The role of chromatic scene statistics in color constancy: Spatial integration

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The human visual system has the ability to perceive approximately constant surface colors despite changes in the retinal input that are induced by changes in illumination. Based on computational analyses as well as psychophysical experiments, J. Golz and D. I. MacLeod (2002) proposed that the correlation between luminance and redness within the retinal image of a scene is used as a cue to the chromatic properties of the illuminant. However, J. J. Granzier, E. Brenner, F. W. Cornelissen, and J. B. Smeets (2005) found that the spatial extent in the field of vision that is relevant for the effect of the luminance-redness correlation on color appearance is very local and therefore questioned whether this scene statistic is used for estimating the illuminant. Here, I present evidence that the spatial extent is substantially more global than claimed by Granzier et al. and consistent with the hypothesis that this scene statistic is used for estimating the illuminant. It is further shown for two figural parameters of the stimuli that they influence the spatial extent and hence could have contributed to an underestimation of the spatial extent by Granzier et al. Finally, it is shown that the spatial extent relevant for the effect of mean surround chromaticity on color appearance is very similar to that found for the luminance-redness correlation.

Keywords: color vision, color appearance/constancy, chromatic scene statistics, illuminant estimation


Introduction

The visual system of humans (as well as that of other species) exhibits the ability to perceive surface colors of objects as approximately constant even under different illuminations. This ability, called color constancy, is remarkable because the light reflected from a surface depends on the spectral reflectance characteristic of the surface as well as on the spectral power distribution of the illuminant and hence the retinal color codes for each surface in a scene vary substantially under changing illumination. But if the visual system has information about the chromatic properties of the illuminant present in the scene (or part of the scene), it could disentangle the retinal input for each surface into the surface and illuminant components and thereby gain color constant surface descriptors that are sufficiently independent of the illuminant-induced changes of the retinal input.

However, the chromatic properties of the illuminant are not generally directly known. Thus, the problem of color constancy is mathematically underdetermined, and additional constraints must be drawn from the regularities of the physical world to reduce the amount of possible combinations of surface and illuminant colors to a unique solution. Among other possibilities, such regularities can be gained from three-dimensional properties of scenes. For instance, highlights at curved surfaces (D’Zmura & Lennie, 1986; Lee, 1986; Maloney & Yang, 2003; Tominaga & Wandell, 1989) or mutual reflections at corners (Bloj, Kersten, & Hurlbert, 1999; Funt & Drew, 1993; Funt, Drew, & Ho, 1991) have been proposed as cues for estimating the chromatic properties of the illuminant. Furthermore, the chromatic distribution in the two-dimensional image of the scene can provide cues to the chromatic properties of the illuminant (Forsyth, 1990; Golz, 2005; Golz & MacLeod, 2002; Lotto & Purves, 1999; MacLeod & Golz, 2003; Mausfeld, 1998; Mausfeld & Andres, 2002).

The idea that one particular statistic of the chromatic distribution, the mean chromaticity, can be used to estimate the illuminant dates back at least to von Helmholtz (1896) and underlies so-called gray-world algorithms of color constancy (e.g., Buchsbaum, 1980). For a given scene this statistic varies systematically with chromatic changes in illumination. But in more realistic situations in which the scenes might change as well, this measure is ambiguous because it can vary substantially for different scenes under the same illuminant (Brown, 1994; Golz, 2005).

In previous work (Golz & MacLeod, 2002; MacLeod & Golz, 2003), MacLeod and I have investigated which other chromatic scene statistics could be used as a cue to the chromatic properties of the illuminant and thus could, in combination with mean chromaticity, facilitate color constancy. As a first step, we analyzed the transformation that the distribution of cone excitations undergoes when the illuminant changes, and which statistics of this chromatic distribution depend systematically on the illuminant. These computational analyses were based on an idealized model of our spectral environment, the so-called Gaussian World, as well as on simulations with hyperspectral images of natural scenes. For those chromatic scene statistics that proved in the computational
analyses to be potential cues to the illuminant, we tested in a second step by psychophysical experiments whether they are effectively taken into account by the human visual system for the perception of surface colors. In each of these experiments, subjects performed gray settings for a test field in variegated surrounds (adapted from Mausfeld & Andres, 2002) in which we varied only the tested scene statistic while keeping all other scene statistics constant.

The correlation between luminance and redness within the retinal image turned out to be the most promising cue to the illuminant. First, in the computational analyses this statistic has been found to be diagnostic for the chromatic properties of the illuminant. This diagnostic value is based on the following characteristic of the spectral interplay of illuminants, surfaces, and cones: Surfaces that are chromatically similar to the illuminant are rendered as lighter in the retinal image relative to surfaces that are dissimilar from the illuminant. Due to this chromaticity-dependent increase in intensity a higher luminance-redness correlation for instance indicates a more reddish illuminant. Second, in the psychophysical experiments the luminance-redness correlation yielded a systematic effect on gray settings, the direction and degree of which was consistent with predictions based on the computational analyses: For higher luminance-redness correlations in the surround subjects selected more reddish chromaticities for the test field to appear achromatic.

This basic experimental result was also found by Granzier, Brenner, Cornelissen, and Smeets (2005). However, in their experiments they furthermore constrained the luminance-redness correlation to have a high value only within an annular region immediately around the test field, the remaining outer region of the surround having a low luminance-redness correlation. By varying the size of the inner annular region, they tested the spatial extent in the field of vision that is relevant for the effect of the luminance-redness correlation on color appearance of the test field and found “that the correlation within about 1° of the target is relevant” (p. 20). On the basis of this local effect, they conclude that the luminance-redness correlation is not used to estimate the chromatic properties of the illumination. For this purpose, the visual system would have to take the chromatic properties from a larger area of the stimulus into account.

