Color appearance: The limited role of chromatic surround variance in the "gamut expansion effect"

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R. O. Brown and D. I. MacLeod (1997) observed that chromatic patches appear much more saturated against an equiluminant, uniform gray surround than against a chromatically variegated surround with the same space-average color. Using asymmetric color matching, we investigated what stimulus conditions are critical for the occurrence of this "gamut expansion effect." We found (a) that the effect diminishes rapidly with increasing color contrast between target and surround, (b) that the amount and the spatial distribution of color variance in the surround plays but a very limited role, (c) that the effect is mainly local, and (d) that basically the same effect can be obtained by comparing two uniform surrounds. These findings, particularly the latter, argue strongly against an explanation solely in terms of contrast adaptation. We suggest that the main features of our findings can be explained in terms of color scission.

Keywords: color vision, color appearance, gamut expansion effect

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Introduction

Brown and MacLeod (1997) observed that chromatic patches may appear much more saturated against an equiluminant, uniform gray surround than against a chromatically variegated surround with the same space-average color (see panels C and D in Figure 1). In their experiments, a standard patch was presented in a uniform gray surround, and the task of the subjects was to match its color by adjusting the color of a comparison patch in a chromatically variegated surround. Standard patches of four different hues (roughly red, green, blue, and yellow) were used that were approximately equiluminant to the surround and had a rather low purity (i.e. a low chromatic contrast to the mean color of the surround). The main finding was that the subjects chose much larger purities for the comparison patch, thus compensating for the desaturating effect of the variegated surround. That is, the ratio between match and standard purity was much larger than 1.

This surround effect is qualitatively different from the kind of effects previously reported and discussed in connection with color induction. While color induction effects are traditionally described as a *translation* of the white point in color space (Helmholtz, 1911; Shevell, 1978; Walraven, 1976; Webster, 2003; Whittle, 2003), Brown and MacLeod's (1997) effect seems to be more appropriately described as a compression or expansion around the neutral point (depending on whether the uniform or the variegated surround is taken as a reference). Brown and MacLeod used the term "gamut compression" or "gamut expansion," implicitly suggesting that the entire gamut of perceived colors is compressed or expanded.

Besides their basic observation, Brown and MacLeod (1997) report several further findings that may be relevant to constrain possible interpretations of the gamut expansion effect: (1) Separating centre and surround in the comparison surround with a thin gray line reduced but did not eliminate the effect. Their conclusion was that the effect cannot be completely local. (2) A similar expansion effect could be observed with respect to luminance: A gray standard patch that was darker (lighter) than the gray uniform standard surround was matched by an even darker (lighter) patch in the variegated surround. (3) If the comparison surround was achromatic and only the luminance varied, then the luminance effect was large and the chromatic effect small; that is, the purity of the match was very similar to the purity of the standard patch. (4) If the comparison surround was nearly equiluminant with mere chromatic variation, then the luminance effect was small and the chromatic effect large. (5) The effect was almost immediate, which led to the conclusion that the gamut expansion effect "is effectively a form of simultaneous color contrast" (Brown & MacLeod, 1997, p. 848).

There have been essentially two different views about what the cause and functional role of the gamut expansion effect is. One line of reasoning postulates that the gamut expansion effect is the result of one of two different kinds of adaptational processes that together govern color perception. Webster (2003), who studied similar "expansion effects" after temporal adaptation, uses the terms "light adaptation" and "contrast adaptation" for these two

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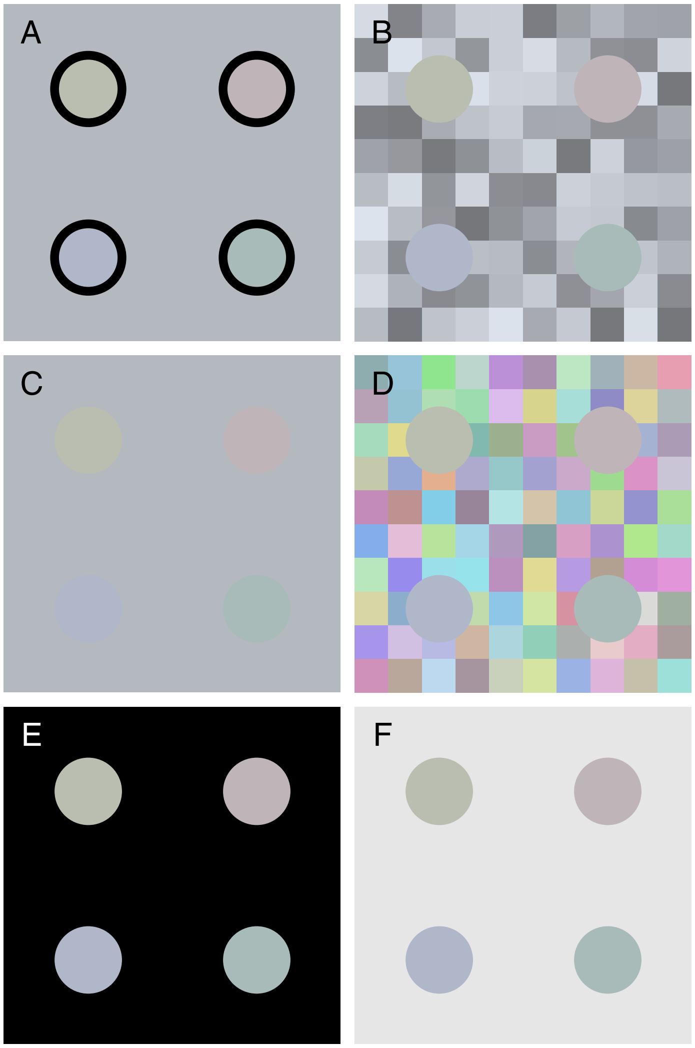

Figure 1. The four discs are identical in all panels. The discs in the uniform surround C appear much more saturated than those in the chromatically variegated surround D. This is the gamut expansion effect as described by Brown and MacLeod (1997). The surrounds A, B, E, and F, which are similar to the stimuli used in Experiments 1C, 2A, and 2B, do not contain chromatic variance but nevertheless have a desaturating effect relative to surround C.

hypothetical processes: "Light adaptation adjusts sensitivity to the mean luminance and chromaticity averaged over some time and region of the image and produces mean shifts in colour perception. Contrast adaptation adjusts sensitivity according to how the ensemble of luminances and chromaticities are distributed around the mean, and instead alters colour appearance by changing the perceived contrast along different directions in colour space" (p. 68). MacLeod proposed a similar explanation for the gamut expansion effect that is more specific with respect to the underlying mechanism: "If cone-opponent neurons are able to increase their sensitivity in response to decreases in the range of inputs, and thereby give their maximum response to the largest visible deviation from "white," this mechanism would explain gamut expansion" (Hurlbert, 1996, p. 1382). Brenner and Cornelissen (2002) also adopted this explanation in terms of two related adaptational processes. They investigated the influence of chromatic variability in the surround on color induction and found that chromatic induction was reduced by chromatic variability. In their explanation of this result, they explicitly refer to the gamut expansion effect and conclude that the "shift in the neutral point takes place after the change in saturation" (Brenner & Cornelissen, 2002, p. 231). In a later experiment, they varied the spatial distribution of the chromatic variability in the surround and found that it hardly made any difference where the chromatic variability was located within the scene. They therefore conclude that "chromatic induction arises from local spatial interactions between cone-opponent signals that have been scaled by a global measure of the chromatic variability within the scene" (Brenner, Ruiz, Herráiz, Cornelissen, & Smeets, 2003, p. 1420).

A different line of reasoning interprets the gamut expansion effect as the result of color scission (Ekroll, Faul, & Niederée, 2004). Color scission refers to the fact that colors are sometimes separated in two or more components that are attributed to different causes (Anderson, 1997; Ekroll, Faul, Niederée, & Richter, 2002). The best known example of color scission is the phenomenon of perceptual transparency, where the local color in the region of the transparent overlay is split into a background and a transparent layer component (D'Zmura, Colantoni, Knoblauch, & Laget, 1997; Faul & Ekroll, 2002; Metelli, 1970). These two components are represented separately and have independent attributes. This is demonstrated by the fact that it is possible to match properties of the transparent layer in front of different backgrounds (Singh & Anderson, 2002). The application of color scission to the gamut expansion effect is mainly motivated by (1) the observation that uniform patches in a uniform surround often appear transparent at low color contrasts (see, for instance, panel A in Figure 6) and (2) the observation that it often seems impossible to find a perfect match in the asymmetric matching task used to measure the gamut expansion effect. The following assumptions are made to explain the gamut expansion effect and these two additional observations: A low contrast uniform patch in a uniform surround fulfils the chromatic (low contrast) and figural (background in plain view and seen through the overlay region have the same texture) conditions for color scission. The test patch is therefore split into a background component of roughly the color of the surround (gray) and a separately represented layer component, which is determined by the contrast of the test patch color to the surround color. The uniform patch in the variegated comparison surround, in contrast, violates both scission conditions and is therefore not split up. This implies that an observer performing the asymmetric matching task would have to compare a standard patch that is split into a gray background color and a "thin" but highly saturated chromatic contrast component with an unsplit and therefore grayish color in the comparison surround. Clearly, in a strict sense this would be an impossible task and this would explain the matching problems. The gamut expansion effect is to be expected if the subjects in this case seek to compensate for the highly saturated contrast component of the standard patch by increasing the saturation of the comparison patch.

The two approaches outlined above emphasize different aspects of the stimulus situation and make qualitatively different predictions. From the adaptational perspective, the focus is mainly on chromatic variance and therefore on the properties of the comparison stimulus. The underlying idea that the sensitivity of cone-opponent neurons adapts to the range of chromaticities in the scene leads to three expectations. First, it is to be expected that the strength of the gamut expansion effect is a monotonic increasing function of the amount of chromatic variance in the comparison surround. Second, the effect of the variance should not be completely local because otherwise the reference to properties of the "scene" would be meaningless. Third, the assumption that the properties of a basic detection mechanism are changed suggests that the effect is of a general nature, that is, that all colors are affected in a similar way.

The scission approach, on the other hand, focuses on the properties of the uniform standard stimulus. From this view, the gamut expansion effect depends on the precondition that color scission occurs in exactly one of the two stimuli that are compared in the asymmetric matching task. The focus on the uniform standard stimulus results from the fact that color scission is a rather delicate phenomenon that depends on very specific stimulus conditions. It is therefore expected that the effect deteriorates quickly with slight deviations from the uniformity of the surround and the low color contrast between central patch and surround that was realized in the standard stimulus in Brown and MacLeod's (1997) experiment. The properties of the comparison surround are less important because conditions that *prevent* color scission are abundant. The effect should therefore be rather robust against changes of the properties of the comparison stimulus—they should not matter as long as color scission remains suppressed. This implies in particular that chromatic variance has no special status and may be replaced by other suitable stimulus properties that prevent color scission.

In order to evaluate the plausibility of these alternative explanations, we conducted a series of experiments in which we observed the consequences of changing properties of both the standard and the comparison surround on the strength of the gamut expansion effect.

Experiments

Most of the experiments reported below can be regarded as variants of the basic experiment of Brown and MacLeod (1997) that was briefly described in the Introduction section. Our aim was to investigate more extensively which properties of the stimulus influence the strength of the "gamut expansion effect." In one set of experiments (Experiments 1A–1C), we manipulated properties of the standard stimulus and in a second set of experiments (Experiments 2A–2D) the surround of the comparison patch.

