The strengths of simultaneous colour contrast and the gamut expansion effect correlate across observers: Evidence for a common mechanism

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Abstract

We present the results of an experiment aiming to clarify the relation between simultaneous colour contrast and Brown and MacLeod's (1997) gamut expansion effect. These two context effects are often thought to be due to two different mechanisms, but this assumption has not previously been subjected to empirical test. Here we used inter-individual variability in the susceptibility to these effects to test this assumption. The individual variability was found to be quite substantial for both context effects. As would be expected if a common underlying mechanism contributes to both effects, a significant correlation across observers was found. It is suggested that this putatively common mechanism of 'crispening' accounts completely for the gamut expansion effect, and partially for the simultaneous colour contrast effect, which seems to depend on von Kries adaptation also.

Keywords: Simultaneous colour contrast, colour induction, crispening, gamut expansion effect, von Kries gain control, individual differences, perceptual transparency
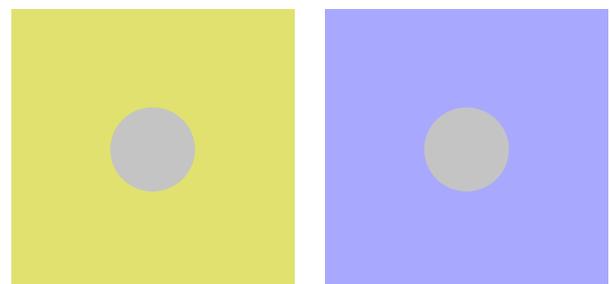
1. Introduction

Brown and MacLeod's (1997) gamut expansion effect has stirred much interest because it is at odds with traditional ideas about the basic quantitative features of simultaneous colour contrast. A standard demonstration of the latter is shown in Fig. 1a. The two central discs are nominally grey, but each of them appear tinged with a colour roughly complementary to that of its surround. This observation is in accordance with the traditional general description of simultaneous contrast as a translation in color space. The gamut expansion effect is demonstrated in Fig. 1b. Here, the four discs embedded in the uniform gray surround are physically equal to those embedded in the variegated surround, yet the former appear more saturated than the latter. This effect clearly cannot be described as a translation in colour space. Rather, an expansion in colour space centred at the coordinates of the surround would seem to yield a better description of the observed effect.

According to the standard perspective (Webster, 2003), these two observable phenomena are due to separate visual mechanisms. Simultaneous contrast is thought to be due to a mechanism adapting to the mean colour of the surround ('light adaptation') while the gamut expansion effect is due to a mechanism adapting to the variance in the surround ('contrast adaptation').
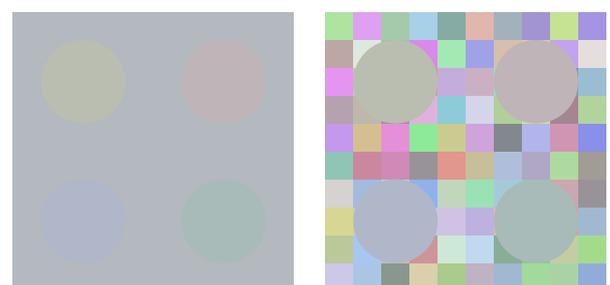

Figure 1: a) A standard demonstration of simultaneous colour contrast. The two discs are both the same nominal grey, but each of them appear tinged with a colour complementary to that of its surround. b) A demonstration of the gamut expansion effect (after Brown and MacLeod, 1997). The four discs embedded in the uniform gray surround are physically equal to those embedded in the variegated one, but the former appear more saturated.

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An attractive corrollary of this view is that it should be relatively easy to eliminate the contribution of either of the mechanisms, such that the other may be studied in isolation. The former mechanism could by silenced in an asymmetric matching experiment by using surrounds with the same mean colour, as in Brown and MacLeod's (1997) experiments, while the latter could by eliminated by using surrounds with the same variance, as in traditional asymmetric matching experiments with uniform (i.e. zero variance) surrounds (Smith and Pokorny, 1996; Ekroll et al., 2004).

Recent work of ours (Ekroll and Faul, 2009), though, suggests that the gamut expansion effect and classical simultaneous contrast are more intimately related than previously thought. Indeed, one may even speculate that the two phenomena are identical. Investigating simultaneous contrast using asymmetric matching we obtained rather complex data, but interestingly, we found that the measured effect could be modelled as a combination of von Kries adaptation and 'crispening' (Ekroll and Faul, 2009). If one assumes that von Kries adaptation is a temporal adaptation effect, this could be taken to mean that the *simultaneous* contrast effect (i.e. the purely spatial induction effect) is identical to the 'crispening effect' studied by Takasaki (1966, 1967) and Whittle (1986, 1992), which in turn, is presumably intimately related to the heightened discriminability of targets similar to the surround documented by many studies (Krauskopf and Gegenfurtner, 1992; Hansen et al., 2008; Giesel et al., 2009). At the same time, it would seem that the gamut expansion effect is also identical to the 'crispening' effect. Thus, simultaneous colour contrast, the gamut expansion effect and crispening could all be different names for the same basic phenomenon (Ekroll and Faul, 2009). If this is indeed the case, then the fact that crispening and the gamut expansion effect violate classical laws of simultaneous contrast should not be interpreted as evidence for further mechanisms distinct from those responsible for classical simultaneous contrast, but rather as evidence that the mechanisms responsible for the simultaneous contrast effect obey different laws than generally believed. First, the purely spatial, time-independent part of the total effect, that is most appropriately referred to as *simultaneous* contrast, may be better described as a local expansion in colour space than as a translation. Second, Kirschmann's (1891) 4th law, which states that the effect increases with surround saturation may be wrong (Bosten and Mollon, 2007; Kinney, 1962; Ekroll and Faul, 2009), because both the gamut expansion effect and the crispening effect actually decrease with target-surround contrast (except at very low contrasts).

The aim of the present experiment was to test the idea that simultaneous contrast and the gamut expansion effect share a common mechanism. One way to test the hypothesis that two observable phenomena share a common underlying mechanism would be to manipulate the strength of the mechanism and look for correlating variations in the observable effects. Such direct manipulation hardly appears feasible, however. A second possibility would be to manipulate properties of the stimuli that triggers or inhibits the action of the underlying mechanism. Thus, for instance, the finding that both crispening (Whittle, 1992) and the gamut expansion effect (Brown and MacLeod, 1997;

Faul et al., 2008) are abolished or strongly reduced by drawing a thin black border between target and surround may be taken to suggest that the two phenomena share a common mechanism.