However, the stimuli that Granzier et al. (2005) used in their experiments differ with respect to several parameters from stimuli typically used when investigating the role of chromatic scene statistics for color constancy and it can be questioned (as discussed later), whether their stimuli are suitable to obtain an estimate of the typical spatial extent that is taken into account for the luminance-redness correlation in natural situations. Therefore, in Experiment 1 an analogous test of the spatial extent relevant for the effect of the luminance-redness correlation is presented, but instead of their type of stimuli, the same type of stimuli as in our previous work on this scene statistic (Golz, 2005; Golz & MacLeod, 2002) is used here. Since in Experiment 1 the effect of the luminance-redness correlation turns out to be based on a substantially more global region of the field of vision than in the experiments of Granzier et al., I then survey two of the stimulus properties which differ between their study and Experiment 1, showing that these properties have an influence on the spatial extent for the luminance-redness correlation that could explain, at least partially, why Granzier et al. found a much more local effect: firstly, the size of the elements making up the variegated surround (Experiment 2), and secondly, the visual salience of the border separating the surround into the two regions with different values for the luminance-redness correlation (Experiment 3). In Experiment 4 an analogous investigation as in Experiment 1 is carried out for the mean chromaticity in order to compare the spatial extent for this scene statistic and that for the luminance-redness correlation.

**Experiment 1: Luminance-redness correlation**

**Methods**

In order to measure the spatial extent of the area in the field of vision that is relevant for the effect of the luminance-redness correlation, I varied the size of an annular region with high luminance-redness correlation immediately surrounding the central test field for which subjects had to make gray settings. With increasing size of this inner region, the remaining outer region in the periphery of the stimulus with zero luminance-redness correlation gets smaller and the effect of the high luminance-redness correlation on the test field settings (i.e., selecting more reddish chromaticities to appear gray) should increase until the area that is taken into account by the visual system for this effect is completely covered by the inner region. The size of this inner region with high luminance-redness correlation was varied in five conditions: 0°, 2°, 4°, 8°, and “all,” where the visual angle 0°–8° specifies—following the notation of Granzier et al. (2005)—the width of the annular inner region around the central test field (see Figure 1). So, for 0° there is no such inner region with high luminance-redness correlation. In the “all” condition, the inner region covers the entire rectangular surround (width × height: 40° × 31°).

**Stimuli**

The type of stimuli used in this experiment (see Figure 1) is—except for the division of the surround into two regions with different correlation values—the same as the type used in Golz and MacLeod (2002) and Golz (2005).
are the luminance-normalized excitations of L and S cones respectively. The units for L, M, and S cone excitations were chosen such that $l = 0.7$ and $s = 1.0$ for an equal-energy white (see Golz & MacLeod, 2003). By luminance-redness correlation, the correlation between $l$ and luminance is meant.

The chromatic statistics of the stimuli are given in Table 2. Except for the correlation between $l$ and luminance (for which the size of the inner region with a value of 0.8 and the outer region with a value of 0.0 varied as the experimental conditions), all statistics were equal for the inner and the outer region. The values were chosen to resemble the chromatic statistics of natural scenes (Ruderman, Cronin & Chiao, 1998) under daylight of 7000 K color temperature. In order to calculate the color codes for variegated surrounds with the intended chromatic statistics, the same algorithm as in our previous work on chromatic scene statistics (which is similar to the algorithm described in Mausfeld & Andres, 2002) was used, the only modification being that the algorithm now allows for different statistics within an inner and outer region of the surround. For each region, the colors of the circles belonging to that region (i.e., circles for which the center lies within that region) are chosen to produce the intended chromatic statistics. All pixels of a particular circle are assigned the same color even if that circle reaches partially into the other region. The chromatic statistics of each region are not calculated on the basis of individual circles but on the basis of all individual pixels that lie within that region. Note that the circular border between the inner and outer region of the surround is only virtual in that the algorithm ensures that for both regions the chromatic statistics calculated over all pixels within the respective region have the intended values while a particular circle in the surround can lie across this border without being split with regard to its color. (Therefore, the border between the two regions is visually not salient in the stimuli, a point that becomes important in Experiment 3.)

The same set of four different spatial layouts for a random but fixed placement of the circles in the surround was used for each condition, such that for each spatial layout only the colors used to paint these circles differed between the conditions of different sizes of the inner region.

<table>
<thead>
<tr>
<th>Stimulus parameter</th>
<th>Experiment 1</th>
<th>Granzier et al. (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of display (width × height)</td>
<td>$40^\circ \times 31^\circ$</td>
<td>$16^\circ \times 16^\circ$ (Experiment 1)</td>
</tr>
<tr>
<td>Size of surround elements</td>
<td>1.5$^\circ$ (diameter)</td>
<td>0.42$^\circ$ (edge length)</td>
</tr>
<tr>
<td>Surround colors</td>
<td>&gt;2000 different chromaticities</td>
<td>2 different chromaticities</td>
</tr>
<tr>
<td>Surround structure</td>
<td>Overlapping circles</td>
<td>Disjoint squares</td>
</tr>
<tr>
<td>Relation test field/surround elements</td>
<td>Same form and size</td>
<td>Different form and size</td>
</tr>
</tbody>
</table>

Table 1. Differences in stimulus parameters between Experiment 1 and the experiments of Granzier et al. (2005). The specification “42 min of arc” given in Granzier et al. (p. 22) for the size of their surround elements is a mistake according to coauthor J. B. J. Smeets (personal communication, November 26, 2007). Correct is the value 0.42$^\circ$ as given here.

Figure 1. Example of stimuli used in Experiment 1. The dashed elements were not displayed in the experiment but are used here to indicate the inner region of the surround (dashed circle) in which a higher luminance-redness correlation was present than in the remaining outer region of the surround. The size of this inner region (measured as the width of the annulus surrounding the test field: dashed vertical lines) is manipulated in the experiment. The central test field is indicated here by black marking. This image is an example for the condition with a size of the inner region of 4$^\circ$.
were content with the adjustment, subjects pressed a key and the next trial started with a new stimulus. The initial color of the adjustable disk was randomly chosen. After dark adapting for 5 min and viewing the first stimulus for 2 min, subjects made a total of 80 settings (16 repetitions × 5 conditions) within a single session. In order to balance potential carry-over effects between conditions, 8 settings for each of the 5 conditions in the order of 0°, 2°, 4°, 8°, “all” were collected first and then another 8 settings for each condition in reversed order. (However, in the analysis of the results no indications of systematic carry-over effects were found.) For all conditions, the same four different spatial layouts for the placement of the circles in the surround were used, so for each condition each of the four layouts was collected four times.