The stimuli were presented on a CRT monitor (Sony GDM F500R, screen size 30 × 40 cm, 1280 × 1024 pixels, 85-Hz refresh rate) that was controlled by a graphics card (ATI Radeon 9600) with a color depth of 8 bits. We used a colorimeter (LMS 1290) to calibrate the monitor following a standard procedure (Brainard, 1989). The methods described in Golz and MacLeod (2003) were used to transform back and forth between CIE 1931 XYZ coordinates and LMS cone excitation values with respect to the 2° cone fundamentals estimated by Stockman, MacLeod, and Johnson (1993). During the experiments, the monitor was the only light source in the room. The viewing distance was approximately 80 cm.

Experiment 1A: The influence of standard patch purity

Brown and MacLeod (1997) varied the hue of the standard patch in four steps but used only one contrast level for each hue. In their experiment, the colorimetric purity (Wyszecki & Stiles, 1982, p. 174) of the patches was rather low (note that in this context, where the background of the surround is neutral, purity corresponds to the chromatic contrast of the standard patches to the surround). Informal observations suggested that a low purity is essential for the gamut expansion effect and that it is much weaker at higher purities. In Experiment 1A, we therefore investigated systematically how the gamut expansion effect depends on the purity of the standard patch.

Figure 2 shows the surrounds used in the asymmetric matching task of Experiment 1A. The standard patches were presented in the uniform gray surround [CIE 1931 xyY = (0.309, 0.315, 9.12); this is the chromaticity of CIE illuminant C]. In the variegated surround of the comparison patch, the spatial mean of the colors was identical to the gray color of the uniform surround, and the covariance matrix C describing the distribution of LMS cone excitation values was

$$C = \begin{pmatrix} 1.6384 & 0.7209 & 0 \\ 0.7209 & 0.3441 & 0 \\ 0 & 0 & 3.24 \end{pmatrix}. \tag{1}$$

Variance and mean of a color distribution depend on the underlying color space. Our choice to use the LMS color

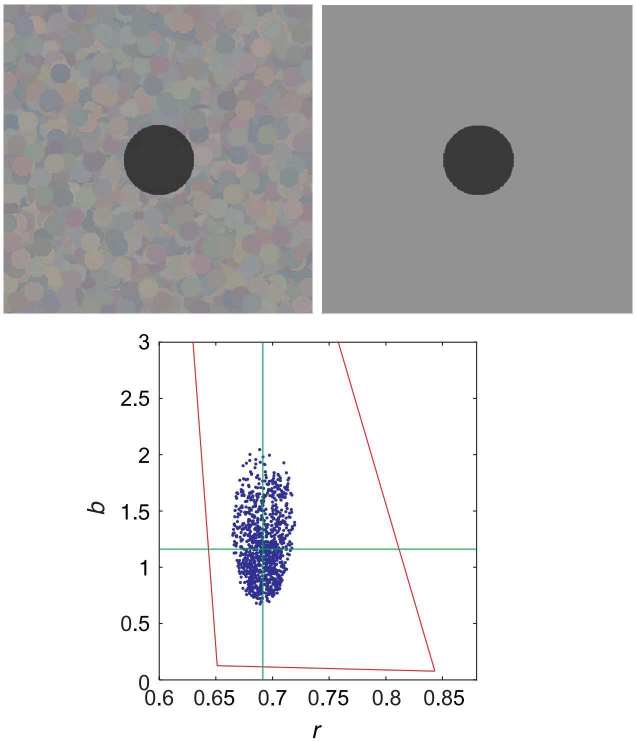

Figure 2. *Top:* The variegated and uniform surrounds used in Experiment 1A. *Bottom:* Color distribution in the variegated surround projected onto the MacLeod–Boynton chromaticity diagram.

space rested on the assumption that additive color mixtures of both spatial and temporal origin are most naturally defined in terms of cone excitations. To calculate variegated surrounds with specified mean and covariance matrix in LMS cone excitation space, an algorithm similar to that described in Mausfeld and Andres (2002) was used. Figure 2 shows a projection of the "cloud of points" in LMS space onto the MacLeod–Boynton chromaticity diagram (MacLeod & Boynton, 1979). Each point in this diagram corresponds to a chromaticity realized in the surround.

The stimuli were presented side by side on a black screen, with a centre-to-centre distance of 10.7°. The horizontal position of the standard and the comparison stimulus was balanced over the trials. The size of each surround was 8.8° × 8.8°, and the diameter of the central patches was 2°. To enhance the effective color resolution beyond the 8 bits per channel provided by the hardware, we used Floyd–Steinberg error diffusion dithering (Floyd & Steinberg, 1976) with respect to the CIE 1931 XYZ space.

In each trial, the standard patch had one of four different hues, which can roughly be described as red, green, blue, and yellow. More precisely, it was one of the four hues that can be realized along the two cardinal axes (Krauskopf, Williams, & Heeley, 1982) through the chosen white point (the cardinal axes are parallel to the r and b axis in the MacLeod–Bonyton diagram). For each hue, the purity was varied in seven steps. To make the differences between purity steps approximately perceptually equidistant, we varied the purity in equidistant steps along the hue directions in CIELUV space (Wyszecki & Stiles, 1982, p. 165) and transformed the chosen positions back to the MacLeod–Boynton space (see Figure 3).

Informal observations suggested that low purity values are especially interesting. Thus, in the experiment, we tried to include the lowest possible purities at which a gamut expansion effect can reliably be measured. In a pilot experiment, we estimated the lowest purity at which an equiluminant target patch embedded in the uniform standard surround could reliably be detected and its hue clearly identified. This was done for all four hues used in the main experiment. We used a method of constant stimuli, that is, we presented—in random order—patches of fixed purity taken from a small purity interval $[0, x_0]$ in the standard surround. For each hue, x_0 was a low purity that nevertheless was clearly discernable from the surround. Each purity interval was further divided into ten equidistant purity levels along the hue directions in CIELUV space. In the pilot experiment, only the uniform standard surround was shown in the centre of the screen. The target patch was always equiluminant to the surround. In each trial, the subjects' task was to indicate whether they could see a central patch and if so which of four possible hues it had. For reference, the four possible hues were presented as small colored patches against a black background at the bottom of the screen. No feedback was given to the subjects. Four experienced observers with normal color vision (the authors and one naive subject) judged each purity level 20 times. Thus, this pilot experiment comprised a total of 800 trials (4 hues × 10 purity levels × 20 repetitions).

Each panel in Figure 4 shows the results for one of the four hues. The data underlying these plots were aggregated over all four subjects; individual results were very similar. In each panel, the relative frequency of "target seen" responses is plotted against target purity level. A total number of 2210 "target seen" responses were given in the 3200 trials performed by the four subjects, and only 2 of them were erroneous reports of detecting a non-existing target at purity 0 ("false alarm") and in only 8 cases—that were seemingly randomly distributed over the purity levels—the wrong hue was identified. The fact that virtually no hue identification errors were made at purities near detection threshold is remarkable because it suggests that as soon as the target patch is visible at all, its hue can also be identified. This fits well with the subjects' reports after the experiment that even barely discernible patches appeared in a sense highly saturated and with the concept of "saturation scale pretruncation" introduced in Ekroll et al. (2004). Important for the present purposes is the fact that there is no need to use correct hue identification as a separate criterion.

Thus, only the detection thresholds were used to determine the lowest purities for the main experiment:

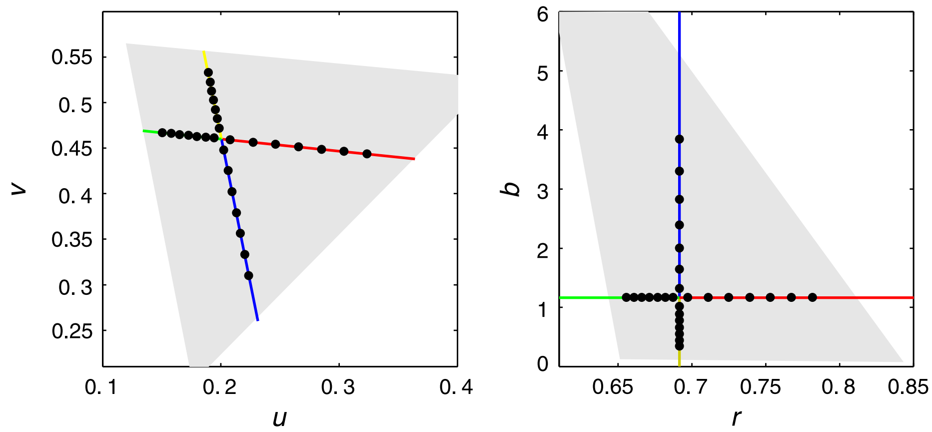

Figure 3. Chromaticities of the standard patch in Experiment 1A. The shaded regions show the monitor gamut. *Left side:* Purities of a given hue were equidistant in the CIELUV space. *Right side:* The same chromaticities plotted in the MacLeod–Boynton diagram.

First, the purity levels t corresponding to the 95th percentile were estimated from Weibull distribution functions fitted to the data. The uv-chromaticity of the color at the lower boundary of the purity interval was then calculated as $2t\Delta_{uv}$, that is, we duplicated the purity that was estimated to allow a correct detection of an equiluminant patch in the standard surround with a probability of 0.95. This increase above estimated detection threshold was necessary because at lower purities the subjects had a hard time discerning the standard patch from its surround when they needed to look back and forth between standard and comparison patch in the matching

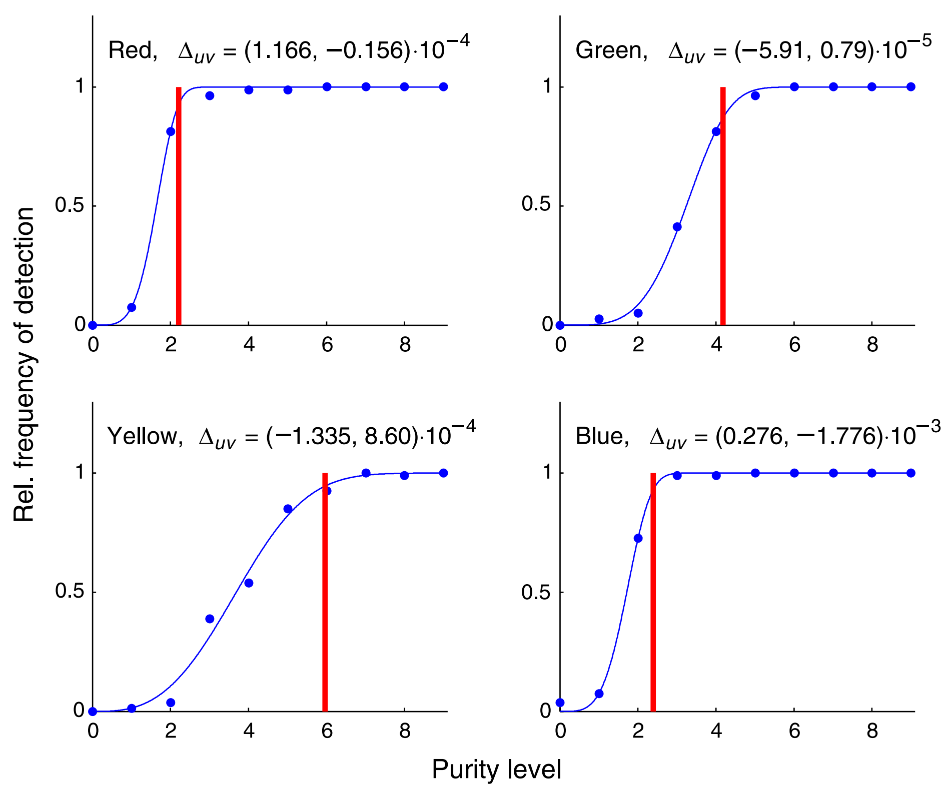

Figure 4. Results of the pilot experiment (pooled across observers) and estimated psychometric functions for detecting the central patch with increasing purity. In each plot, Δ_{uv} is a vector in the given hue direction in CIELUV space whose length corresponds to one purity level. The curves are Weibull distribution functions fitted to the data. Vertical lines show the position of the 95th percentile estimated from the fit.

task. The upper boundary of each purity interval was the point along the corresponding hue direction lying at 80% of the distance from the neutral point to the boundary of the monitor gamut (see Figure 3).