A third possibility, which we pursue in the present paper, is to investigate natural variation (Wilmer, 2008; Hamburger and Hansen, 2010) in the 'strength' of the underlying mechanism(s). If two observable phenomena share a common underlying mechanism, and the strength of this mechanism varies across observers, then one would expect the strengths of the observable phenomena to correlate accordingly across observers.

A prerequisite for this kind of analysis is of course that there are any interindividual differences in the observable effects at all. Many studies report fairly good agreement across observers, but this provides only limited information about how much individual variation there is, because most of them report experiments with very few observers, often just the authors themselves. Some studies with somewhat larger observer samples, however, suggest that the strength of simultaneous contrast may vary quite substantially from one observer to the other (Katz, 1911; Thouless, 1932; Takasaki, 1966, 1967; Cataliotti and Becklen, 2007; Ekroll and Faul, 2009). In the present study, we replicate the findings previously reported in Ekroll and Faul (2009), where large interindividual differences in simultaneous contrast were found. Importantly, though, we also measured the strength of the gamut expansion effect for the same observers. Based on the model presented in Ekroll and Faul (2009) we assumed that the measurements of classical simultaneous contrast should be a combination of von Kries adaptation and crispening, while the measurements of the gamut expansion should be attributable to crispening only. This is confirmed by the results reported in the present paper: Individual estimates of the crispening parameter from the gamut expansion experiment (Fig. 2 bottom) correlate with the estimates of the crispening parameter from the simultaneous contrast experiment (Fig. 2 top). Thus, Brown and MacLeod's (1997) gamut expansion experiment may be said to be a particularly convenient way to study the crispening effect in isolation. In a similar way, our hypothesis posits that the von Kries adaptation mechanism can be studied in isolation by using a pair of variegated surrounds with different mean colours. This latter aspect of our general hypothesis is supported by the results from previous experiments (Ekroll et al., 2004; Ekroll and Faul, 2009) and is not explicitly tested in the present paper.

2. Experiment

2.1. Stimuli and methods

The stimuli were presented on a CRT monitor (Viewsonic Professional Series P227f, screen size 41×31 cm, 1280×960 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
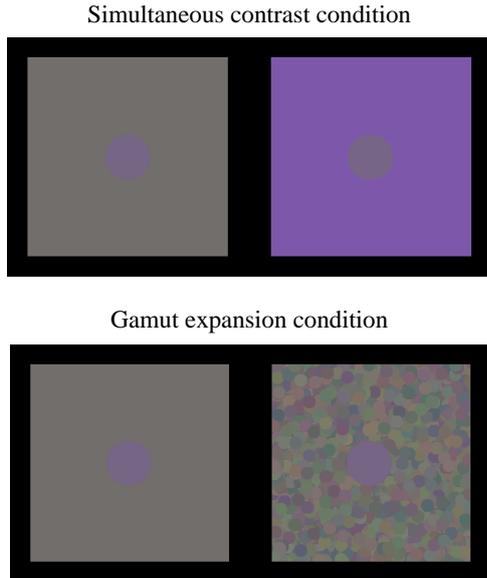
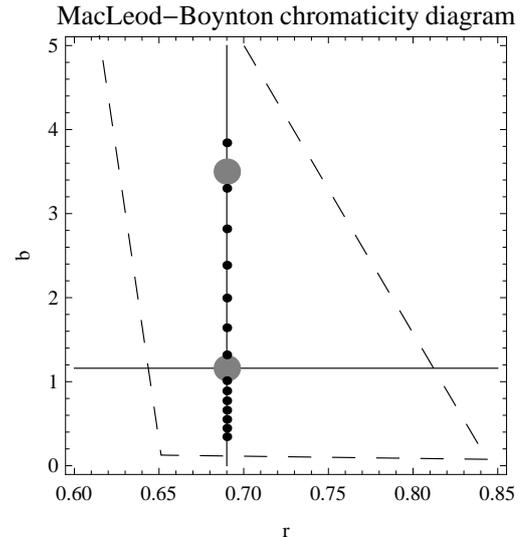Figure 2: The two pairs of centre-surround stimuli used in the experiment.

Figure 3: Chromaticities of the stimuli used in the experiment plotted in the MacLeod-Boynton chromaticity diagram (MacLeod and Boynton, 1979). Large gray disks: Surround chromaticities. Black dots: Target chromaticities. The dashed lines show the border of the gamut of our monitor.

by Stockman et al. (1993). During the experiments, the monitor was the only light source in the room. The viewing distance was approximately 80 cm. To enhance the effective color resolution beyond the 8 bits per channel provided by the hardware, we used Floyd-Steinberg error diffusion dithering (Floyd and Steinberg, 1976): Deviations between the desired XYZ value from that attainable with the discrete 8 bit colour resolution at at a given screen position (x,y) were distributed channel-wise to neighbouring pixels using a fixed scheme. The advantage of this dithering method is that it does not produce visible patterns in the stimulus. The stimuli were pairs of centre-surround stimuli (Fig. 2) presented side by side on a black screen, with a centre-to-centre distance of 10.7°. The surrounds were square with a side length of 8.8°, and targets presented at their centres were circular with a diameter of 2°.

The colour of the uniform surround in which the fixed targets were presented was always gray with MacLeod-Boynton (r,b) coordinates (MacLeod and Boynton, 1979) of (0.69,1.16) and a CIE luminance of 9.2 cd/m^2. This chromaticity corresponds to CIE 1931 Illuminant C. The other surround, in which the adjustable surround was presented, was either variegated and had the same space average gray colour (**gamut expansion experiment**) or it was uniform and violet (**simultaneous contrast condition**). The violet surround differed from the gray one only with respect to the b coordinate, which was raised from 1.16 to 3.5. The variegated surround was a 'Seurat' (Andres, 1997; Mausfeld and Andres, 2002) consisting of overlapping disks. 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. The covariance matrix of the distribution of LMS

cone excitation values was

$$Cov = \begin{pmatrix} 1.3271 & 0.5839 & 0 \\ 0.5839 & 0.2787 & 0 \\ 0 & 0 & 2.6244 \end{pmatrix}. \qquad (1)$$

As can be seen in Fig. 3, the mean chromaticities of the two surrounds and the 14 different chromaticities used for the fixed target presented in the gray uniform surround were located on the same constant r axis in the MacLeod-Boynton chromaticity diagram. Both the fixed and the adjustable targets were equiluminant to the surrounds (in terms of $l+m$). The adjustable target presented in the 'violet' surround was restricted to the same constant r axis. The 14 target chromaticities and 2 surround conditions (simultaneous contrast and gamut expansion) resulted in 28 different stimuli. Each measurement was repeated four times. Thus, each subject made 128 settings. To balance any effects due to spatial inhomogenies of the monitor, the horizontal position of the two surrounds was swapped in half of the trials.