**Results**

As mentioned in the Introduction, the basic effect of the luminance-redness correlation (the spatial extent of which is measured in this experiment) is that a higher luminance-redness correlation within the surround results in more reddish chromaticities (i.e., higher l values) for the gray settings of subjects. Because the absolute l values of gray settings can differ systematically between subjects even for the same condition, the values of each subject are normalized to yield values relative to the range of values for that subject. These relative values are easier to compare and are presented in all following figures. A relative value of 0.0 corresponds to the mean of the condition with the lowest l values, 1.0 corresponds to the mean of the condition with the highest l values. The absolute l values of these minimum and maximum means used for the normalization are given for all subjects in Table 3. The minimum means arise from the 0° condition for all subjects and the maximum means arise either from the 8° or the “all” condition. (In the discussion of Experiment 4, these values are further commented on in comparison with the corresponding values of that experiment.)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Minimum mean of l</th>
<th>Maximum mean of l</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>0.6870</td>
<td>0.6889</td>
</tr>
<tr>
<td>BJ</td>
<td>0.6781</td>
<td>0.6797</td>
</tr>
<tr>
<td>CB</td>
<td>0.6881</td>
<td>0.6904</td>
</tr>
<tr>
<td>DS</td>
<td>0.6866</td>
<td>0.6885</td>
</tr>
<tr>
<td>IG</td>
<td>0.6692</td>
<td>0.6733</td>
</tr>
<tr>
<td>JF</td>
<td>0.6763</td>
<td>0.6810</td>
</tr>
<tr>
<td>JG</td>
<td>0.6849</td>
<td>0.6882</td>
</tr>
<tr>
<td>KM</td>
<td>0.6829</td>
<td>0.6864</td>
</tr>
<tr>
<td>NS</td>
<td>0.6801</td>
<td>0.6834</td>
</tr>
<tr>
<td>SA</td>
<td>0.6889</td>
<td>0.6918</td>
</tr>
</tbody>
</table>

Table 3. Absolute l values of the minimum and maximum means used for the subject-wise normalization of the data (see text).
The effect of the luminance-redness correlation on the gray settings increases when the inner region with a high correlation value is enlarged from $0^\circ$ to $8^\circ$. (Surprisingly however, it decreases again when the inner region covers the entire stimulus in the “all” condition. This point is taken up again in the discussion below.) The following function was fitted to the data points for the conditions of $0^\circ$ to $8^\circ$ (omitting the “all” condition due to the above-mentioned decrease):

$$f(x) = 1 - \alpha \exp(-\beta x^2)$$

This function has been found for all subjects to describe the underlying data sufficiently well and is used to determine the size of the inner region for which the effect of the luminance-redness correlation is $75\%$ of the maximum effect. For subject AG, this $75\%$ criterion is reached at $5.0^\circ$ (vertical straight line in Figure 2). The values for all ten subjects are given in Table 4 (along with values for an analogous $90\%$ criterion). The $75\%$ measures range from $1.6^\circ$ to $5.8^\circ$ with a mean of $4.3^\circ$. Figure 3 shows the results obtained by averaging the relative values of all subjects (hereafter referred to as “average observer”).

The overall effect of the size of the inner region on the gray settings is individually statistically significant for all subjects [$F(1,4) > 3.7, p < 0.01$, respectively]. The increase of the effect when enlarging the inner region beyond $2^\circ$ toward $8^\circ$ is statistically significant for all but one subject [$t(30) > 2.2, p < 0.05$, one tailed, respectively] and the increase when enlarging the inner region beyond $4^\circ$ toward $8^\circ$ is statistically significant for five of ten subjects [$t(30) > 2.0, p < 0.05$, one tailed, respectively]. The decrease of the effect when the inner region is enlarged from $8^\circ$ to the entire surround (“all”) is statistically significant for five of ten subjects [$t(30) > 2.4, p < 0.05$, one tailed, respectively].

### Discussion

The effect of the luminance-redness correlation on the gray settings measured in this experiment increases when the inner region with a high correlation value is enlarged, and subjects require on average an inner region of $4.3^\circ$ to exhibit an effect of $75\%$ of the maximum effect. This spatial extent relevant for the luminance-redness correlation effect is substantially more global than that measured by Granzier et al. (2005). In their experiments enlarging the inner region beyond $1^\circ$ had little effect on color appearance. Based on this finding they concluded (p. 20) that “it is unlikely that the visual system uses the correlation between luminance and color to explicitly determine the chromaticity of the illuminant. Instead, this correlation is presumably implicitly considered in the way

<table>
<thead>
<tr>
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<th>AG</th>
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<th>JF</th>
<th>JG</th>
<th>KM</th>
<th>NS</th>
<th>SA</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>5.0</td>
<td>3.9</td>
<td>2.9</td>
<td>1.6</td>
<td>4.4</td>
<td>5.8</td>
<td>4.8</td>
<td>5.4</td>
<td>5.3</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>90%</td>
<td>6.6</td>
<td>4.2</td>
<td>5.1</td>
<td>2.3</td>
<td>5.4</td>
<td>10.7</td>
<td>6.3</td>
<td>6.7</td>
<td>6.9</td>
<td>7.8</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 4. Spatial extent relevant for the effect of the luminance-redness correlation measured in Experiment 1 for all subjects. The values specify (in degree visual angle) the size of the inner region for which each subject exhibits 75% (or 90%) of the maximum effect of the luminance-redness correlation.
that the color contrast at borders is determined.” This general conclusion has to be questioned in the light of the findings of Experiment 1. Remember that the size of the inner region is given as the width of an annular region surrounding the test field. So, a size of 4.3° corresponds to an area (including the 1.5° test field) of 10.1° in diameter. In this area on average more than 120 differently colored patches are present in the stimuli used here. That the visual system requires this area to exhibit 75% of the maximum effect of the luminance-redness correlation can be regarded as compatible with the hypothesis that the visual system uses this scene statistic to estimate the chromatic properties of the illuminant for the central part of the stimuli that incorporates the test field. (There is no reason to assume that the visual system would have to take into account the whole scene including the most peripheral parts to estimate the illuminant, all that is necessary is a spatial extent that is sufficiently large for this purpose. This point is further dealt with in the general discussion below.)