The same four subjects that conducted the pilot experiment participated in the main experiment. Each subject made 10 settings for each of the 28 different conditions (4 hues $\times$ 7 purity levels). The arrow buttons on the computer keyboard were used to adjust either the purity or the luminance (L + M) of the comparison patch. By pressing the space key the subjects could toggle between these two input modes. In both cases, the left/right keys were used for adjustment along the chosen dimension; the top/down keys allowed additional adjustments on a very fine scale. Purity settings were along the cardinal axes on which the hue of the standard patch lied. The subjects were instructed to make the color of the comparison patch as similar as possible to that of the standard patch, paying special attention to the correspondence in saturation.

Results and discussion

Figure 5 shows the results for pooled data of all four subjects. In the top panels, the mean chromaticities of the matches are plotted against the chromaticities of the standard patch. In the middle panels, the effects are given in terms of purity ratios between match and standard. This ratio is essentially identical to the "relative richness" measure used by Brown and MacLeod (1997). The purity ratio is defined in terms of the chromaticity coordinates x_m, x_s, and x_w of the match, the standard, and the gray surround, respectively, by the expression $\|x_m - x_w\| \,/\, \|x_s - x_w\|$. To estimate intermediate purity ratios, exponential decay functions $A + B \exp(-D \left| x_s - x_w \right|^C)$ were fitted to the purity ratios for each hue direction. The bottom panels show the ratios of match to standard luminance.

The results are in close agreement with the main findings of Brown and MacLeod (1997): At low standard patch purities, the purity of the match was always clearly larger than that of the standard patch. Under comparable conditions, Brown and MacLeod found purity ratios of about three to four. Their values correspond closely to those found at the lowest purity levels in the present experiment. As Brown and MacLeod, we also found that the luminances in the matches are slightly increased.

The main new finding of the present experiment is that the "gamut expansion effect" decreases rapidly with increasing purity of the standard patch. The lowering of the effect is obvious with respect to purity ratios but can also be seen in the raw matching data (top panels of Figure 5). In light of this finding, the term "gamut expansion" seems somewhat inappropriate because the results indicate that the maximal saturation that can be perceived in each surround does not change. Instead there seems to be a distortion of the color space in the vicinity of the surround color.

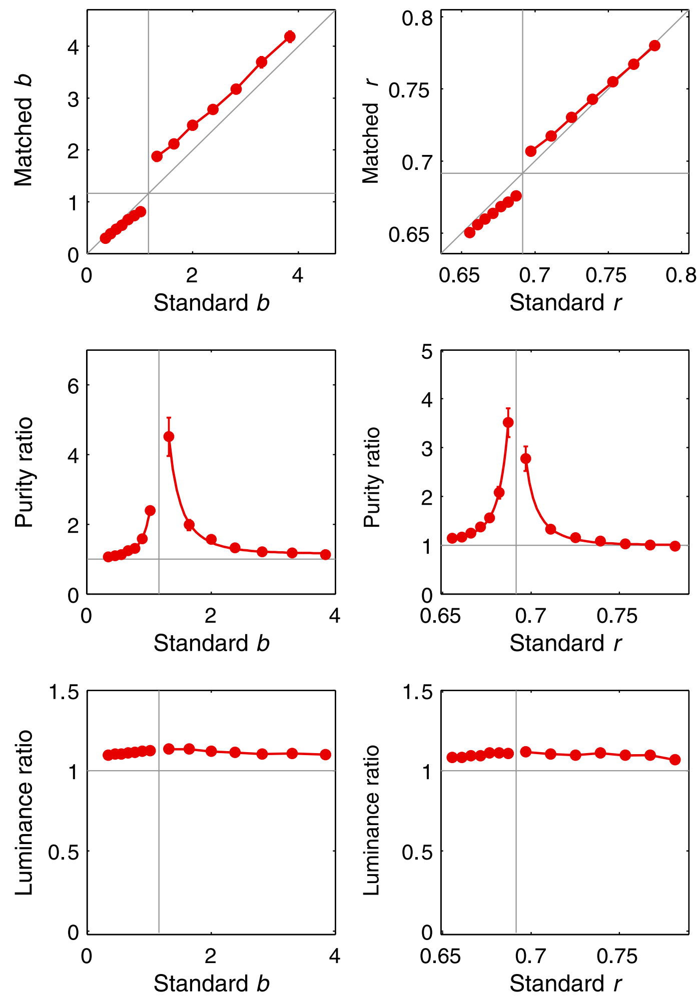

Figure 5. Results of Experiment 1A, based on the pooled data of all four subjects. *Top panels:* Mean chromaticities of the matches plotted against the chromaticities of the standard patch. *Middle panels:* Effect size given as ratio between match and standard purity. A purity ratio of 1 means that there is no effect. *Bottom panels:* Ratio of match to standard luminance. The vertical lines and the horizontal one in the top panels indicate the coordinate of the gray surround color. The error bars show ±2 *SEM* and each data point represents the mean of 40 settings.

An aspect of our findings that does not show up in the data but is nevertheless of great theoretical interest is that the subjects were often unable to find a complete match. These difficulties—that were especially severe at low purities—stemmed mainly from the fact that standard and comparison patch appeared *qualitatively* different. Whereas low contrast patches in the uniform surround often appeared transparent, the patches in the variegated surround lacked this phenomenal quality and looked more like opaque patches.

Figure 6 demonstrates the main findings of the experiment. With decreasing purity (from left to right) the patches in panel A look increasingly transparent. At very low contrasts, the impression is that of a thin but

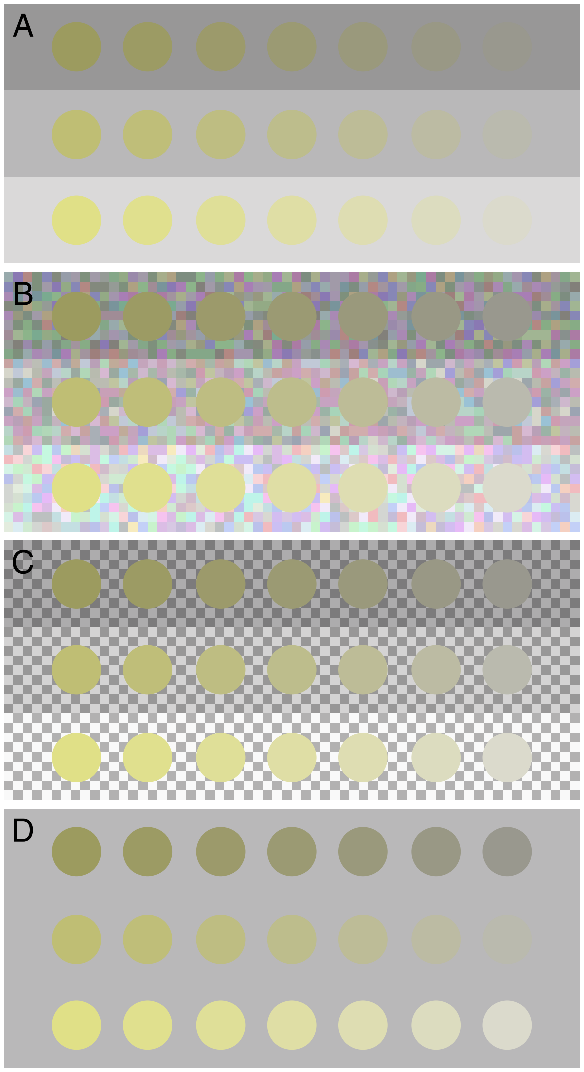

Figure 6. The top row of patches is physically identical in panels A, B, C, and D. The same holds true for the middle and bottom rows. All patches in a column have the same purity, and the purity decreases monotonically from left to right. The patches in panels A, B, and C and the middle row of panel D are approximately equiluminant to the mean color in their immediate surround. In panel A, the low contrast patches appear transparent and in a sense highly saturated. In the variegated backgrounds of panels B and C, the perceived saturation of low contrast patches is clearly reduced. The top and bottom rows of panel D, where the patches are no longer equiluminant, demonstrate the effect of a luminance contrast to the surround: The transparency impression is lost and the patches appear much more desaturated than in panel A. (Please view on screen, the effect may be reduced in print.)

nevertheless highly saturated transparent layer. The perceptual similarity of corresponding patches in different rows in panel A is remarkable, given their great difference in luminance, which is obvious in panel D. A comparison of panels A and B reveals that the desaturating effect of a chromatically variegated surround relative to a uniform one is especially pronounced at low contrasts. Comparing panels B and C suggests that pure luminance variation in the surround has a similar effect as full color variation (see also Experiment 2B). In panel D, the patches in the top and bottom row are no longer equiluminant to the surround, and the transparency impression is lost. The patches appear now much more desaturated especially on the right end of the rows (see also Experiment 1B and Experiment 2A). The phenomenal difference between the rows in panels A and D suggests an interpretation in terms of scission: In panel A, the "grayness" in each patch is attributed to the surround and there remains a highly saturated chromatic contrast color. In the top and bottom row of panel D, in contrast, a part of the "grayness" of the patches can no longer be attributed to the surround and is instead interpreted as an integral part of the patch color itself. In the top row, for instance, the part of the patch's color not accounted for is a decrement relative to the surround leading to the addition of a "blackness" component.

Experiment 1B: The influence of standard patch luminance

The main result of Experiment 1A was that the "gamut expansion effect" decreases rapidly with increasing purity, that is, with increasing *chromatic* contrast. A natural question is then whether the effect is also lowered when the *luminance* contrast of the standard patch to its surround is increased. To investigate this question, two of the subjects (VE, WM) who participated in Experiment 1A repeated the experiment under almost identical conditions. The only difference was that the luminance of the standard patch was now no longer equiluminant to the surround but slightly decremental. The luminance was 8.21 cd/m^2, that is, 10% lower than that of its surround.

Results and discussion

The results depicted in Figure 7 show that both the chromatic and the luminance effect are considerably reduced for standard patches with slightly decremental luminance. The effects are reduced to approximately one half of the size observed in the condition with equiluminant centre and surround. This result indicates that the gamut expansion effect depends on low contrasts in both the chromatic and the luminance dimensions.