The subjects varied the chromaticity of the test target along the preset axis in chromaticity space by using the left/right keys of the keyboard. Each button press produced a minimal change in the RGB-values along the chosen direction at 8 bit per channel colour resolution. Using colour dithering, the top/down keys allowed additional adjustments on a scale approximately 10 times finer. The observers where instructed to make the central targets as similar in colour as possible. It has often been reported that making truly satisfactory asymmetric colour matches is sometimes difficult, if not even impossible (Gelb, 1929; Ekroll et al., 2004; Faul et al., 2008; Vladusich et al., 2007), and that observers may make their matches according to different criteria producing different results (Arend and Goldstein, 1987; Arend and Spehar, 1993a,b). In Ekroll et al. (2004)

we introduced the descriptive notion of 'saturation scale truncation and extension' to describe a seemingly important aspect of the matching problems occuring in this kind of experiment. In particular, it would seem that in a surround of a given hue, targets of the same hue cannot appear less saturated than the surround itself, no matter what chromaticity is chosen[1]. Thus, if the surround is violet, targets appearing in a less saturated violet cannot be produced. Since less saturated violets can be produced in the white surround, the subject may find it difficult to match these in the violet surround. Confronted with this problem, a subject may revert to two different strategies. Either, he may choose the correct hue (violet instead of chartreuse), in which case the targets cannot be equated for saturation, or he may equate them for saturation, in which case the hues will be opponent (violet vs. chartreuse). In an attempt to minimise interobserver differences due to different strategies, the subjects were instructed to avoid matches between opponent hues at all cost.

The stimuli were presented in random order. On average, the experiment lasted about 2 hours. The subjects were instructed to make their settings as accurately as possible and were free to use as much time for each setting as they found necessary. In addition to the first author 23 students served as observers. Some of them were participating in an advanced course on visual perception, and involved in the planning of the experiment and others were naive. All subjects were colour normal as tested with the Ishihara plates (Ishihara, 1967).

2.2. Results

The results are shown in Fig. 4, along with those previously reported in Ekroll and Faul (2009). In the left hand panels, each data curve shows the mean data of a single observer. The right hand panels show the corresponding means across observers. In all panels, the MacLeod-Boynton b-coordinate (MacLeod and Boynton, 1979) of the adjustable patch, which was presented either in the violet uniform surround (panels a, b, c and d) or in the gray variegated surround (panels e and f) is plotted against the MacLeod-Boynton b-coordinate of the fixed patch, which was presented in the gray uniform surround. The horizontal dashed lines show the b-coordinate of the surround in which the adjustable target was embedded, the vertical ones that of the other surround. The oblique dashed line shows where settings would fall in the absence of any effect at all. The present results on simultaneous contrast (panels c and d) are similar to those of Ekroll and Faul (2009). Considering that the scale of these plots corresponds to the entire range of colours along the b-axis that can be realised on our monitor, it can be seen that the individual variation is quite substantial. The variation even seems to be somewhat larger in the present study than in the previous one, but it should be kept in mind that more subjects participated in the present study (24 vs 12). There is also a substantial amount of inter-individual variation in the gamut expansion condition (panel e), although the individual data curves in this absolute plot differ less than in the simultaneous contrast

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condition. This may be related to the fact that the net effect is also smaller in this condition. The number of subjects for which the data deviated significantly from linearity at the 5% level was 23 out of 24 (i.e. 96%) in the simultaneous contrast condition and 17 out of 24 (i.e. 71 %) in the gamut expansion condition. This was tested by means of a one-way anova of the residuals of a linear fit. A somewhat larger percentage of significant deviations in the simultaneous contrast condition is to be expected considering that crispening is, in that case, present in both surrounds rather than just one, which will tend to produce a larger net nonlinearity.

2.2.1. Modelling the data

In order to see whether the simultaneous contrast effect correlates with the gamut expansion effect across observer, a parameter representing the size of the effect is needed. Here, we rely on a model we found to describe the data reported in Ekroll and Faul (2009) rather well. According to the model, the total effect is due to a combination of von Kries adaptation (von Kries, 1905) and crispening (Takasaki, 1966, 1967).

The von Kries-Takasaki model. In the model we let an expression C represent the colour appearance of a target with a nominal cone excitation value T embedded in a surround with a nominal cone excitation value S. For present purposes, T and S are S-cone excitation values, and therefore, C is a scalar value describing that aspect of colour appearance that depends on S-cone excitation only. Perceptually, this roughly corresponds to changes along the continuum from chartreuse over gray to its complementary colour violet (Valberg, 2001). According to the model, the colour appearance of the target is given by the expression

$$O_{S,\rho,\alpha,\sigma}(T) := C_{S,\alpha,\sigma}(K_\rho(T),(K_\rho(S)) \qquad (2)$$