But why did Granzier et al. (2005) measure a substantially more local effect of the luminance-redness correlation than those presented here? One possibility is that the stimuli they used have led to a constriction of the area that is taken into account by the visual system for the color appearance of the test field and that such a constriction does not (or only to a smaller degree) occur with the stimuli used here. If this were the case, the results of Granzier et al. would presumably not be representative for the functioning of the visual system in other situations and should not be used as a basis for general conclusions about the role of the luminance-redness correlation in the estimation of the illuminant. Two of the properties for which the stimuli of Granzier et al. and Experiment 1 differ and which could hypothetically have led to such a constriction in the experiments of Granzier et al. are the size of the elements making up the surround and the salience of the border that separates the two regions of the surround. First, the visual system could adjust the size of the area taken into account for the estimation of the illuminant depending on the size of the elements in the surround in the sense that for smaller elements a smaller area suffices to determine the chromatic statistics on the basis of the same number of elements. Second, the border between the inner region with high luminance-redness correlation and the outer region with low correlation is visually salient in the stimuli of Granzier et al. This could have led the visual system to abandon a more global estimation of the illuminant and instead to perform for both regions a separate estimation (e.g., in the sense of a segregation into two different local reference frames for which a different anchoring of the input is carried out, see Gilchrist et al., 1999). Consider a hypothetical case of a separate estimation for both regions in which the area taken into account by the visual system to estimate the illuminant at the test field always shrinks to the experimentally manipulated size of the inner region as outlined by the salient border. In this case the experimental results would resemble those of Granzier et al.: Even for a small inner region, the full effect on the color appearance of the test field would be found (i.e., the same effect as that for the largest inner region). However, this does not rule out the possibility that in other situations (e.g., with a non-salient border) the visual system takes into account a larger area for estimating the illuminant. But this can only be tested by a border type that does not trigger a separate estimation of the illuminant for the inner region: only then the area taken into account by the visual system remains the same while the size of the inner region is experimentally varied in order to measure the size of the inner region that is necessary to get the full effect on the color appearance of the test field.

Therefore, the next two experiments investigate whether these stimulus parameters influence the spatial extent relevant for the effect of the luminance-redness correlation in a way that could explain the differences between the results of Granzier et al. (2005) and those of Experiment 1: The size of the surround elements is tested in Experiment 2 and the salience of the border in Experiment 3.

But first two more aspects of Experiment 1 deserve mention. First, in Figures 2 and 3 the effect of the luminance-redness correlation decreases when the inner region with high luminance-redness correlation is enlarged from 8° to the entire surround (“all” condition). However, this unexpected effect is significant only for five of ten subjects. Comparable heterogeneous evidence for a decrease in the “all” condition is found for the effect of the mean chromaticity in Experiment 4 (see below). The algorithm used to generate the stimuli of these experiments ensures that this effect is not an artifact due to changes of scene statistics in more central parts of the stimuli when the inner region grows beyond 8° in the “all” condition. More research is necessary to find out whether this is a general effect of the way in which the visual system takes into account chromatic statistics in the periphery and what causes this effect. One candidate factor that could contribute to this decrease can possibly be derived from the results of Experiment 3 and will be dealt with in the discussion of that experiment.

Second, except for the luminance-redness correlation that differs between the inner and outer region of the surround the means, standard deviations and other correlations in the (l, s, luminance) space are the same for both regions. In particular, both regions are equated with respect to the mean of the chromaticity coordinate l (hereinafter referred to as the “unweighted mean”). But there is a different measure for the average redness that could be used and this measure differs for the two regions with different luminance-redness correlation even if the unweighted mean redness does not differ: The l coordinates of a region are averaged after each of these values are weighted by the corresponding luminance (and divided by the average luminance of the region to make the weighting factors sum up to 1.0). This so calculated
measure (hereinafter referred to as the “luminance weighted mean”) is equivalent to calculating the average redness by first averaging the coordinates in the (L, M, S) cone excitation space and then projecting the resulting mean values onto the MacLeod–Boynton chromaticity plane (l, s). So, if one uses the same luminance weighted mean redness for both regions, the two are equated on the level of cone excitations, but if one uses the same unweighted mean, the two regions are equated on the opponent level of the MacLeod–Boynton measures. In Golz (2005), I have shown that the basic effect of the luminance-redness correlation holds no matter which of the two measures for the mean is used, so this effect is not merely a consequence of equating the average redness on the wrong level. Furthermore, Granzier et al. (2005) did not find substantial differences for the spatial extent relevant for the effect of the luminance-redness correlation when equating in these two different ways (which they called “matched ratio method” and “matched sum method” for their situation with only two different chromaticities in each region). And finally, in an additional (not presented) experiment analogous to Experiment 1 but with stimuli equated for the luminance weighted mean redness the results were very similar to those presented above. So, the method chosen for equating the average redness does not seem to be critical for the spatial extent relevant for the effect of the luminance-redness correlation.

**Experiment 2: Size of surround elements**

For the reasons mentioned in the discussion of Experiment 1, it is tested in Experiment 2 whether the spatial extent relevant for the effect of the luminance-redness correlation is influenced by the size of the elements making up the surround.

**Methods**

As in Experiment 1, the spatial extent of the area in the field of vision that is relevant for the effect of the luminance-redness correlation is measured by manipulating the size of an inner region with high luminance-redness correlation. In addition, in Experiment 2 the size of the elements making up the surround is varied with three conditions: “standard” (1.5°, as in Experiment 1), “small” (1°), and “tiny” (0.44°).

**Stimuli**

The stimuli for the condition with a “standard” size of surround elements (1.5°) are exactly the same as in Experiment 1. For the other two conditions, only the circles in the surround are drawn with smaller diameters (1° and 0.44°, respectively). However, to avoid difficulties of subjects with the gray settings for a too small test field its size remained 1.5°. So, for these two conditions the test field and the surround elements differed in size.

**Apparatus**

The same apparatus as in Experiment 1 was used.

**Subjects**

Eight subjects took part in Experiment 2, all of whom had also participated in Experiment 1.