Experiment 1C: The influence of local contrast

The results of Experiments 1A and 1B indicate that a strong "gamut expansion" effect can only be observed if both the chromatic and the luminance contrast between standard and surround are low. It is, however, unclear whether this effect depends mainly on the local contrast at the border of the test patch or if it is of a more global

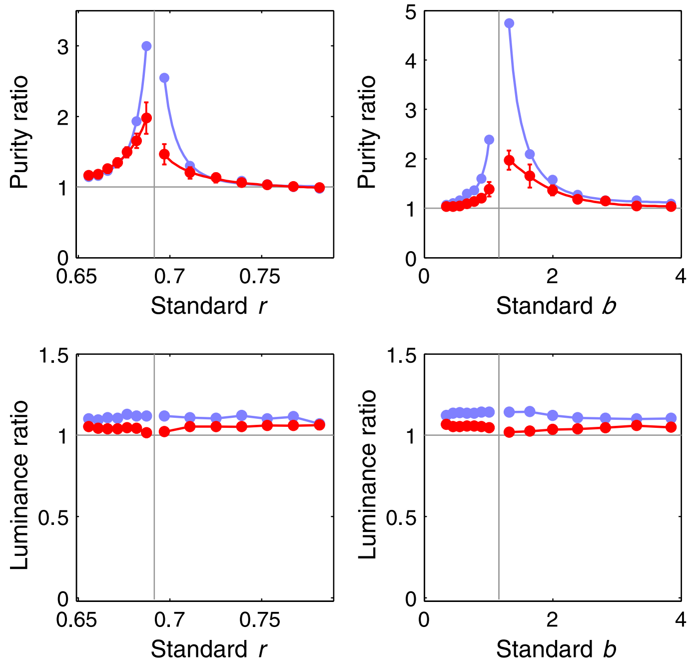

Figure 7. Results of Experiment 1B, based on the pooled data of two subjects. Each panel shows the data of Experiment 1B (red) and the corresponding results of the same subjects from Experiment 1A (blue) to allow easy comparisons. The top panels show the ratios of match to standard purity, the bottom panels the ratios of match to standard luminance. The vertical lines denote the coordinate of the gray surround color. In each plot, the error bars show ±2 *SEM* and each data point represents the mean of 20 settings.

nature. A demonstration by Hurlbert (1996, Figure 2B, p. 1384) suggests a predominantly local influence. In this demonstration, it is shown that the gamut expansion effect can be considerably reduced if the test patch in both the standard and the comparison stimulus is outlined in black.

In Experiment 1C, we investigated this question with a focus on the properties of the standard stimulus. To this end, we replicated Experiment 1A with a slightly different standard stimulus, in which a thin black line of 0.13° width was drawn at the border between centre and surround. That is, in contrast to the demonstration in Hurlbert (1996) a black outline was only added to the patch in the uniform standard stimulus, whereas the comparison stimulus was not changed. This manipulation leaves the global color relations in the standard stimulus unaltered but presumably disrupts local interactions between the central patch and the large gray uniform surround. Two of the subjects (FF and VE) from Experiment 1A participated in the experiment.

Results and discussion

The results depicted in Figure 8 show that the gamut expansion effect disappears almost completely, when a thin black line is drawn around the standard patch. The large reduction of the effect compared with Experiment 1A is especially obvious in the plot of purity ratios in the middle panel of Figure 8. An interesting conclusion that can be drawn from this result is that a purely achromatic surround (the black line plus the adjacent gray surround in the uniform standard stimulus) can have almost the same effect on the perceived saturation of an embedded patch as a chromatically variegated surround. Furthermore, our results indicate that the reduction of the effect observed in the demonstration by Hurlbert (1996) can almost completely be attributed to a change in the appearance of the standard patch. Or, put the other way around, it indicates that the gamut expansion effect is mainly due to rather specific relations at the border between centre and surround in the *uniform* standard stimulus.

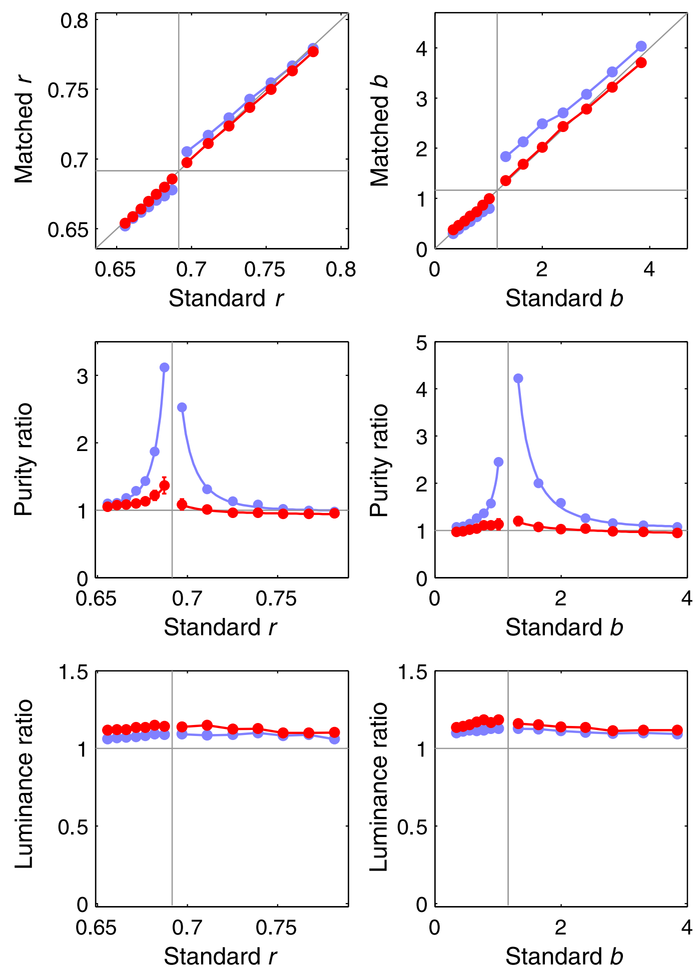

Figure 8. Results of Experiment 1C, based on the pooled data of two subjects. Each panel shows the results of Experiment 1C (red) and the corresponding results of the same two subjects from Experiment 1A (blue) to allow easy comparisons. The top panels show the mean chromaticity of the match plotted against the chromaticity of the standard patch, the middle panels show purity ratios, and the bottom panels luminance ratios. All other properties of the plots are identical to those in Figure 5.

A possible explanation for the reduction of the effect observed in Experiment 1C is that the effect is mainly of a local nature and that the black ring interrupts local interactions between centre and surround. However, adding the black line does not only separate centre and surround but it also provides a new black context to the central patch. One may therefore argue that it is not the blocking of effects from the larger surround but the direct influence of the narrow "black surround" on the central patch that is of main importance. Since these two influences are confounded, it is indeed not clear to what extent they contribute to the reduction of the gamut expansion effect. However, an observation that speaks against a large direct influence of the black ring is the marginal effect on the luminance. We will come back to these issues in the General discussion section.

The basic effect of the surround used in Experiment 1C is demonstrated in Figure 1: The patches in panel A appear less saturated than those in panel C. Note that the chromatic effect in the demonstration is partially masked by a brightness effect, which was eliminated in the experiments through the subjects' brightness settings.

Experiment 2A: Uniform achromatic comparison surrounds

Experiment 1C showed that a completely achromatic surround can have almost the same effect on the perceived saturation of an embedded patch as a chromatically variegated one. This leads to the expectation that a gamut expansion effect may also be observed even when the variegated surround is replaced by a uniform one, provided that there is a luminance difference between patch and surround.

To test this hypothesis, we replicated Experiment 1A under slightly different conditions: We replaced the variegated surround of the comparison patch used in Experiment 1A with a uniform achromatic surround. The uniform comparison stimulus was either much brighter ("white surround," 45.6 cd/m^2) or much darker ("black surround," < 0.1 cd/m^2) than the gray standard surround (9.12 cd/m^2). Here, only the "blue" and "yellow" hue directions were tested and the subjects made 6 settings for each of the 14 conditions (7 purity levels × 2 hues). All other conditions were identical to those realized in Experiment 1A, and the same four subjects performed the experiment.

Results and discussion

The results shown in Figure 9 confirm the hypothesis that a "gamut expansion effect" can also be observed in asymmetric matching tasks with two achromatic uniform surrounds. With both the "white" and the "black" comparison surround the observed pattern of the gamut expansion effect is similar to that observed with a variegated surround. Somewhat surprisingly, we found in most cases that the effect with uniform achromatic surrounds was even stronger than that observed with a variegated surround (the only exception is the "blue" hue direction in the "white surround" condition).

These results confirm the conclusion drawn from our Experiment 1B that the perceived saturation of a chromatic

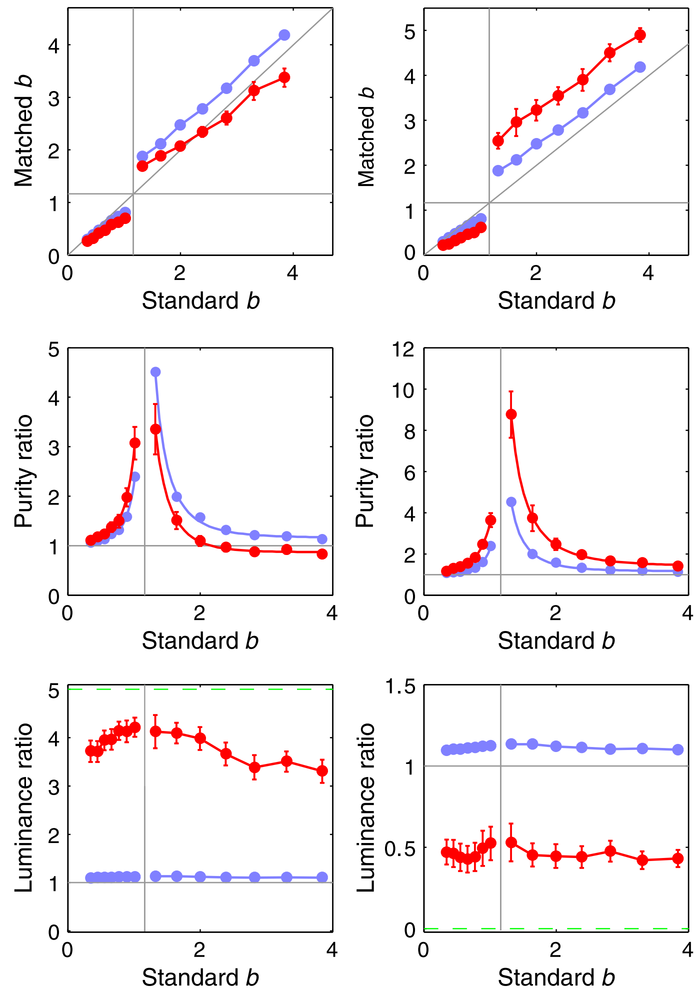

Figure 9. Results of Experiment 2A, based on the pooled data of all four subjects. Each panel shows the results of Experiment 2A (red) and as a reference the corresponding results of the same subjects from Experiment 1A (blue). The plots in the left column show the results for the 'white surround', the plots in the right column those of the 'black surround'. The top panels show the mean chromaticities of the matches plotted against the chromaticities of the standard patches. The middle panels show ratios of match to standard purity, and the bottom panels show ratios of match to standard luminance. The green dashed horizontal lines in the relative luminance plots show the luminance of the comparison surround relative to that of the standard surround. All other properties of the plots are identical to those in Figure 5.

patch in an achromatic surround decreases with increasing luminance contrast between centre and surround. It is obvious that these results are hard to reconcile with approaches that try to explain the gamut expansion effect with a renormalization of chromatic contrast that depends either on chromatic variance or the maximum chromatic excursion from white in the surround: There simply is no chromatic variance and all cone opponent channels should be at their (neutral) equilibrium point.