where the function

$$K_\rho(T) := \rho T, \qquad (3)$$

represents the von Kries adaptation and the function

$$C_{S,\alpha,\sigma}(T,S) := T + (T-S)\alpha e^{-|T-S|/\sigma}, \qquad (4)$$

represents the crispening. It is assumed that $\alpha \geq 0$ and $\sigma > 0$. The scaling of the nominal cone excitation values with the gain factor ρ is intended to capture the effects of von Kries adaptation (von Kries, 1905), which we assume to affect target and surround equally. In accounts of colour induction effects based on the von Kries model, it is generally assumed that the gain factors are inversely related to the nominal cone excitation values of the surround. The crispening function in Eqn. 4 stems from the work of Takasaki (1966, 1967). Intuitively, it produces an amplification of the differences between target and surround, whereby the amount of amplification decreases swiftly towards zero as the absolute difference between target and surround increases. As illustrated in Fig. 5, mapping T onto $T + (T-S)\alpha$ represents a linear expansion around the surround colour S with a gain factor equal to $\alpha + 1$. Inclusion of the multiplication with the final term $e^{-|T-S|/\sigma}$ from Eqn. 4 lets the amount of expansion decrease rapidly towards zero as the absolute difference $|T-S|$ between target and surround increases.
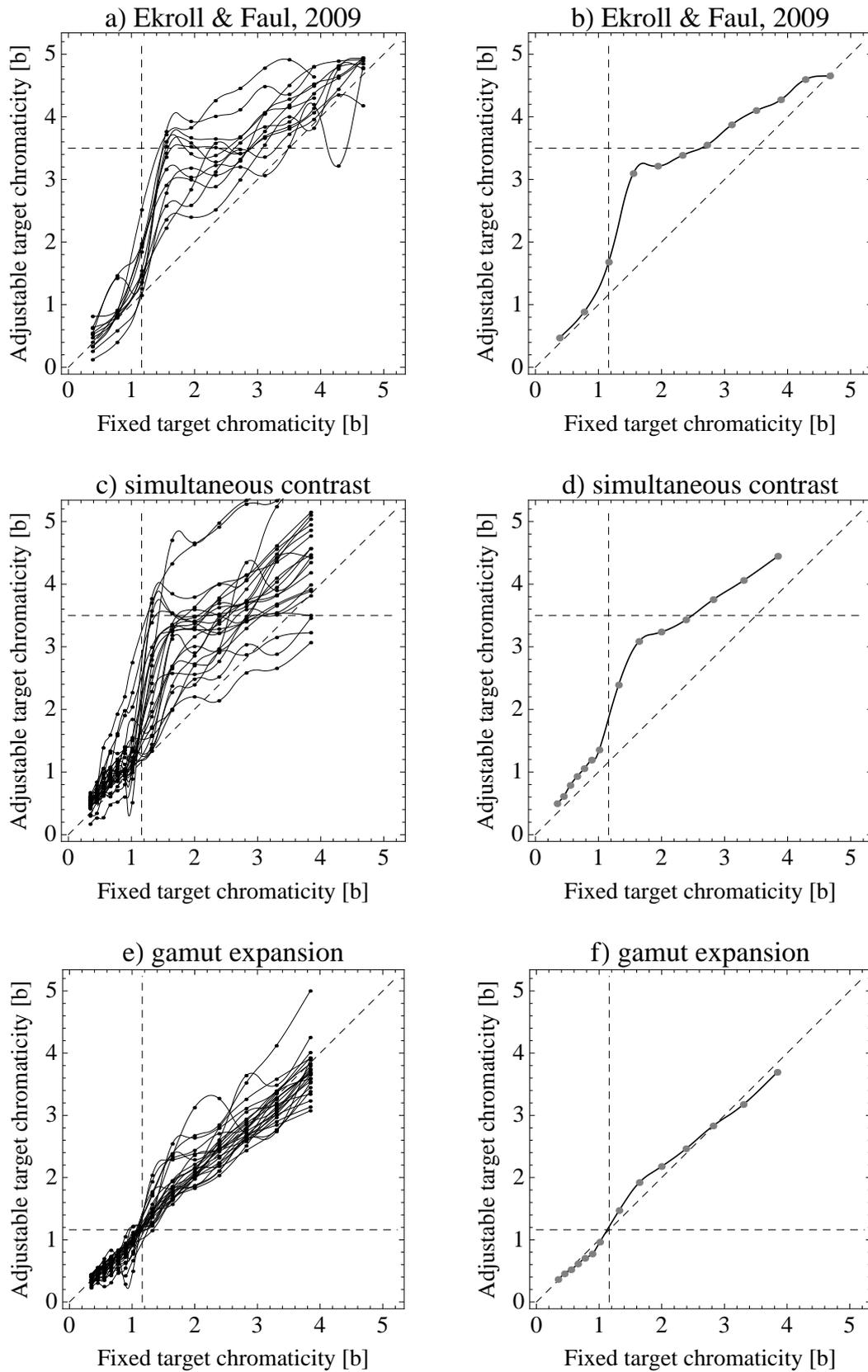
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Figure 4: Individual (left panels) and mean (right panels) results from the simultaneous contrast condition (middle panels) and the gamut expansion condition (bottom panels). The top panels show results from a previous experiment (Ekroll and Faul, 2009) similar to the simultaneous contrast condition. In all panels, the subjects' settings for the chromaticity of the adjustable target in the uniform violet (top four panels) or the variegated 'gray' (bottom panels) surround are plotted against the chromaticity of the fixed target in the uniform gray surround. The horizontal dashed line represents the chromaticity of the surround in which the adjustable target was presented, the vertical one that in which the fixed target was presented. The diagonal dashed line shows where settings would fall in the absence of any induction effect at all.
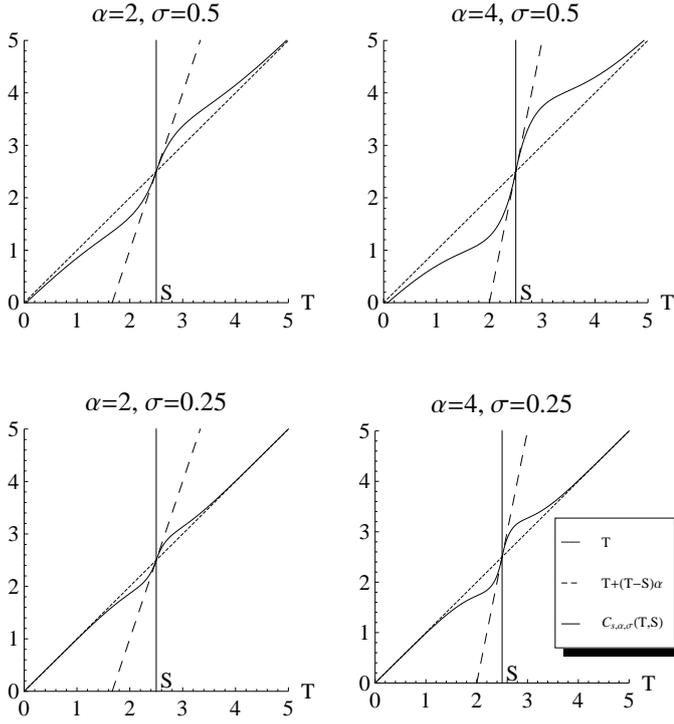
Figure 5: Illustration of the crispening function and how it depends on its two parameters α and σ.

