not attribute more of the overall difference in chromaticity between the two regions to a difference in illumination under circumstances that suggested that the difference was due to a difference in illumination. Explicitly instructing subjects to consider scenes in a certain manner can influence the extent to which differences in spectral content are attributed to illumination (Arend & Reeves, 1986; Cornelissen & Brenner, 1995). Why does evidence from within the image that the differences in spectral content are probably due to a difference in illumination not make any difference? We had the subjects view the two scenes through two windows, so that the abrupt changes in luminance at the edges of the (visible parts of the) screens are accounted for. We manipulated one surface's physical orientation to increase the credibility that the difference in color was due to a difference in illumination. Moreover we simulated illumination by a 'visible' lamp. Our finding that doing so does not make any difference to the matched colors is consistent with some reports, each using different methodologies (Amano et al., 2005; Granzier et al., 2009b; Valberg & Lange-Malecki, 1990), which show that the visual system does not try to make an estimate of the illuminant's color in order to achieve color constancy, but uses illuminant-invariant properties (e.g., color contrast) instead. Our results are in agreement with our previous study (Brenner, Granzier & smeets, 2011) in which we have found that the extent to which differences in the surrounding chromaticity are attributed to the illumination depends on how the scene is interpreted. However, this effect was only found for a color naming task and not for a color matching task. Our current results are contradictory to the findings of studies showing an influence of the surface's orientation with respect to the illumination (see also Bloj, Kersten & Hurlbert, 1999; Boyaci, Doerschner & Maloney, 2004). Finally, our data also contradict the work of Lotto and Purves (1999; 2000; 2000) who claim that increasing the probability that a change in the wavelength distribution of the light reaching the eyes arises from different illumination conditions enhances chromatic induction. The larger perceived differences between physically identical patches in their complex, virtual scenes is probably a consequence of using conditions in which luminance induction enhances the change in perceived hue (e.g. changing yellow to brown). This interpretation is in agreement with the results of our study showing much higher levels of luminance induction (higher levels of discounting the illuminants' luminance) compared to the amount of chromatic induction.

The present study tried to compensate for the drawbacks of a previous study (Granzier et al., 2005) where we concluded that an 'unexplained' transition at the borders of the screen, presenting a single surface and being aware of having to judge emitted light rather than reflected light (see also Granzier, Brenner & Smeets, 2009c) may have influenced the results. Our manipulations to make it more credible that the illumination changed between trials did have some effect on the retinal statistics. The most obvious example is that the background of the reference was smaller in the *simulated lamp* session, as was the reference disk itself (because it was viewed at an angle). The image size is unlikely to make very much difference though, because there was always at least 2.6° of visible background between the edge of the disk and that of the window. The known local chromatic effects generally saturate within this distance (e.g. Brenner & Cornelissen 1991; Granzier et al., 2005), whereas for more global effects, such as effects of overall color contrast within the scene, the difference in image size should not matter (Brenner, Ruis, Herraiz, Cornelissen, Smeets, 2003). A more important difference between the sessions may be that the gradient in illumination and the specular component from the simulated lamp increase the overall variability in color and luminance within the image, which can under certain conditions decrease simultaneous color contrast (Brenner, Granzier & Smeets, 2007a; Shevell & Wei, 2000). Apparently all these issues are not very important because the results are very similar for both sessions.