The general pattern of the luminance settings is as expected: To compensate for the "brightness induction" (Whittle, 1994a, 1994b) from the "black surround," the subjects lowered the luminance of the comparison patch relative to the standard patch. Analogously, they increased the luminance of the comparison patch in the "white surround" to compensate for the "blackness induction" from the bright surround.

The basic effect of the surrounds used in Experiment 2A is demonstrated in Figure 1: The patches in panels E and F appear less saturated than those in panel C. Note that the chromatic effect in the demonstration is partially masked by a brightness effect, which was eliminated in the experiments through the subjects' brightness settings.

Experiment 2B: Achromatic surrounds with luminance variation

Brown and MacLeod (1997) investigated two variants of the comparison surround with full color variation: In the "chromatic condition," the colors in the surround were isoluminant and varied only in chromaticity, whereas the surround in the "luminance condition" was achromatic and varied only in luminance. They found that the increase in perceived saturation observed with chromatic test patches in the "chromatic" condition was almost identical to that observed with "full color variation." In the "luminance" condition, however, the effect on the saturation of chromatic test patches was greatly reduced.

These findings are consistent with the assumption that the sensitivity of cone-opponent neurons adapts to the range of chromatic variation in the surround and that this causes the gamut expansion effect: The amount of *chromatic* variation is unaffected in the "chromatic" condition and the gamut expansion effect persists, whereas chromatic variation is absent in the "luminance" condition and so is the gamut expansion effect (with respect to saturation). However, the latter finding seems to be at odds with the results of Experiment 2A, in which we found that the gamut expansion effect persists even if a completely uniform achromatic comparison surround is used, which contains no chromatic variance at all.

To investigate this apparent inconsistency, we decided to replicate the "luminance" condition in essentially the same setting that we used in the previous experiments. The only difference to Experiment 1A was that an achromatic comparison stimulus with pure luminance variation was used. In this special case, the color ellipsoid in LMS space, which describes the variance of the surround colors, degenerates to a line segment through the (achromatic) mean color m. This line segment is oriented in the direction of the vector from zero to m. Using the methods in Golz and MacLeod (2003), the coordinates $xyY_m = (0.309, 0.315, 9.12)$ of m translate to LMS coordinates $\mathrm{LMS}_m = (6.91511, 3.08489, 11.6165)$, with $\|\mathrm{LMS}_m\| = 13.87$. The standard deviations 5 and 2.5 were used to realize a high and a low variance condition. In this experiment, we only used hues on the red/green direction. Each subject made 6 settings per purity step. Three of the subjects from Experiment 1A (FF, VE, WM) participated in the experiment.

Results and discussion

The results shown in Figure 10 indicate that the gamut expansion effect in both the high and low variance condition is virtually identical to the effect observed in Experiment 1A, in which a comparison surround with full color variation was used. This observation again suggests that chromatic variation in the surround is not necessary for the occurrence of the gamut expansion effect. This conclusion is in line with our findings in Experiments 1C and 2A but it is inconsistent with the results of the second experiment of Brown and MacLeod (1997).

Brown and MacLeod (1997) regard the "dissociation" between luminance and chromatic effects in their second experiment as an important finding. For instance, they conclude that this finding "weights heavily against models of color appearance based on contrasts within cone channels" (p. 847) and that "the gamut expansion effect apparently occurs at or beyond the level of an opponent transformation" (p. 847). Given the great theoretical relevance of the finding, we explored possible reasons for the inconsistent results. To check whether the deviations between their and our results were possibly due to additional figural cues or differences in the absolute luminance level, we reproduced the stimuli of Brown and MacLeod's second experiment as exactly as possible. Unfortunately, the authors did not specify the amount of luminance variation used. We therefore tested a range of variances. Our informal results showed unequivocally that also with the type of stimuli used by Brown and MacLeod, pure luminance variation in the surround can lead to a noticeable desaturation of chromatic test patches. Our informal results indicate that a large fraction of the maximally possible desaturation effect is already reached at low absolute values of luminance variation. The latter observation also may explain why we found approximately the same effects under the low and high variance conditions realized in our Experiment 2B.

Given these additional observations, one possible reason for the different results of Brown and MacLeod (1997) is that they used a very low luminance variation.

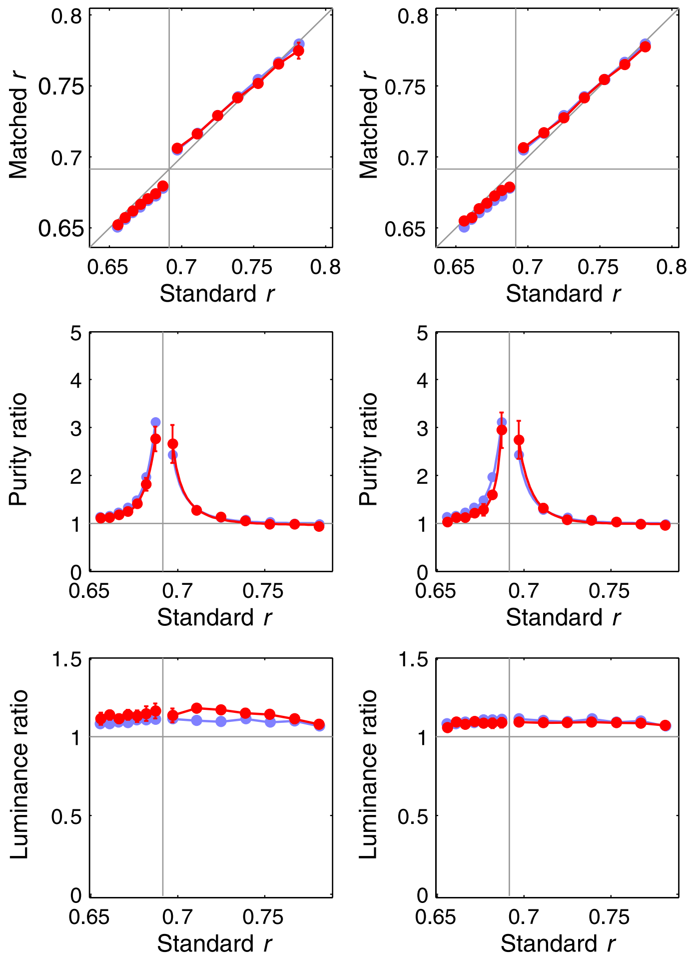

Figure 10. Results of Experiment 2B, based on the pooled data of all three subjects. Each panel shows the data of Experiment 2B (red) and as a reference the corresponding results of the same subjects from Experiment 1A (blue). The plots in the left column show the results for the 'high variance' condition, the plots in the right column those of the 'low variance' condition. The top panels show the mean chromaticities of the matches plotted against the chromaticities of the standard patches. The middle panels show ratios of match to standard purity, and the bottom panels show ratios of match to standard luminance. All other properties of the plots are identical to those in Figure 5.

Another possible factor that may in part be responsible for the different results is that our stimuli contained only one matching target, whereas their stimuli contained six matching targets of different color. Somewhat surprisingly, informal observations suggest that this can indeed make a difference.

It is however clear that their general conclusion that pure luminance variation does not influence perceived saturation of chromatic patches is not warranted. This is evident from the pattern of results we obtained in our experiments and the additional informal observations just mentioned (compare also panels B and C in Figure 1). It therefore seems necessary to re-evaluate the theoretical conclusions based on their original finding.

Experiment 2C: Effect of chromatic variance

Current theoretical explanations of the gamut expansion effect focus on the chromatic variance in the surround as the relevant variable. As already mentioned in the introduction, a popular variant of these approaches is based on the idea that the sensitivity to chromatic contrast depends on the amount of chromatic variance in the scene.

The experiments reported so far have shed serious doubt on the validity of this hypothesis. They suggest that the gamut expansion effect can be greatly reduced without changing the variance in the surrounds (Experiments 1A–1C) and that the same or an analogous effect can be produced by other means than chromatic variance in the comparison surround (Experiment 2A). It is still not clear, however, what was the critical aspect of the variegated surround leading to the gamut expansion effect in Brown and MacLeod's (1997) original experiment. In two additional experiments, we therefore investigated to what extent the gamut expansion effect is affected by variations in the amount and distribution of chromatic variance in the comparison surround.

The general procedure in Experiment 2C was similar to that used in Experiments 1A–2B but differed in several details. The subjects viewed two centre-surround configurations with a horizontal centre-to-centre distance of 9.5°. The central patches had a radius of 0.516°, and the square surrounds had a width of 7.64°. The standard surround was uniform with the chromaticity of CIE Illuminant C (MacLeod–Boynton coordinates r = 0.692, b = 1.149) and a luminance L + M = 10 (corresponding to a value of Y = 9.12 cd/m^2 in the CIE 1931 system). The comparison surround was one of the six shown in Figure 11. All these surrounds had the same spatial mean as the uniform standard surround but differed in the amount and distribution of chromatic variance. In the surrounds I and D, the amount of chromatic variance varied radially from the centre to the periphery. The top left panel in Figure 11 shows how the relative amount of variance increases towards the periphery in stimulus I, and the right top panel shows the decrease of the relative variance in stimulus D. For both stimuli I and D, two additional surrounds (IL, IG and DL, DG, respectively) were generated which had a variance that was either locally (i.e. at the border with the central patch) or globally (i.e. on average) identical to that of I and D.

To compute the variance in the comparison stimuli, the surround area was partitioned into 11 concentric annular regions with a constant width of 0.382°. The colors of the disks within these regions were chosen such that in each region i the distribution of pixel colors (in LMS-space)

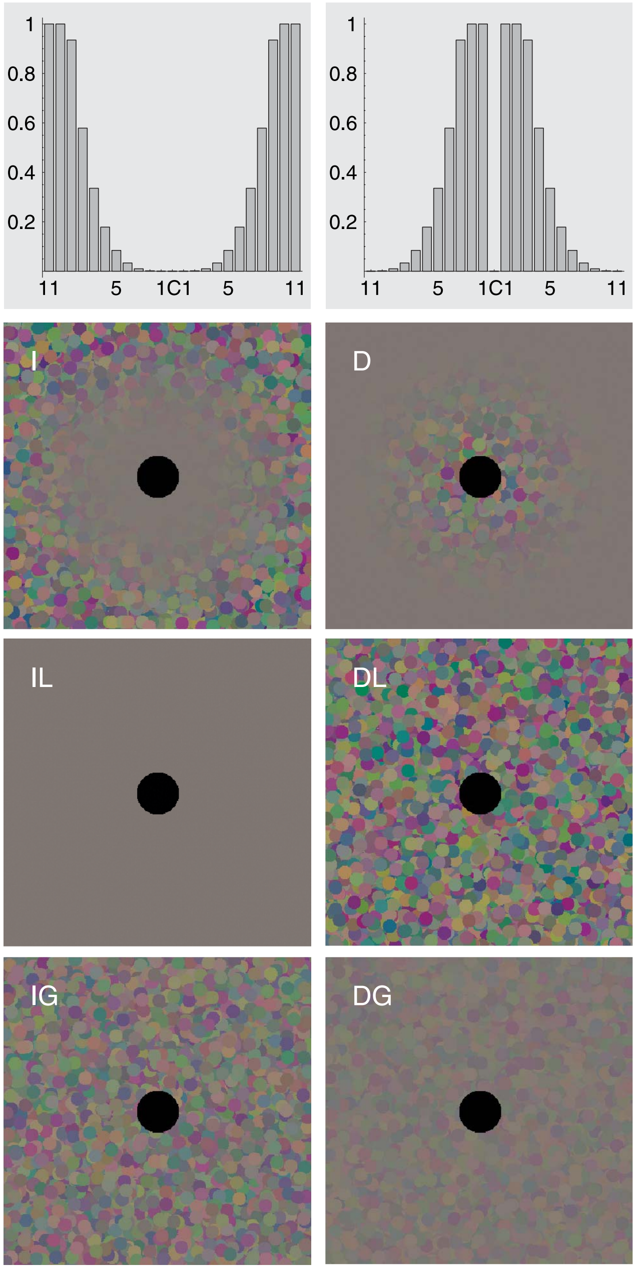

Figure 11. Comparison surrounds used in Experiment 2B. *Left column*: Surround with increasing variance distribution I and two comparison surrounds which are locally (IL) or globally (IG) identical. *Right column*: A surround with decreasing variance distribution D and the locally (DL) and globally (DG) identical surrounds. The plots in the top panels show the distribution of surround variance in the surrounds I and D in 11 concentric rings of equal width.