A target T_1 embedded in a surround S_1 should match a target T_2 embedded in another surround S_2 whenever the corresponding expressions for O in Eqn. 2 have the same value. Thus, to model asymmetric matching data the equation

$$O_{S_1,\rho_1,\alpha_1,\sigma_1}(T_1) = O_{S_2,\rho_2,\alpha_2,\sigma_2}(T_2) \qquad (5)$$

has to be solved for T_2. In all of the following we use the convention that the von Kries adaptation parameter has unit value for the grey uniform surround, i.e. $\rho_1 = 1$. Accordingly, Eqn. 5 can be rewritten as

$$C_{S_1,\alpha_1,\sigma_1}(T_1) = O_{S_2,\rho_2,\alpha_2,\sigma_2}(T_2). \qquad (6)$$

General model assumptions. In Ekroll and Faul (2009) we used the above model to describe data from an asymmetric matching experiment similar to the present simultaneous contrast condition. There, we assumed that crispening occurred to the same extent in both surrounds, i.e. $\alpha_1 = \alpha_2$ and $\sigma_1 = \sigma_2$. The von Kries adaption parameters, on the other hand, was assumed to depend on the mean colour of the surround. Thus, in the simultaneous contrast condition, where the colours of the (uniform) surrounds differ, the adaptation parameters are expected to differ, i.e. $\rho_1 \neq \rho_2$. With these assumptions, the above matching equation (Eqn. 6) can be rewritten as

$$C_{S_1,\alpha,\sigma}(T_1) = O_{S_2,\rho_2,\alpha,\sigma}(T_2) \qquad (7)$$

for the **simultaneous contrast condition**.

A central motivation for the present study was to test the idea that the gamut expansion effect is identical to the crispening effect. As we pointed out in Ekroll and Faul (2009), this hypothesis seems fairly plausible in light of the available evidence, if one assumes that crispening does not occur in a surround with sufficiently high colour variation. If this hypothesis is indeed correct, data from the simultaneous contrast condition should be due to a combination of crispening and von Kries adapation. Data from the gamut expansion effect, on the other hand, should represent a much simpler case. Here, von Kries adaptation should not play any role, since the mean colours of the surrounds are equal and hence $\rho_1 = \rho_2$, and the sole determinant of the data should be the crispening that occurs in the uniform surround. This implies that the matching equation (Eqn. 6) reduces to

$$C_{S_1,\alpha,\sigma}(T_1) = T_2 \qquad (8)$$

for the **gamut expansion condition**.

Global nonlinearity. Results from a previous study (Faul et al., 2008) suggest that Eqn. 8 describes the main features of the gamut expansion effect rather well, but a systematic deviation is also evident. To appreciate the nature of this deviation, it is particularly convenient to represent the data in terms of Brown and MacLeod's (1997) relative richness measure $R := (T_2 - S_2)/(T_1 - S_1)$, i.e. the relative purity ('saturation') of the two targets at the setting where they appear equal. Eqn. 8 and the fact that the mean surround chromaticitites S_1, S_2 are equal in the gamut expansion condition together imply that $R = 1 + \alpha e^{-|T_1 - S|/\sigma}$, which is a symmetric function of $T_1 - S$ such as the solid curve in Fig. 6 a). The height of the curve is determined by the crispening parameter α, and the spread is determined by σ. As can be seen, the mean data are qualitatively similar to this prediction, but the expected symmetry is not quite borne out. To accomodate this asymmetry in the data, two simple alternative modifications of the model suggest themselves. The first would be to assume that the crispening parameter σ assumes different values for increments and decrements. Fig. 6b shows how this improves the fit to the data. The second possibility would be to assume that the cone excitation values of both target and surround are subjected to a compressive nonlinearity prior to application of our model. Fig. 6c shows the results obtained when T and S are transformed with the power function $f(x) := x^{0.5}$. Transformed in this way, the data are in better accord with the symmetry postulated by the model. We prefer the latter option because it has the additional advantage of accomodating results from scaling and discrimination studies which demonstrate a global non-linearity clearly distinct from the local non-linearity introduced by crispening. It should be noted, though, that the existence and strength of a global non-linarity is generally difficult to document based on the results of asymmetric matching experiments alone. Intuitively, this is because the effect of this global nonlinarity largely cancels out of the matching equation. This is illustrated in Fig. 7. Thus, it is not easy to deduce the exact nature of the global nonlinearity based on the present data. The scaling data of Ovenston (1998), however, suggest that for stimuli differing in S-cone excitation,

a power function with an exponent of about 0.5 is appropriate, and in the following, all of our modelling will be based on this assumption. That is, we always apply the model to the power transformed S-cone excitation values.

Individual estimates of the crispening parameters α and σ were obtained by fitting the function defined by Eqn. 7 – with the free parameters α, σ and ρ – to the transformed data from the simultaneous contrast condition and the function defined by Eqn. 8 – with the free parameters α and σ – to the transformed data from the gamut expansion condition. A closed-form solution to Eqn. 7 is not known to us, so in order to model the data we solved it numerically. The parameters were estimated by minimising the squared deviations from the prediction using Mathematica's FindMinimum function. To gain speed, the model predictions were computed with a C-routine using the GNU Scientific Library and the MathLink interface.