**Procedure**

The same procedure as in Experiment 1 was used, only that the data collection within each of the 10 blocks for the 5 conditions of the size of the inner region was triplicated to incorporate a block for the “standard,” “small,” and “tiny” size of surround elements, respectively. Subjects made a total of 120 settings (8 repetitions × 5 sizes of the inner region × 3 sizes of the surround elements) within a single session.

**Results**

Figure 4 shows the result pattern for one of the subjects. At lower sizes for the inner region of 2° and 4° the relative effects of the luminance-redness correlation are higher for the “tiny” condition than for the “standard” condition, while the differences between the “small” and the “standard” condition are not substantial. Thus, for the “tiny” condition the fitted function is steeper and reaches a
plateau earlier compared to the “standard” condition. This indicates that the spatial extent relevant for the effect of the luminance-redness correlation becomes more local when the size of the surround elements is reduced from “standard” (1.5°) to “tiny” (0.44°).

The subject shown in Figure 4 is the subject with the smallest standard errors (the author). Though the variability was higher for the other seven subjects, the more local effect for the “tiny” condition appears in their results as well: the higher relative effects for the “tiny” condition compared to the “standard” condition was individually statistically significant for six of eight subjects at a size of the inner region of 2° \[t(14) > 2.0, p < 0.05, \text{one tailed}, \text{respectively}\] and for three subjects still at 4° \[t(14) > 2.0, p < 0.05, \text{one tailed}, \text{respectively}\]. Figure 5 shows the result for the average observer established by averaging the relative values of all subjects.

Discussion

This experiment provides evidence that the spatial extent relevant for the effect of the luminance-redness correlation becomes substantially more local when the size of the surround elements is reduced from “standard” (1.5°) to “tiny” (0.44°). Therefore the smaller spatial extent that Granzier et al. (2005) measured for the effect of this scene statistic compared to those found in Experiment 1 is likely to be caused at least in part by the difference in the size of the surround elements in the stimuli of these studies.

Methods

As in Experiment 1, the size of an inner region with high luminance-redness correlation is manipulated in order to measure the spatial extent of the area in the field of vision that is relevant for the effect of the luminance-redness correlation. But in addition to the virtual border separating the inner region from the remaining outer region with zero luminance-redness correlation in Experiment 1, two other, more salient types of border are used in Experiment 3 (see Figure 6). Thus, in addition to the size of the inner region, there is now a second independent variable for the border type, the conditions of which are named as follows:

1. “non-salient” (same as in Experiment 1): The circular border is only virtual in that the algorithm for determining the color codes of the circles in the surround ensures that for both regions the chromatic statistics have the intended values, but all circles are painted homogeneously even those of the inner region that extend beyond this virtual border into the outer region (see Figure 6b).
2. “color change”: Circles crossing the border are still drawn with an intact circular form but not painted homogeneously—the color of each circle differs on either side of the border (see Figure 6c).
3. “form change”: The outlines of circles are truncated at the border and different circles with different colors are painted on the other side of the border, so the outlines do not match across the border (see Figure 6d).

Note, that for the sake of clarity the chromatic differences have been exaggerated in Figures 6c and 6d in order to ensure that the color and form changes respectively are visible in this reproduction. But even without this amplification in the calibrated experimental displays the circular border was visually salient for these two conditions.

Stimuli

The stimuli for the condition with the “non-salient” border type are exactly the same as in Experiment 1. The stimuli for the other two border type conditions have the same chromatic statistics and differ only in the way the border is realized as described above. However, this affects only the stimuli for sizes of the inner region of 2°, 4°, and 8° because for 0° and “all” there exists no...
separation of the surround in two different regions and hence no border. Thus, for the latter two sizes of the inner region there is no distinction between different border types.

The algorithm for calculating stimuli with the intended chromatic statistics for the “non-salient” border type (the same algorithm as in Experiment 1) cannot be used to generate stimuli with a size of the inner region smaller than 2° because the algorithm is not able to find a solution that fulfill the mathematical constraints when there are too few elements in the inner region. The stimuli for the other two border types, on the other hand, are generated by clipping (with a circular filter mask) an inner region from one stimulus image and inserting it onto a second image (where the whole surround of the first image had the intended statistics for the inner region and the second image for the outer region). Thus, it is possible to generate stimuli with an inner region size of 1° for the border type conditions “color change” and “form change” and these were included in the experiment. It was checked whether the chromatic statistic of the regions in these stimuli deviated from the intended values. (Because the clipped regions were smaller than the larger images from which they were clipped and for which the algorithm ensured the intended chromatic statistics, they could principally have deviated if colors were placed spatially biased by accident.) All deviations were negligible.

**Apparatus**

The same apparatus as in Experiment 1 was used.

**Subjects**

Seven subjects took part in Experiment 2, all of whom had also participated in Experiment 1.
Procedure

The same procedure as in Experiment 1 was used, except that the data collection within each of the 6 blocks for the 3 conditions with sizes of the inner region of 2°, 4°, and 8° was triplicated to incorporate a block for each of the three border types “non-salient,” “color change,” and “form change.” For the conditions 0° and “all” no such triplication was necessary for reasons mentioned above. For the border types “color change” and “form change” data for a 1° inner region was collected additionally. Subjects made a total of 104 settings (8 repetitions × ((3 sizes of the inner region × 3 border types) + (2 sizes of the inner region × 1 border type) + (1 size of the inner region × 2 border types))) within a single session.

Results

Figure 7 shows first the result for the subject with the smallest standard errors (the author). The mean relative effects of the luminance-redness correlation systematically increase when the inner region is enlarged from 2° to 8° for the “non-salient” condition but not so for the “color change” and “form change” conditions. Thus, the resulting fitted functions indicate a smaller spatial extent for the “color change” and “form change” conditions than for the “non-salient” condition. Note that the overall level of the relative effects seems to be reduced for the “color change” and “form change” conditions such that even at 8° the mean effects are substantially lower for these two condition than that of the “non-salient” condition. However, the standard errors of all subjects were relatively large and in contrast to the results of the Experiment 1, 2, and the following Experiment 4, a consistent result pattern was not evident for all subjects.