had a fixed constant mean m and covariance matrix c_i. The mean color was identical to the color of the uniform standard surround. The covariance matrices used for the different regions were scaled versions of the covariance matrix

$$Cov = \begin{pmatrix} 4.4283 & 1.9361 & 0 \\ 1.9361 & 0.9401 & 0 \\ 0 & 0 & 10.24 \end{pmatrix}, \tag{2}$$

that is, $c_i = s_i\, Cov$, $s_i \in [0,1]$. The covariance matrix Cov describes an ellipsoidal distribution in LMS color space close to that maximally realizable within the monitor gamut for the given mean. The scaling factors s_i used in surrounds I and D are shown graphically in the top panels of Figure 11. For the surround IL, the scaling factors s_i were all zero, and for the surround DL they were all one. The surrounds IG and DG had constant scaling factors 0.4602 and 0.1707. These factors were chosen such that the *total* variance in the surround IG and DG was identical to that of I and D, respectively.

We used essentially the same procedure as in the previous experiments to measure the strength of the effect for each of the six surrounds: The standard patch presented in the uniform standard surround had one of the 8 patch chromaticities shown in Table 1. The subjects adjusted the purity and the luminance of a second patch embedded in one of the six comparison surrounds. The adjustments were made along one of eight hue directions defined by the lines from the white point through the standard patch chromaticities given in Table 1. Note that in the case of surround IL, test and comparison surrounds are identical. Each measurement was repeated 8 times resulting in 384 trials for each subject (6 surrounds $\times$ 8 patch chromaticities $\times$ 8 repetitions), presented in random order. The assignment of the uniform and variegated stimulus to the left or right hand side of the monitor was balanced. Between each trial a blank screen was shown for 3 s.

Five subjects participated in the experiment, including one of the authors (GW). Two of the subjects were naive with respect to the purpose of the experiment and had no experience as psychophysical observers. All subjects had normal color vision according to the Ishihara Tests for Colour-Blindness.

Hue	1	2	3	4	5	6	7	8
r	0.704	0.701	0.692	0.683	0.679	0.683	0.692	0.701
b	1.149	1.326	1.399	1.326	1.149	0.973	0.899	0.973

Table 1. MacLeod–Boynton coordinates of the standard patches used in Experiment 2C.

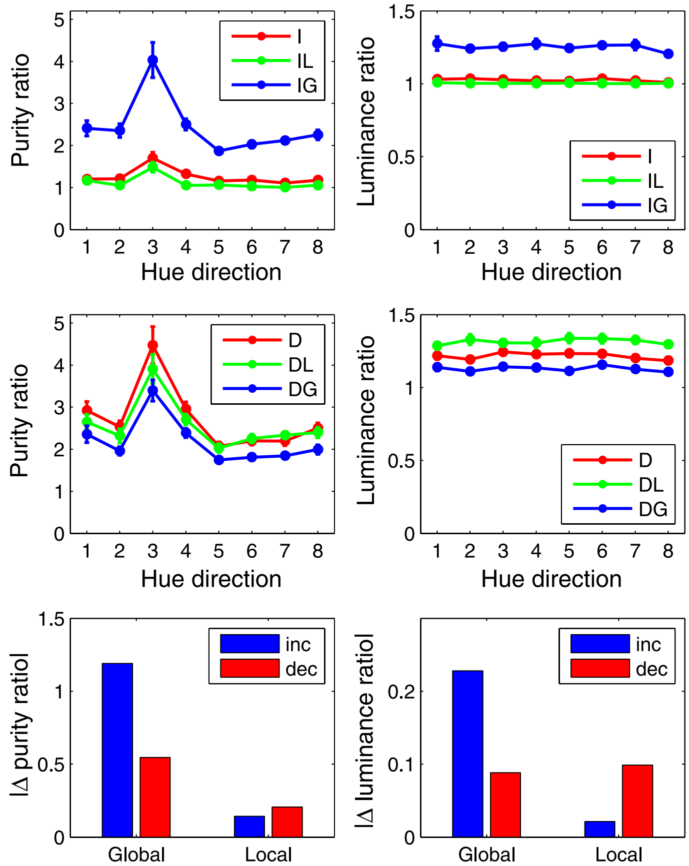

Figure 12. Results of Experiment 2C. The top row shows the purity ratios (left) and luminance ratios (right) between match and standard for the three surrounds I, IL, and IG in the 'increasing' condition. The middle row shows the same data for the three surrounds D, DL, and DG in the 'decreasing' condition. Error bars show ±1 *SD*. The bottom panels show the deviations from the predictions of the global and local hypothesis, in terms of purity ratios (left) and luminance ratios (right). Hue directions correspond to the target chromaticities given in Table 1.

Results and discussion

The mean results for all five subjects are plotted in Figure 12. The top panels show the purity ratios and the luminance ratios for the reference surround I and the middle panels show the same information for the reference surround D. The bottom panels compare the deviation from the predictions of two different "extreme" hypotheses: One possibility would be that the effect depends only on the parts of the surround immediately adjacent to the target patch (local hypothesis). Another possibility is that the effect is determined by the mean variance of the entire surround (global hypothesis).

In the case of the reference surround I, both the purity and the luminance ratios indicate that it is mainly the variance along the border to the central patch that matters and not the global variance: The effects obtained with I and IL are almost identical, whereas those obtained with IG are clearly different. The results obtained with reference surround D point in the same direction but are less clear-cut. The main reason for this is that the expansion effects found for the three surrounds used in the decreasing condition are very similar. The plots in the bottom row of Figure 12, where the data are pooled over all hue directions, summarize our findings: In the left plot, the absolute differences in purity ratio between the reference surrounds I and D and surrounds with globally identical variance (IG, DG) or locally identical variance (IL, DL) are shown. In the right plot the same information is shown with respect to the luminance ratios.

The data of this experiment also yield information about how the strength of the expansion effect depends on the amount of variance in the surround. In Figure 13, the purity ratios obtained with the surrounds IL, IG, DL, and DG, which all have a spatially uniform variance distribution, are compared. The values on the abscissa are the surround variances relative to the maximum variance, which was realized in surround DL. Interestingly, the surround DG, having only 17% of the maximum color variance, already leads to an effect which amounts to 68% of the effect observed in surround DL (100% effect).

In order to understand the different effect of locally uniform and locally variegated surrounds observed in the experiment it may be instructive to consider each surround condition in turn: The purity ratios close to 1 found with surround IL are trivial since IL was identical to the uniform standard surround. Interestingly though, the same results were obtained with surround I, which is only locally identical to the standard surround. The high variance in distant parts of the surround apparently had no significant influence. The surround IG, in contrast, which was locally (as well as globally) variegated, had a distinctly different effect than the uniform standard surround. Thus, although surrounds I and IG have the same total variance, they have clearly different effects.

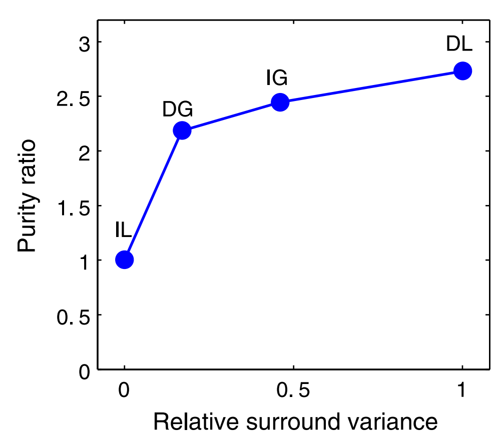

Figure 13. Mean purity ratios plotted against the total amount of variance in the surround. The four data points correspond to the mean values obtained for the four surrounds IL, DG, IG, and DL (see Figure 12).

The three surrounds in the "decreasing" condition, which are all variegated in the vicinity of the central patch, led to very similar effects. Neither the spatial distribution of the chromatic variance nor the amount of variance in the vicinity of the target patch seems to be of great importance, provided that the total variance is not close to zero (cf. Figure 13).

Taken together, the results of this experiment suggest that local chromatic variance is much more important than the global variance. Furthermore, the strength of the effect is a highly nonlinear function of the amount of surround variance: It rises steeply at the transition from a uniform to variegated surround and levels out swiftly after that.

Experiment 2D: Retinal range of surround influence

The results of Experiment 2C have shown that the gamut expansion effect mainly depends on the chromatic variance in the vicinity of the central patch. Brown and MacLeod's (1997) finding that a thin gray line around the target patch reduced but did not eliminate the effect indicates "that the effects of color variance in the surround cannot be entirely local" (Brown & MacLeod, 1997, p. 846). In Experiment 2D, we therefore investigated how large the retinal extent of the "local" area of influence is.

We used two types of surround. The first set of surrounds was obtained by stepwise transforming a variegated surround into a uniform one by replacing its inner part with uniform annuli of increasing width (see Figure 14, top row). The second set of surrounds was obtained by an analogous transformation, in this case from a uniform surround to a variegated one (see Figure 14, bottom row). The variegated and the uniform parts of the surround had the same spatial mean and variance as the surrounds DL and IL in Experiment 2B, respectively. For both types of surround, the same 10 annulus widths were used: 0, 0.019, 0.095, 0.287, 0.477, 0.668, 1.012, 1.394, 2.349, and 3.304 degrees of visual angle (where a width of 0 means no annulus). The central patch had a radius of 0.516 degree.

The general experimental setting and the procedure were the same as in Experiment 2C: The task of the subjects was to match the color of a standard patch in a uniform surround by adjusting the purity and the luminance of a patch embedded in one of the above mentioned comparison surrounds. Standard and comparison surround had the same mean color (Illuminant C at 9.12 cd/m^2). We used 4 different chromaticities for the standard patch, corresponding to hue directions 1, 3, 5, and 7 of Experiment 2C. For each combination of the 20 different comparison surrounds and the 4 standard chromaticities, 8 repetitions were made, resulting in a total of 640 trials for each subject. The stimuli were presented in random order. Three subjects (including author GW) who had also participated in Experiment 2C performed the experiment.