Constraints on the parameter values. We constrained the search to values of α less than $e^2 \approx 7.4$ and values of σ greater than 0.07. The former is motivated by the fact that when α is larger than that, the amount of crispening is so large that the function relating cone-excitation values to colour appearance becomes non-monotonic. On the theoretical level, we do not consider this impossible, but it introduces the practical problem that the matching equation then has multiple solutions. Violations of monotonicity were infrequent in the individual data sets, so the assumption that α is less than e^2 is presumably correct for most subjects.[2] The restriction on σ is motivated by the following reasoning: According to our model, the absolute effect of crispening on colour appearance is a function $g(\Delta) := \alpha \Delta e^{-\Delta/\sigma}$ of the absolute difference $\Delta := |f(T) - f(S)|$ between target and surround. Fig. 8 plots this function for different parameter values. The function has a unique maximum at $\Delta = \sigma$, where it assumes a value of $h := \alpha\sigma/e$, while the slope of the tangent of the function at $\Delta = 0$ correspondes to α. In Fig. 8, σ varies, and in each case α is chosen such that $h = 1$, i.e. $\alpha = e/\sigma$. With this constraint, variation of σ amounts to mere scaling along the horizontal axis. As can be seen in the figure, the function is essentially zero when Δ is large relative to σ. Thus, the function can be made arbitrarily close to zero for all values of Δ above any given critical value Δ_0 by letting σ decrease unconstrained towards zero. Thus, if we obtain measurements which are zero at all measured values of Δ, this need not imply that there is no crispening, i.e. that α is zero. Instead, it could in principle also mean that σ is so small that the crispening is limited to a range below the least value of Δ for which measurments were made (henceforth referred to as Δ_{min}). This raises two problems. The first one is that if the true value of σ is sufficiently small relative to Δ_{min}, the crispening cannot be measured at all. This is less troublesome, because Δ_{min} was only just above threshold in our experiments, such that any crispening occuring below that point is of merely academic value, as it falls in the threshold range anyway. The second, practically
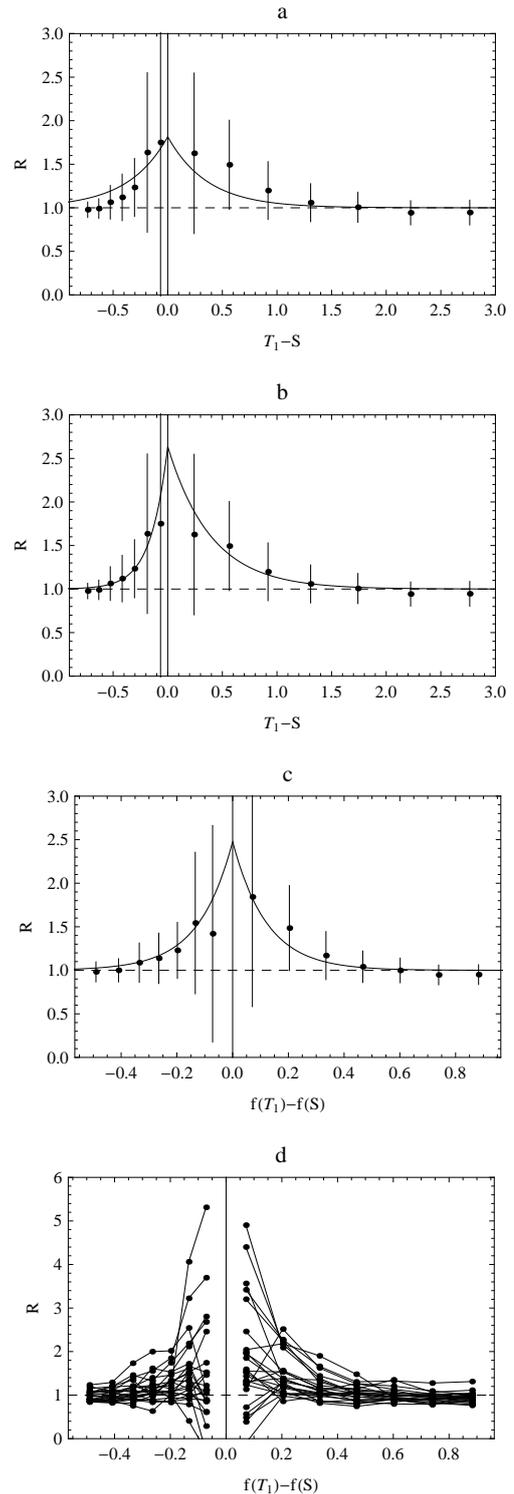
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[2]The data of one subject, though, shown in the bottom panel of Fig. 11, exhibits violations of monotonicity that may be taken to suggest that the true value of α was in fact greater than e^2.

Figure 6: a-c) Mean data from the gamut expansion condition. a) Relative richness R plotted against the difference between the chromaticity T_1 of the fixed target presented in the uniform surround and the chromaticity S of the surrounds. Error bars represent one standard deviation of the individual means in each direction. Note that the horizontal symmetry predicted by the model (solid line) is not quite borne out in the data. b) The asymmetry evident in the data can be modelled by allowing for different crispening parameters σ for increments ($T_1 > S$) and decrements ($T_1 < S$). c) Alternatively, the raw data can be transformed with the power function $f(x) := x^{0.5}$ to make them accord better with the symmetry predicted by the model.
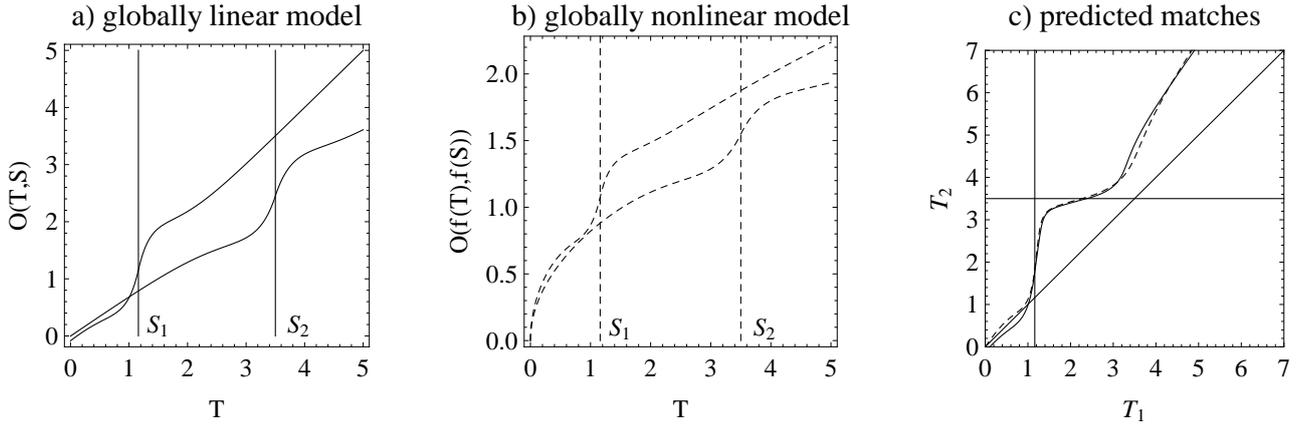
Figure 7: a) Predicted colour appearance as a function of target S-cone excitation T for two different surrounds S_1 and S_2 according to the original globally linear model (for a given set of parameter values α, σ, ρ_1 and ρ_2). The prediction for asymmetric colour matches corresponding to these two colour appearance functions is shown as a solid curve in panel c). b) A pair of globally nonlinear colour appearance functions that yield a very similar prediction (dashed curve in panel c).
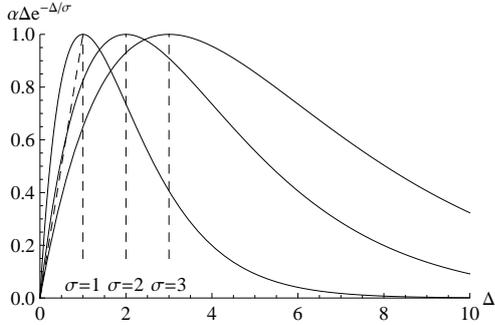