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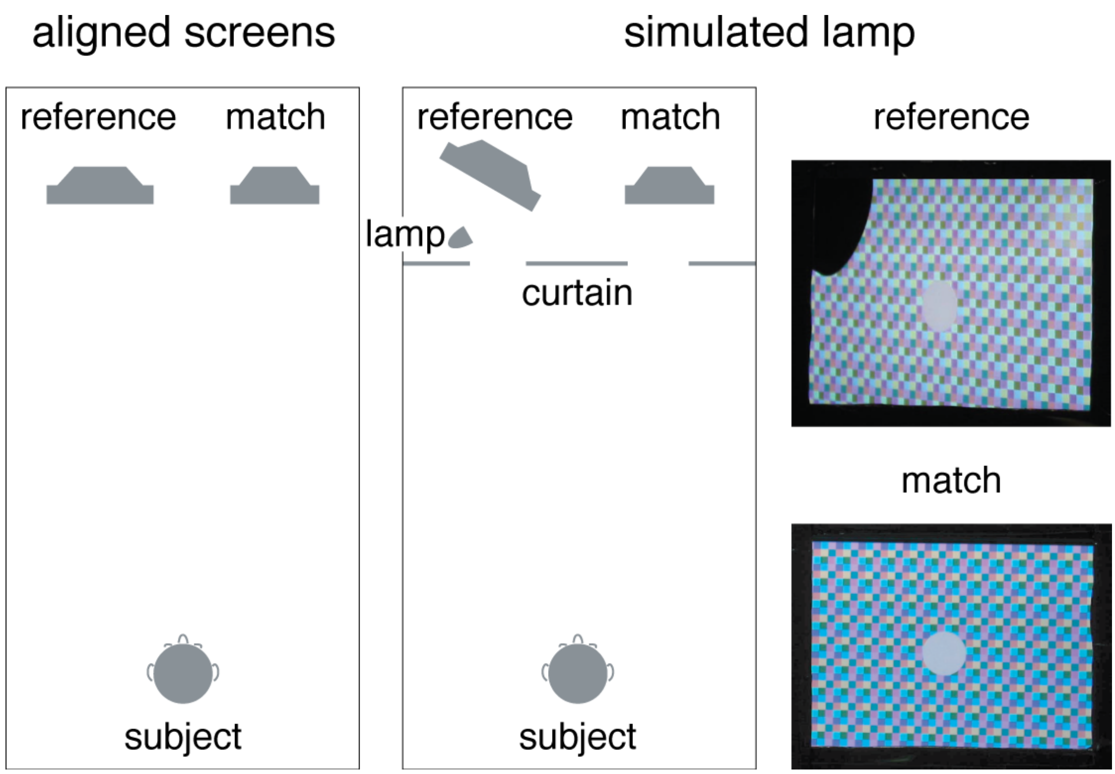

Figure 1. *Schematic overview of the two sessions. Subjects set the color and luminance of the matching disk on the right screen to match that of the reference disk on the left screen. The photographs on the right give an impression of what the subjects saw through the two windows in the lamp on trials of the simulated lamp session.*

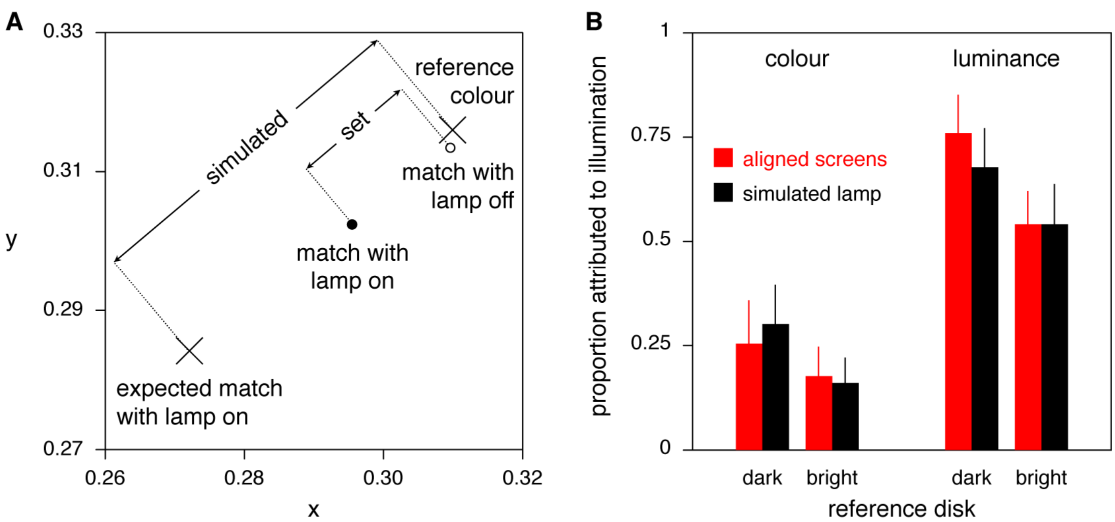

Figure 2. *A. One subject's median color settings for the dark reference disk in the simulated lamp session (in 1931 CIE$_{xy}$ color space). The cross at the top right indicates the color of the reference disk. This is also the correct value to set on trials in which the backgrounds of the test and reference disk are identical because the additional lamp is off. The cross at the lower left indicates the color that the test disk would have to be set to match the reference disk if the difference between the colors of the tiled backgrounds on trials in which the additional lamp was on were all attributed to the illumination. The open circle and filled disk show the settings for the lamp off and lamp on conditions. Since the light from the additional simulated lamp is yellowish, the same reference color should appear bluer when the lamp is on, which indeed it does. The proportion of the difference in the light coming from the two surfaces that is attributed to different illumination is estimated from the ratio of the distance between the settings in trials with the lamp on and off (set) and the distance they would have had if all changes had been attributed to the illumination (simulated). B. Averages of 12 subjects' values for this proportion (with 95% confidence intervals for these averages) for both color and luminance, and both dark and bright reference disks.*