Results and discussion

Figure 15 shows typical results from this experiment (subject GW). In each panel, ratios between match and standard purity are plotted against the width of the inner

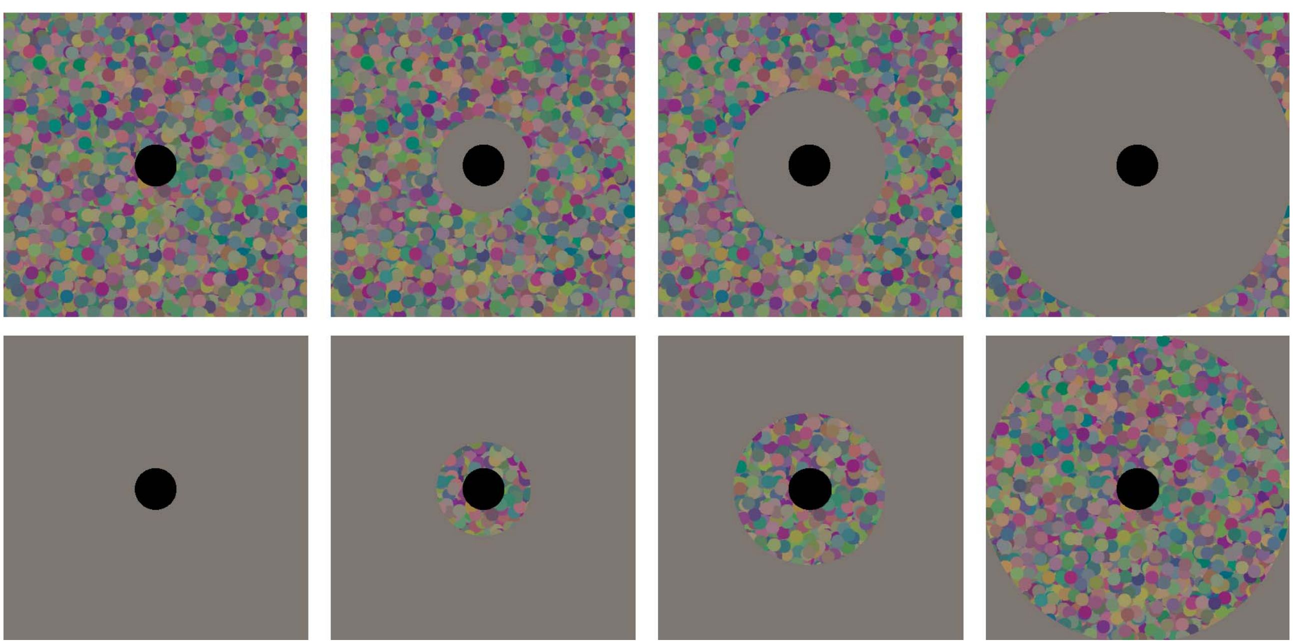

Figure 14. Illustration of the comparison surrounds used in Experiment 2D. *Top row*: Four of the 10 surrounds with uniform inner annulus (leftmost annulus width is zero). *Bottom row*: Surrounds with variegated inner annuli.

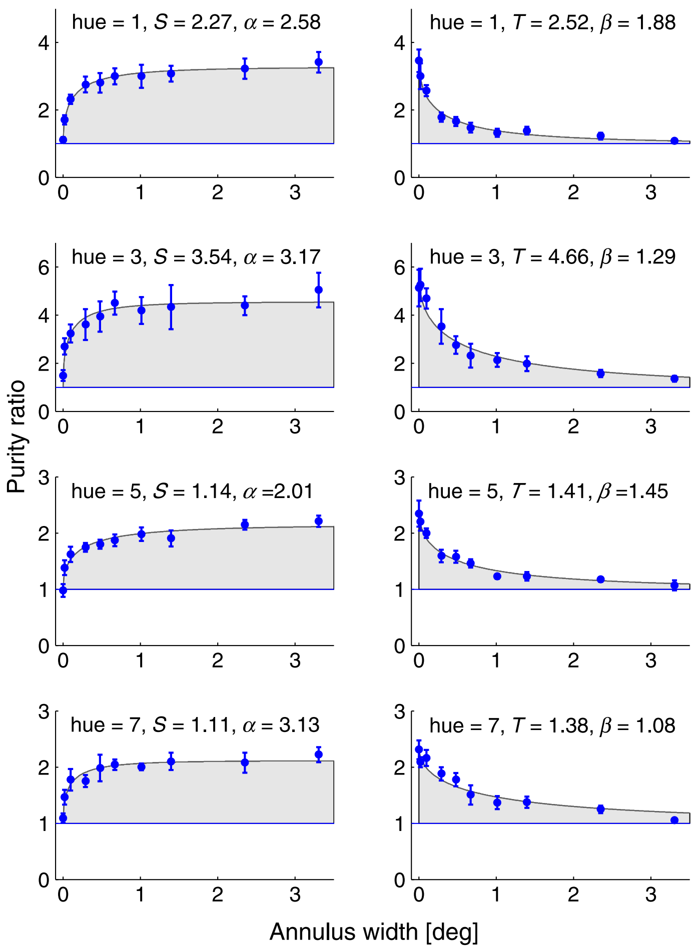

Figure 15. Results of Experiment 2D for subject GW. In each panel, purity ratios are plotted against inner annulus width. In the left column, the data for variegated inner annuli are shown, in the right column those for uniform inner annuli. The error bars show ±2 *SEM*. The gray regions show the gamut expansion effect (according to the fitting procedure described in the text).

annulus. The left column shows the results for variegated inner annuli, which means that at an annulus width of zero the entire surround was uniform. Since in this case the comparison surround is identical to the standard surround, a purity ratio of one must result. With increasing width of the variegated annulus the purity ratios increase rapidly and soon flatten out at a constant value. The right column shows the results for uniform inner annuli, which means that at an annulus width of zero the entire surround was variegated. In this case, large purity ratios are obtained that rapidly decrease to the limiting value 1, which is of course expected for a completely uniform surround identical to the standard surround. In both cases the data change exponentially: For variegated and uniform inner annuli the functions $f(x) = S[1 - \exp(-\alpha x^{1/2})] + 1$ and $g(x) = T\exp(-\beta x^{1/2}) + 1$, respectively, describe the data quite well (see curves in Figure 15). Intuitively, the parameters S and T are the heights of the gray regions in the left and right column of Figure 15 and thus describe the maximum observed deviation of the purity ratios from unity. The parameters α and β determine the steepness of the curves: Large values for these parameters mean that the curves reach their asymptotic values rapidly.

Such fits were made for each of the four hue conditions and each of the three subjects separately. In all cases, the quality of the fits was quite good and comparable to the ones shown in Figure 15. Thus, to save space, we only report the parameters of the fit for the other subjects in Table 2. Since we are mainly interested in the retinal range of the surround influence, we also computed the annulus widths δ_v and δ_u (in degrees of visual angle) at which the initial (at annulus width 0) distance from the asymptotic values shrinks to 25%. These values are simply related to the parameters α and β, respectively: $\delta_v = (-1/\alpha \ln 0.25)^2$ and $\delta_u = (-1/\beta \ln 0.25)^2$. Although the "height" parameters T and S vary considerably with subject and hue condition, the curves are clearly steeper

		Variegated			Uniform		
Subject/hue		S	α	δ_v	T	β	δ_u
GW	1	2.267	2.580	0.289	2.520	1.881	0.543
	3	3.543	3.166	0.192	4.656	1.291	1.154
	5	1.143	2.010	0.476	1.415	1.451	0.912
	7	1.115	3.130	0.196	1.379	1.080	1.648
AS	1	3.398	3.104	0.200	3.920	1.592	0.758
	3	5.703	3.230	0.184	6.714	1.131	1.502
	5	2.057	2.433	0.325	2.374	1.431	0.938
	7	1.450	4.846	0.082	1.892	1.478	0.879
CS	1	1.095	2.998	0.214	0.953	0.865	2.568
	3	2.142	2.731	0.258	2.026	1.075	1.664
	5	1.091	1.826	0.576	0.965	1.047	1.754
	7	0.845	1.881	0.543	0.757	1.057	1.720
Mean		2.154	2.828	0.294	2.464	1.281	1.337

Table 2. Parameters of the fits for each subject and hue condition. Parameters δ_v and δ_u correspond to the estimated annulus width (in degrees visual angle) at which the initial distance from the asymptotic values shrinks to 25%.

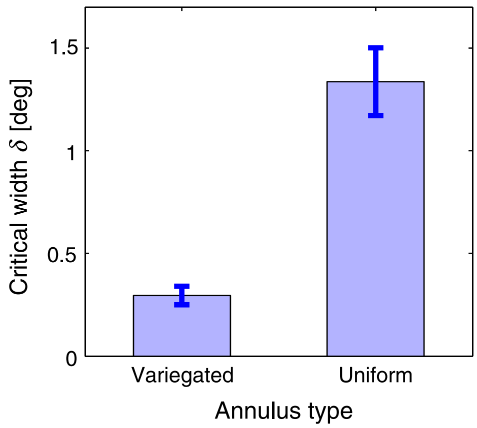

Figure 16. Mean estimated values of δ_v and δ_u for variegated and uniform inner annuli, respectively. Error bars show ±1 *SEM*.

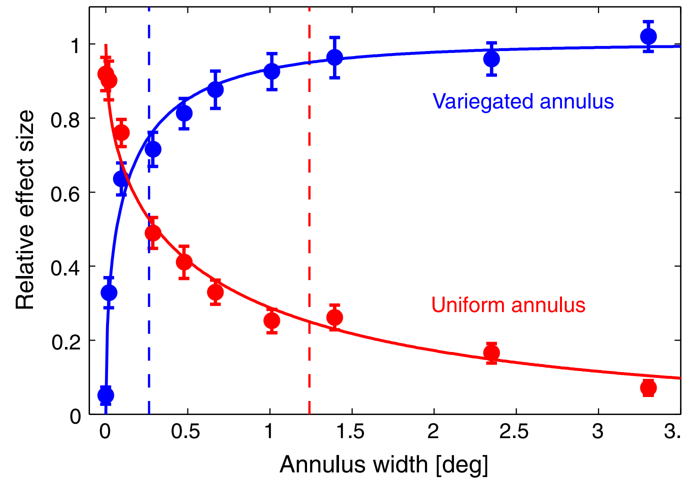

Figure 17. Relative strength of the gamut expansion effect plotted against inner annulus width for variegated (blue) and uniform (red) inner annuli. The vertical lines show where, based on the fit, 75% of the asymptotic effect change is reached. The error bars show ±2 *SEM*.

for variegated inner annuli throughout, i.e., α is always larger than β. Accordingly, the estimated annulus widths δ_v and δ_u are clearly different, as can be seen in Figure 16.

For each hue condition and subject, the height parameters T and S give an individual estimate of the difference between the purity ratio PR obtained with a fully variegated surround (PR = T + 1 or PR = S + 1, respectively) and the value (PR = 1) obtained with a completely uniform surround. Provided that all individual curves describe the same dependence on the width of the inner annulus in spite of the different individual estimates of T or S, dividing each data curve by these values should lead to curves of essentially the same shape. Figure 17 shows the means of the such normalized data, pooled over all subjects and hue conditions, for variegated inner annuli (increasing blue curve) and uniform inner annuli (decreasing red curve). The narrow error bars indicate that the dependence on annulus width is indeed similar across subjects and hue conditions. In this plot, it is obvious that the curve describing the transition from a uniform to a variegated surround is clearly steeper than the converse transition from a variegated to a uniform surround.

With respect to the ratios of match and standard luminance, the results were less clear-cut. Generally, the luminance ratios were quite small (always less than 1.3 for all subjects, and even less than 1.1 for subject GW) and rather noisy. The general pattern of results was similar, but the relatively low signal-to-noise ratio of the data does not allow precise comparisons between different experimental conditions.