Figure 8: The predicted absolute effect of crispening should be given by the function $g(\Delta) := \alpha \Delta e^{-\Delta/\sigma}$, which is shown here for three values of σ. The maximum effect is predicted to occur at $\Delta = \sigma$, where it assumes the value $h := \alpha \sigma e^{-1}$. Here, the functions have been scaled vertically so that they all have a maximum of $h = 1.0$.

more relevant problem is that linear matching data actually indicating the absense of any crispening effect (i.e. $\alpha = 0$) can be well fitted by the model with any value of α provided that σ is sufficiently close to zero. In order to avoid artifacts related to this problem, we constrained the value of σ to 0.07, which corresponds to Δ_{min} in our experiment. This amounts to the assumption that the maximum of $g(\Delta)$ (Fig. 8) occurs at a value of Δ larger than Δ_{min} and thus falls within the range for which measurements are available. A simulation study indicated that this provision was effective in making it possible to recover the true value of $\alpha = 0$ reasonably well: Fitting the model to artificial data sets generated by adding Gaussian noise with a standard deviation corresponding to our empirical data to the model with $\alpha = 0$ we obtained estimates of α with a mean absolute deviation from the true value of 0.46 using the constraint on σ. Without this constraint, the mean absolute deviation was 5.7×10^9.

Boostrapping of the parameter estimates. In order to evalute the robustness of the parameter estimates obtained by fitting our model to the real data, we applied a bootstrap procedure. The original individual data sets for each condition consisted of four repeated measurements at 14 target chromaticity levels. For each target chromaticity level, a sample of four measurements was drawn with replacement among the original four. Proceeding in this manner we created 100 new samples from each original data set and estimated the model parameters based on each of these resamples. The relatively small number of bootstrap samples was necessary due to the fairly large amount of computer time needed.

Main results. In Fig. 9 a) the individual mean bootstap estimate of α from the gamut expansion condition is plotted against that from the simultaneous contrast condition. The correlation is positive with $R^2 = 0.57$ and a slope of 0.77. The correlation is highly significant (p=0.00002). Panel b) shows the same as panel a), but with the potential outlier in the upper right corner of panel a) removed. The correlation and the slope are reduced but still significant (p=0.00336). Panel c) is analogous to panel a), with the mean bootstrap estimates replaced by the estimates based on the original sample. Panel d) shows the same as panel c), but with the potential outlier removed, as in panel b). All of the alternative analyses in panels a,b,c and d indicate a significant positive correlation with a slope less than unity. Only the analysis in panel b) though, indicate that the slope is significantly different from unity at the 5% level.

Panel e) replots the data points from panel a) with error bars representing the standard deviation of the bootstrap estimates. Panel f) shows the individual mean bootstrap estimates of σ from the gamut expansion condition plotted against those from the simultaneous contrast condition. The large error bars indicate that the estimation of σ is sometimes far less robust than that of α. Furthermore, some of the estimates of σ were implausibly large. Conceptually, crispening is conceived of as an
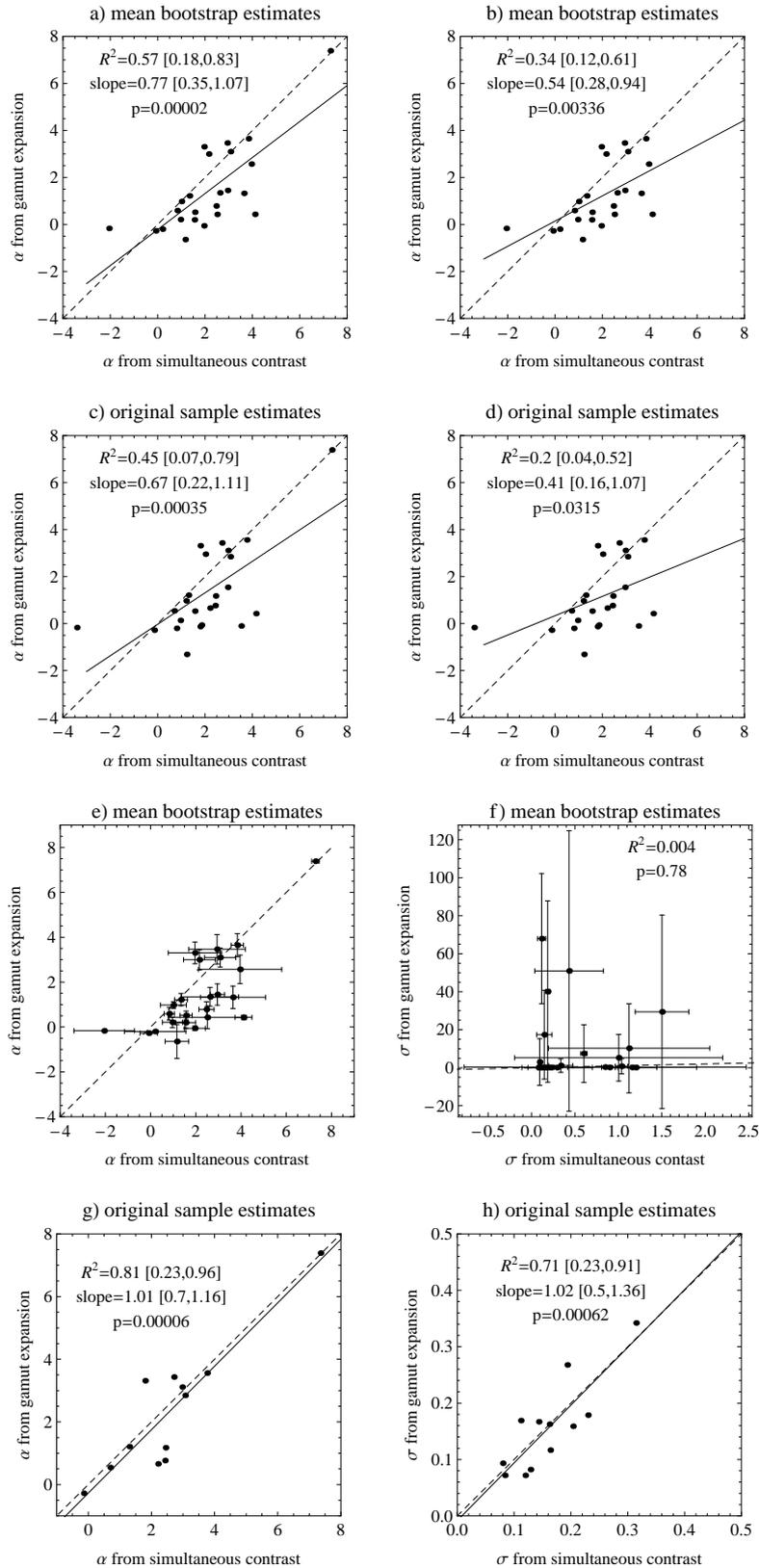
Figure 9: a) Scatterplot of the individual mean bootstrap estimates of α obtained in the two experimental conditions. The solid line shows the estimated regression line, the dashed line shows the predicted correspondence. Values in brackets represent confidence intervals. b) As in a), but with the potential outlier in the upper right corner removed. c) Correlation between the individual estimates of α based on the original samples in the two experimental conditions. d) As in c), but with the potential outlier removed. e) As in a), with error bars representing the standard deviations of the bootstrap estimates. f) Scatterplot of the individual mean bootstrap estimates of σ obtained in the two experimental conditions, with error bars representing the standard deviations of the bootstrap estimates. g) Scatterplot for α but without data points for which the corresponding estimates of σ were classified as unrealistic (> 0.5). h) Same as g), but for σ.
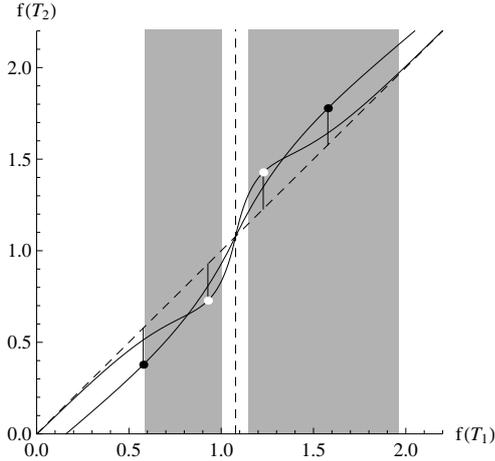
Figure 10: Predictions for the gamut expansion condition for two values of σ. The vertical dashed line represents the chromaticity $f(S)$ of the surround, and the grey regions indicate the range of target chromaticities for which data were collected. The curve passing through the white dots represent a small value of σ (0.15). In this case the maximum effect (deviation from the diagonal) falls within the range of target chromaticities for which measurements are available (grey regions), both for increments (right of the vertical line) and decrements (left of the vertical line). The curve passing through the black dots represents a larger value of σ (0.5). In this case, the maximum effect for decrements occur just outside the range of decrements for which measurements are available. For larger values of σ the maximum would occur even further outside the measurement range.