Thus, the evaluation of the results of Experiment 3 is not based on the individual results but instead on the results for the average observer established by pooling the relative values of all subjects. This of course makes the conclusions somewhat weaker than those of the other three experiments presented. The result pattern for the average observer (see Figure 8) is similar to that described for subject JG above. The increase of the relative effect when enlarging the inner region from 2° to 8° is statistically significant for the “non-salient” condition \((t(110) = 3.48, p < 0.001, \text{one tailed})\) but neither for the “color change” nor the “form change” condition. Furthermore, at 8° the relative effect is significantly lower compared to the “non-salient” condition for the “color change” condition \((t(110) = 2.74, p < 0.01, \text{one tailed})\) as well as for the “form change” condition \((t(110) = 2.68, p < 0.01, \text{one tailed})\).

Discussion

This experiment provides evidence that the spatial extent relevant for the effect of the luminance-redness correlation is more local for the two salient border types “color change” and “form change” than for the “non-salient” border type that was also used in Experiment 1. Therefore the smaller spatial extent that Granzier et al. (2005) measured for the effect of this scene statistic compared to those found in Experiment 1 is likely to be caused at least in part by the fact that the border that separates the inner region of the surround from the outer region was visually salient in their experiments. However, the statistical evaluation of the results of Experiment 3 is based on the average observer, so this conclusion is not warranted to the same degree of confidence as those of the other Experiments 1, 2, and 4 which are based on significant individual results.

On the basis of the results of this experiment one could conjecture about a potential factor that could contribute to the decrease of the effect of the redness-luminance
correlation that is found in Experiment 1 when the inner region is enlarged beyond 8° to cover the entire surround in the “all” condition (and similarly for the decrease of the effect of the mean chromaticity in Experiment 4). In these experiments, the inner region is circumscribed by a non-salient border in the 8° condition, but in the “all” condition the inner region adjoins the very salient border to the dark region outside of the monitor screen. This difference could possibly result in a decrease of the effect between these two conditions since Experiment 3 has provided evidence that the overall level of the effect is reduced for salient border types. But as already mentioned above, more research is necessary to find out whether such a decrease is a general effect of the way in which the visual system takes into account chromatic statistics in the periphery and what causes this effect.

**Experiment 4: Mean chromaticity**

In this experiment the spatial extent of the area relevant for the influence of the mean chromaticity of the surround on the appearance of the central test field is measured in a way analogous to Experiment 1, except that the role of the luminance-redness correlation is now assumed by the mean chromaticity. This makes a comparison of the spatial extent for these two chromatic scene statistics possible.

**Methods**

The spatial extent relevant for the effect of the mean chromaticity of the surround is measured by manipulating the size of an inner region with slightly reddish mean chromaticity (using the same conditions for the size of the inner region as in Experiment 1: 0°, 2°, 4°, 8°, and “all”) while the remaining outer region has a neutral mean chromaticity.

**Stimuli**

The stimuli in this experiment are similar to those used in Experiment 1 except that the two regions of the surround have two different mean chromaticities but the same luminance-redness correlation (see Table 5). All other chromatic statistics are unchanged. As in Experiment 1, the size of the elements making up the surround is 1.5° and the non-salient border type is used.

**Apparatus**

The same apparatus as in Experiment 1 was used.

<table>
<thead>
<tr>
<th>Chromatic statistic</th>
<th>Inner region:</th>
<th>Outer region:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of chromaticity l</td>
<td>0.69</td>
<td>0.685</td>
</tr>
<tr>
<td>Mean of chromaticity s</td>
<td>1.14</td>
<td>1.27</td>
</tr>
<tr>
<td>Mean of luminance</td>
<td>20 cd/m²</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of l</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of s</td>
<td>0.1536</td>
<td></td>
</tr>
<tr>
<td>Standard deviation of luminance</td>
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<td></td>
</tr>
<tr>
<td>Correlation l and luminance</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Correlation s and luminance</td>
<td>-0.1153</td>
<td></td>
</tr>
<tr>
<td>Correlation l and s</td>
<td>-0.2133</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Chromatic statistics of the stimuli used in Experiment 4. The inner and outer region of the surround differ only in the mean chromaticity values.

**Subjects**

Seven subjects took part in Experiment 4. Four of these had participated in Experiment 1. The other three likewise had normal color vision and were naive with respect to the design and purpose of the study.

**Procedure**

The same procedure as in Experiment 1 was used.

**Results**

As in the previous experiments, the absolute values of each subject are normalized to yield values relative to the range of values for that subject. A relative value of 0.0 corresponds to the mean of the condition with the lowest values of the chromaticity coordinate l, 1.0 corresponds to the mean of the condition with the highest l values. The absolute l values of the minimum and maximum means used for this normalization are given for all subjects in Table 6.

Figure 9 shows the typical result pattern for one of the subjects. The effect of the mean chromaticity on the gray settings increases when the inner region with a more reddish mean chromaticity is enlarged from 0° to 8°. A similar trend was observed in Experiment 1, the function of Equation 1 is fitted to the data points to determine the size of the inner region for which the effect of the mean chromaticity is 75% of the maximum effect (vertical straight line in Figure 9). The values for all seven subjects are given in Table 7 (along with values for an analogous 90% criterion). The 75% measure range from 1.9° to 5.7° with a mean of 4.1°. Figure 10 shows the results for the average observer established by averaging the relative values of all subjects. The overall effect of the size of the inner region on the gray settings is individually statistically significant for all
Discussion

In order to exhibit 75% of the maximum effect of the mean surround chromaticity on the color appearance of a test field subjects require on average an inner region with more reddish mean chromaticity than the remaining outer region of 4.1°. Thus, the spatial extent relevant for the effect of the mean chromaticity measured in Experiment 4 is similar to the spatial extent relevant for the effect of the luminance-redness correlation measured in Experiment 1 where an average value of 4.3° was obtained for an analogous 75% criterion.