The results of the present experiment show that the region of the surround that influences the color of the central patch is rather limited. A narrow annulus with a width of less than 1.5° gives rise to an effect of more than 75% of the maximal effect obtained with a large extended surround. Our results are in good agreement with Brown and MacLeod's (1997) finding that a thin gray border (8 min visual angle) around the central patch led only to a moderate reduction of the gamut expansion effect. From their Figure 2, we may estimate that the effect in the condition with gray border was reduced to about 60% of the value found without border. From our data, almost the same reduction (62%) was estimated for a uniform annulus of the same width as the border used by Brown and MacLeod.

This finding confirms the conclusion of Brown and MacLeod (1997) that the effect of chromatic variance in the surround cannot be entirely local. The data of our experiments show that the opposite alternative—an entirely global effect—can also be ruled out. Instead, the influence of the surround diminishes very rapidly with increasing retinal distance from the central patch. An interesting aspect of the present data is the finding that the two transition curves in Figure 17 are not equally steep, as one would perhaps intuitively expect: In the case of a uniform surround, adding a narrow variegated annulus of a few pixels width changes the color impression dramatically, whereas a uniform annulus that is added to a variegated surround has to be much wider in order to elicit the same amount of perceptual change.

General discussion

Main findings

In order to identify determinants of the gamut expansion effect, we performed several variants and extensions of

Brown and MacLeod's (1997) original matching experiment. Our main findings are as follows:

1. The strength of the gamut expansion effect depends strongly on the relation between the central patch and the surround in the uniform standard stimulus: The effect is maximal when the central patch and the surround are equiluminant and have a very small chromatic contrast. It diminishes rapidly if either the chromatic contrast (Experiment 1A) or the luminance contrast (Experiment 1B) are increased.
2. The gamut expansion effect disappears almost completely when centre and surround in the standard stimulus are separated by a thin black line (Experiment 1C).
3. The gamut expansion effect persists when the chromatically variegated comparison surround is replaced by a uniform achromatic one with high luminance contrast (Experiment 2A) or by an variegated achromatic surround with mere luminance variation (Experiment 2B).
4. The amount and the distribution of the variance in the comparison surround has only a very small influence on the strength of the gamut expansion effect as long as the variation is not completely absent (Experiment 2C).
5. The influence of the comparison surround is predominantly local: A thin variegated annulus around the central patch in the comparison surround has almost the same effect as an extended variegated surround. Analogously, a thin uniform annulus has almost the same effect as an extended uniform surround (Experiment 2D).
6. It was noted that producing a perfect asymmetric match was sometimes impossible. In particular, targets of low purity presented in a uniform gray surround were difficult to match by any patch presented in a variegated surround.

Evaluation of the contrast adaptation hypothesis

The above pattern of results speaks against the contrast adaptation hypothesis, at least against the version of it outlined in the introduction. The central assumption of this hypothesis is that the sensitivity of cone-opponent neurons adapts to the chromatic variance or chromatic range in the scene and that the gamut expansion effect observed by Brown and MacLeod (1997) is due to the different chromatic variance or chromatic range in the standard and comparison surround. The most direct contradiction to this hypothesis is our result that the gamut expansion effect persists in asymmetric matching tasks in which neither of the stimuli contains chromatic variation in the surround (Experiments 2A and 2B). The further findings that the influence of the comparison surround is mainly local (Experiment 2C) and that the strength of the effect and the amount of variance in the comparison surround are only weakly correlated (Experiment 2D) provide additional evidences against this explanation.

The predominantly local character of the surround influence found in Experiment 2D and the results of Experiments 1A and 1B, which indicate that the gamut expansion effect occurs only under very specific contrast conditions, also stand in stark contrast to the picture of contrast scaling outlined in Brenner et al. (2003): These authors interpret their findings in terms of a rather general contrast scaling mechanism that precedes a possible shift of the neutral point and that depends on a global measure of chromatic variability in the scene. Given these qualitative differences, it seems highly improbable that the mechanism underlying the gamut expansion effect is identical to the scaling mechanism postulated by Brenner et al. (2003).

An observation that the contrast adaptation hypothesis fails to account for is that perfect asymmetric matches are sometimes impossible to make. Any approach that models the influence of the surround as a transformation of three dimensional color codes predicts that such matches should always be possible (except for gamut problems, which can safely be excluded as a possible explanation in the present case).

Evaluation of the scission hypothesis

From the adaptational perspective, the observed difference in the effects of uniform and variegated surrounds is inherently symmetric. It is therefore not possible to attribute a special status to any of the surrounds. The scission hypothesis, on the other hand, attaches special significance to the uniform surround because this is the surround in which color scission—and hence the perceptual color effect—takes place. In line with this expectation, the results of Experiments 1A, 1B, and 1C indicate that the critical condition for the gamut expansion effect lies in the uniform standard stimulus. They suggest that the perceived saturation of a uniform patch is *enhanced* if it is enclosed by a uniform gray surround with very low color contrast along the common edge. The most direct evidence that this indeed describes the relevant condition is the result of Experiment 1C, which shows that the gamut expansion effect can be switched off and on by adding and removing, respectively, a thin black outline at the border of the central patch in the uniform *standard* stimulus. Thus, on a descriptive level, our results support the speculation of Brown and MacLeod (1997) that the gamut expansion effect may be closely related or even identical to the "crispening effect" (Ovenston, 1998; Takasaki, 1966, 1967; Whittle, 1992) "in which low-contrast edge signals contribute disproportionately to perceived contrast" (Brown & MacLeod, 1997, p. 848).

The scission hypothesis may thus be regarded as a functional explanation of both the "crispening" and the "gamut expansion" effect.

Viewed from the perspective of the scission hypothesis, the variegated surround represents the standard situation in which no scission occurs. As a consequence, it predicts that properties of the variegated surround can be manipulated freely without producing any change in the gamut expansion effect as long as scission is prevented. This is exactly what our results suggest.

Possible objections against dismissing the contrast adaptation hypothesis

In order to test the idea of contrast adaptation it is necessary to make it specific enough to be able to derive predictions of experimental results. The specific contrast adaptation model we have dealt with seems to be a natural interpretation of the general idea underlying the explanation suggested in the literature. It is, however, by no means the only possible incarnation of the general idea of contrast adaptation. We shall briefly consider how the contrast adaptation hypothesis may be modified in order to account for our findings.

Our finding that pure luminance variation in the surround has basically the same influence on perceived saturation as full color variation (Experiment 2B) argues against an explanation in terms of contrast adaptation within cone-opponent pathways. Based on this result, a possible modification of the model would be to assume that adaptation to the variance in the surround works across color and brightness channels, so that pure luminance variation may influence perceived saturation. However, the results of our Experiment 2B suggest that the effect on perceived saturation may occur even in the absence of any surround variance whatsoever. It would seem that the only way to apply the "idea of contrast adaptation" to this situation is to assume that the visual system adapts to the contrast between the target and the uniform (black or white) surround. While this indeed remains a viable theoretical option, this version of the contrast adaptation hypothesis has lost much of its original appeal.

Indications of multiple mechanisms

Comparing the results of Experiment 1C, where a black ring was drawn around the standard patch, and those of Experiment 2C, where a uniform black comparison surround was used, raises an interesting question. On the one hand, it can be concluded that both the thin black ring and the extended black surround are equally successful in preventing the saturation enhancement observed with the original gray surround. On the other hand, they have markedly different effects on the brightness of the target patches (see Figures 8 and 9). A possible explanation for this asymmetry may be that there are two origins of the total effect: One of the effects is classical brightness induction, which is known to depend on the area and distance of the inducing field. In line with models of the spatial extent of the surround influence (De Bonet & Zaidi, 1997), the brightness induction effect of the narrow ring is much weaker than that of the extend surround. The other effect, which affects the perceived saturation to the same extent in both situations, may be explained by referring to the scission hypothesis: Introducing a black ring or replacing the isoluminant gray background entirely with a black one are equally good ways of preventing scission. This explanation is in line with the suggestion of Kingdom (2003) that induction phenomena are best understood within a multi-level framework.

Asymmetry in spatial range of uniform and variegated surrounds

In Experiment 2D, it was found that even a very thin variegated annulus can have almost the same effect as an extended variegated surround. An annulus of 0.3 deg width already produced 75% of the asymptotic effect. A uniform annulus on the other hand must be considerably thicker (about 4 times as large) in order to produce 75% of the effect of an extended uniform surround.

This asymmetry is to be expected from the scission hypothesis. The assumption is that scission is only evoked by uniform surrounds with low contrast to the central patch, where a large component common to the central patch and the surround can be isolated. Obviously, the extraction of a common component is no longer possible as soon as a variegated annulus is placed adjacent to the central patch, however narrow it may be. In the converse case, where a thin uniform annulus is added to a variegated surround, it is more likely that the visual system interprets this thin annulus as a "border" than as a uniform background on which the central patch is overlaid. Thus, one may expect that a minimal width of the uniform surround is necessary before the ring is treated as a background and a scission takes place.

Possible limitations of the scission hypothesis

The contrast adaptation hypothesis as formulated in the introduction cannot explain the full range of effects observed in our experiments. The scission hypothesis on the other hand seems to account well for the majority of our findings. There is, however, also an observation that is not easily accounted for by the scission hypothesis as described in the Introduction section. A central assumption of this hypothesis is that scission does not occur in variegated surrounds because in this case a figural precondition for transparency is violated. Thus, this form of the scission hypothesis cannot explain differences in the effectiveness of different variegated surrounds. Although comparatively small, such differences were observed in Experiment 2C (see Figure 13).

A possible explanation of this observation is that there is indeed a small influence of contrast adaptation that contributes to the total effect. Alternatively, one may assume two different kinds of scission, namely a “local” and a “global” form. In local scission, only the region corresponding to the target patch looks transparent. This would, for instance be the case, when the central target is a transparent overlay through which the background is seen. In global scission, there is a common transparent overlay covering both target and surround. This would for instance be the case if the entire configuration is seen through fog. There is no reason to expect that the latter, global transparency, should depend on the figural relations between target and surround. Hence, a variegated surround may only prevent local but not global scission. In fact, contrast adaptation may well turn out to be part of the mechanisms responsible for global scission.

The distinction between “local” and “global” scission also suggests itself, if one looks at different examples. In panel A of Figure 6, for instance, only the low contrast patches appear as transparent layers, suggesting a local form of scission. Surrounds I and D in Figure 11, on the other hand, may be regarded as examples of “global” scission: Here, the variegated surrounds appear to be covered by “fog” of varying density. See Zavagno (2005) for a presumably related phenomenon.

Are uniform surrounds special?

The results of the present experiment as well as those of Ekroll et al. (2004) suggest that uniform surrounds have a special status. According to the scission hypothesis this is because a uniform surround is figurally compatible with the interpretation of a colored transparent layer in the region of the target patch. If this interpretation is correct, then the uniformity of the surround in itself is not the critical variable but instead the compatibility of the texture in centre and surround. Thus, theoretically it should be possible to invert the gamut expansion effect, in the sense that a variegated patch should look more saturated when embedded in a figurally compatible variegated surround than when embedded in a corresponding uniform surround. Preliminary data of a corresponding experiment seem to confirm this expectation.

Conclusions

Our results show that the strong gamut expansion effect observed by Brown and MacLeod (1997) occurs only under rather specific stimulus conditions.

The pronounced difference in perceived saturation of the central patches occurs only if the centre-surround contrast in the uniform surround is very low. The limited role played by the properties of the variegated surround suggests that chromatic variance has no special status but is just one condition that prevents color scission.

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