Several studies have measured the spatial extent relevant for the influence of background chromaticity on color appearance of a test field, e.g., Walraven (1973), Valberg (1974), and Fairchild and Lennie (1992). In these studies, the spatial extent is typically between 1° and 2° (when a 75% criterion, corresponding to the one used here is applied). But these studies are substantially different from the present Experiment 4 in that they use homogeneous (or isochromatic in the case of Fairchild & Lennie, 1992) backgrounds, briefly flashed test fields, and much smaller total sizes of the background. These stimuli differences may be responsible for the smaller spatial extent found in these studies compared to the results of Experiment 4. Note that in these studies the mechanism whose spatial extent was measured was stimulated by only a single chromaticity. Wesner and Shevell (1992) showed that introducing additionally to an inner adapting field an outer ring (3° i.d., 5° o.d.) with a different chromaticity can have a substantial influence on color appearance of the test field.

For all of the above presentations of experimental results for the dependence of the gray settings on the size

<table>
<thead>
<tr>
<th>Subject</th>
<th>Minimum mean of I</th>
<th>Maximum mean of I</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>0.6846</td>
<td>0.6883</td>
</tr>
<tr>
<td>BJ</td>
<td>0.6859</td>
<td>0.6903</td>
</tr>
<tr>
<td>DW</td>
<td>0.6810</td>
<td>0.6847</td>
</tr>
<tr>
<td>JG</td>
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<tr>
<td>KR</td>
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<td>0.6836</td>
</tr>
<tr>
<td>LT</td>
<td>0.6810</td>
<td>0.6837</td>
</tr>
<tr>
<td>NS</td>
<td>0.6795</td>
<td>0.6841</td>
</tr>
</tbody>
</table>

Table 6. Absolute / values of the minimum and maximum means used for the subject-wise normalization of the data (see text).

<table>
<thead>
<tr>
<th>Subject</th>
<th>AG</th>
<th>BJ</th>
<th>DW</th>
<th>JG</th>
<th>KR</th>
<th>LT</th>
<th>NS</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>5.2</td>
<td>2.9</td>
<td>2.0</td>
<td>5.4</td>
<td>5.7</td>
<td>5.5</td>
<td>1.9</td>
<td>4.1</td>
</tr>
<tr>
<td>90%</td>
<td>9.0</td>
<td>5.3</td>
<td>2.6</td>
<td>8.6</td>
<td>8.2</td>
<td>12.5</td>
<td>2.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 7. Spatial extent relevant for the effect of the mean chromaticity measured in Experiment 4 for all subjects. The values specify (in degree visual angle) the size of the inner region for which each subject exhibits 75% (or 90%) of the maximum effect of the mean chromaticity.

Figure 9. Results of Experiment 4 for subject KR. Mean relative effects for each condition (filled circles) ±1 SEM (error bars). The curve is a function (Equation 1) fitted to the data (as described in Experiment 1). The vertical straight line indicates the size of the inner region for which 75% of the maximum effect of the mean chromaticity is obtained (estimated from the fit).

Figure 10. Results of Experiment 4 for the average observer. Error bars represent ±1 SEM averaged across subjects.
of the inner region (Experiments 1–4), the absolute $l$ values have been transformed into relative values by a subject-wise normalization (as described in the result section of Experiment 1). In absolute terms, the size of the effect on gray settings resulting from differences in mean chromaticity measured in Experiment 4 as well as the size of the effect resulting from differences in luminance-redness correlation measured in Experiment 1 is relatively small compared to the inter-individual differences of the gray settings. To illustrate this, the minimum and maximum means of the subject-wise normalization in Experiment 1 and 4 (given in Table 3 and Table 6) are plotted in Figure 11. Panel a shows the data for all subjects in Experiment 1, panel b for all subjects in Experiment 4. The lower horizontal end of the marker indicates for the respective subject the minimum mean and the upper horizontal end indicates the maximum mean. The vertical lengths of the markers correspond to the size of the effect of the tested scene statistic (i.e., the luminance-redness correlation in Experiment 1 and the mean chromaticity in Experiment 4) and differences between subjects in the vertical position of the markers correspond to inter-individual differences in the location of the subjective gray point.

The size of the effect of the luminance-redness correlation on the $l$ value of the gray settings in Experiment 1 is small and ranges across subjects from 0.00161 to 0.00469 with an average of 0.00294. Note, for comparison, that the standard deviation of $l$ in the variegated stimuli used in the experiments is 0.005 (which equals the average standard deviation in the natural scenes of Ruderman et al., 1998). This size of the effect of the luminance-redness correlation found in Experiment 1 is in good agreement with the size of the effect found in previous studies (Golz, 2005; Golz & MacLeod, 2002). In Golz and MacLeod (2002), we have shown that the size of the effect of the luminance-redness correlation is roughly consistent with the size of the effect that would be expected based on an optimal observer computation of the weight that should be given to the luminance-redness correlation in estimating the illuminant in the natural scenes of Ruderman et al. (1998). The size of the effect measured in Experiment 1 results from stimuli that differ in luminance-redness correlation by 0.8 (see Table 2). This value is comparable to the range of luminance-redness correlation values occurring in natural scenes.

The size of the effect of the mean chromaticity on the $l$ value of the gray settings in Experiment 4 ranges across subjects from 0.00242 to 0.00458 with an average of 0.00362. The difference in mean chromaticity of the stimuli from which this size of the effect results (see Table 5) is comparable in size to the difference in chromaticity between a 7000 K daylight and a 8000 K daylight. The use of larger differences in mean chromaticity was not possible due to constraints of the algorithm used to find colors for the circles in the surround with the intended chromatic statistics for the two different regions. Because some circles reached into both regions but had to be painted with one homogeneous color the realizable difference of the mean chromaticity between the two regions was limited.

The vertical differences between the markers of the different subjects in Figure 11 indicate substantial inter-individual differences in the absolute location of the subjective gray points. In Experiment 1, the standard deviation (across the 10 subjects) of the mean $l$ values of gray settings in the 0° stimuli where the entire surround has a luminance-redness correlation of 0.0 (i.e., the standard deviation of the minimum means plotted as the lower horizontal end of the markers in Figure 11a) is 0.00630. In Experiment 4, the standard deviation (across the 7 subjects) of the mean $l$ values of gray settings in the 0° stimuli where the entire surround has a mean chromaticity of ($l$, $s$) = (0.69, 1.14) (i.e., the standard deviation of the minimum means plotted as the lower horizontal end of the markers in Figure 11b) is 0.00284. These inter-individual differences are in the range of differences found in previous studies measuring gray

Figure 11. Absolute size of the effect of the scene statistics on the gray settings and inter-individual differences in the absolute values of the gray settings. (a) Minimum and maximum means used for the subject-wise normalization for all subjects in Experiment 1 (from Table 3). (b) Minimum and maximum means used for the subject-wise normalization for all subjects in Experiment 4 (from Table 6). See text for details.
settings with the same type of stimuli manipulating various scene statistics (Golz, 2005; Golz & MacLeod, 2002).

**Summary and discussion**

In Experiment 1 the spatial extent of the area in the field of vision that is relevant for the effect of the luminance-redness correlation on the color appearance of a central test field was measured by varying the size of an inner annular region around the test field that had a higher correlation value than the remaining outer region of the surround. Subjects required on average a size of the inner region of 4.3° to exhibit an effect of 75% of the maximum effect. This spatial extent relevant for the luminance-redness correlation effect is substantially more global than that measured by Granzier et al. (2005) who summarized the results of their experiments (p. 20): “However, the results show that only the correlation within 1° of the target is relevant.” Experiment 2 and Experiment 3 provided evidence that the smaller spatial extent found by Granzier et al. is probably at least in part caused by two parameters of the stimuli used in their experiments that differed from those used in Experiment 1: the size of the elements making up the surround and the salience of the border that separates the two regions with different values for the luminance-redness correlation in the surround.

Based on their finding of a very local effect of the luminance-redness correlation Granzier et al. (2005, p. 20) concluded: “Thus, it is unlikely that the visual system uses the correlation between luminance and color to explicitly determine the chromaticity of the illuminant. Instead, this correlation is presumably implicitly considered in the way that the color contrast at borders is determined.” This general conclusion cannot be maintained in the light of the findings presented here. Remember that the value of 4.3° is the width of the annular region around the central test field, so this size corresponds to an area (including the 1.5° test field) of 10.1° in diameter. In this area on average more than 120 differently colored patches were present in the stimuli of Experiment 1. That the visual system requires this area to exhibit 75% of the maximum effect of the luminance-redness correlation speaks against the possibility that the effect of the luminance-redness correlation on the test field is caused by mere dependence of the color contrast at the test field border on the luminance-redness correlation of the directly adjoining patches. It is instead concluded that the spatial extent relevant for the effect of the luminance-redness correlation is compatible with the hypothesis that the visual system uses this scene statistic to estimate the chromatic properties of the illumination by a spatial analysis of a sufficiently large sample of patches. Likewise, the very similar spatial extent relevant for the effect of the mean chromaticity found in Experiment 1 does not contradict the possibility that the visual system uses the mean chromaticity of the surround for this purpose.

A conclusion that the spatial extent relevant for the effect of a scene statistic is too local for this scene statistic being possibly used by the visual system for estimating the illuminant would have to be based on an estimate of the typical spatial extent that is taken into account in natural situations. However, Experiments 2 and 3 provided evidence that the visual system adjusts the spatial extent relevant for the effect of the luminance-redness correlation depending on figural parameters of the stimuli used to measure the spatial extent and that the visual system takes into account a substantially more global spatial extent than that measured by Granzier et al. (2005) when the stimuli differ in these parameters. Their extreme value for the spatial extent should therefore not be taken as an estimate of the typical spatial extent taken into account in natural situations and should not be used for drawing conclusions about the functional role of the luminance-redness correlation in general.

It is of course conceivable that the typical spatial extent taken into account for the luminance-redness correlation in natural situations is even larger than that found in Experiment 1, but this is not necessary for the possibility that this scene statistic is used by the visual system for the purpose of estimating the chromatic properties of the illuminant. Granzier et al. (2005, p. 26) argue that our proposal of the luminance-redness correlation being used for this purpose (Golz & MacLeod, 2002) would comprise “implicit assumptions that the visual system uses the correlation between luminance and color in the whole scene to derive the chromaticity of the illuminant.” We never made the assumption that the visual system uses the whole scene, neither implicitly nor explicitly. (In the experiment reported in Golz & MacLeod, 2002, we therefore designed the stimuli to have the intended chromatic statistics in the whole display and simultaneously in several smaller concentric subregions surrounding the test field). For the following two reasons the visual system might use less than the whole scene in order to estimate the chromatic properties of the illuminant.

First, for successfully estimating the illuminant for a particular region in complex natural situations the visual system has to find the balance between taking into account a local and a global area of the field of vision. If, on the one hand, the area taken into account is too local, the estimate would be too dependent on the contingencies of the surfaces present in that area. If, on the other hand, the area is too large and includes parts of the scene which are illuminated differently, the estimate would be impaired by taking into account irrelevant information from illuminants that do not affect the particular region.

Second, a mechanism with a restricted spatial extent could be used to estimate the illuminant even in situations in which there is a smaller number of surfaces within the
spatial extent of the mechanism than in our experiments: When scanning the scene by eye movements the spatial chromatic modulation of the scene is transformed into a temporal chromatic modulation. By taking this temporal information into account in a suitable way, the visual system could base the illuminant estimate on an analysis of the chromatic properties within a more global area of the scene. This idea of a contribution of eye movements to color constancy has repeatedly been put forward (Cornelissen & Brenner, 1995; D’Zmura & Lennie, 1986; Fairchild & Lennie, 1992; Shevell, 1980; Webster & Mollon, 1995), but how the visual system uses temporal chromatic information for estimating the chromatic properties of the illuminant has not been addressed systematically so far. There is however evidence in experiments of Smithson and Zaidi (2004) as well as Schultz, Doerschner, and Maloney (2006) that the visual system gains information about illuminant chromaticity from a temporal analysis of localized presented color sequences.

The theoretical analyses (summarized in the Introduction) on the role of the luminance-redness correlation as a cue for estimating the chromatic properties of the illuminant (Golz & MacLeod, 2002; MacLeod & Golz, 2003) remain the only computational rationale for the empirical dependence of color appearance on this scene statistic so far. A presumption about an involvement of this scene statistic in the way in which color contrast at borders is determined is not an alternative in the light of the findings presented here.

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References