effect which occurs predominantly for targets which are similar to the surround. Therefore, to the extent that the points at which the maximal amount of crispening occurs — namely at $f(T_1) = f(S) \pm \sigma$ – correspond to a large absolute difference $|f(T_1) - f(S)|$ between target and surround, the model does not represent an effect appropriately conceived of as crispening. Therefore, if the estimated value of σ is large, this must either be an artifact of the fitting proceedure, or due to effects in the data other than crispening. Based on this reasoning, it seems reasonable to ask whether the observed correlation of α is preserved when these potentially misleading parameter estimates are excluded. To test this, we discarded cases involving estimates of σ larger than a value 0.5 and analysed the remaining, presumably more realistic, sets of parameter estimates. As illustrated in Fig. 10, values of σ larger than this value would mean that the maximal effect of crispening occurs outside the measurement range for decrements. Out of the 24 individual data sets, 16 fulfilled this criterion when applied to the simultaneous contrast condition and 17 when applied to the gamut expansion data. Requiring the criterion to be met in both conditions left us with 12 sets of presumably unproblematic parameter estimates.

As can be seen in panel g) of Fig 9 the correlation between the estimates of α resulting from the two conditions is now even better than that observed with the full data set. The estimated slope is also very close to the predicted value of unity. Panel h) shows that the correlation between the estimates of σ resulting from the two conditions is also very satisfactory, again with an estimated slope very close to unity.

In order to illustrate what the covariation of α across the two experimental conditions might look like in terms of the raw data, Fig. 11 shows a selected sample of three individual data sets with corresponding fits. As can be seen in the top row, the data of one subject are almost linear, both in the simultaneous contrast condition (left panel) and in the gamut expansion condition (right panel). The data of another subject are slightly nonlinear and those of Subj. 22 (bottom row) are even more nonlinear. The individual data shown were selected from the full data set by identifying the subjects for which the parameter pair $(\alpha_{sim}, \alpha_{gam})$ was closest to $(0, 0)$, $(3.5, 3.5)$ and $(7, 7)$, respectively.

The estimates of ρ_2 from the simultaneous contrast conditions are of limited interest here, but it may be of passing interest to note that the mean estimate was 0.96 with an SEM of 0.03. In a comparable condition in a previous study (Ekroll and Faul, 2009), we obtained a mean estimate of 0.85. Since the modelling in the previous study did not include the power transform $f(x) := x^{0.5}$ of the raw chromaticities, one would expect the estimate of ρ in the present study to equal the square root of the estimate from the previous study. This is approximately the case ($0.85^2 = 0.92 \approx 0.96$).

3. Discussion

The major findings of the present experiment are as follows:

- The strength of simultaneous colour contrast varies considerably across observers, as was also found in a previous study (Ekroll and Faul, 2009).

- The strength of the gamut expansion effect also varies across observers.

- Our data could be rather well described by a model based on von Kries adaptation and crispening (Ekroll and Faul, 2009).

- The amount of crispening estimated for simultaneous contrast correlated with that estimated for gamut expansion across observers.

3.1. Possible explanations for the individual differences and the correlation

Several investigators have noted that making truly satisfactory asymmetric colour matches is sometimes difficult, if not even impossible (Gelb, 1929; Ekroll et al., 2004; Faul et al., 2008; Vladusich et al., 2007). One may therefore surmise that different observers adopt different strategies and criteria when confronted with such problems. It is also well known that brightness matches depend critically on instructions (Arend and Goldstein, 1987; Arend and Spehar, 1993a,b). Thus, the observed individual differences may reflect criterion or instruction problems rather than natural variation in the strength of the underlying visual mechanisms. Such an explanation is difficult to rule out, but it should be noted that we informed the subjects
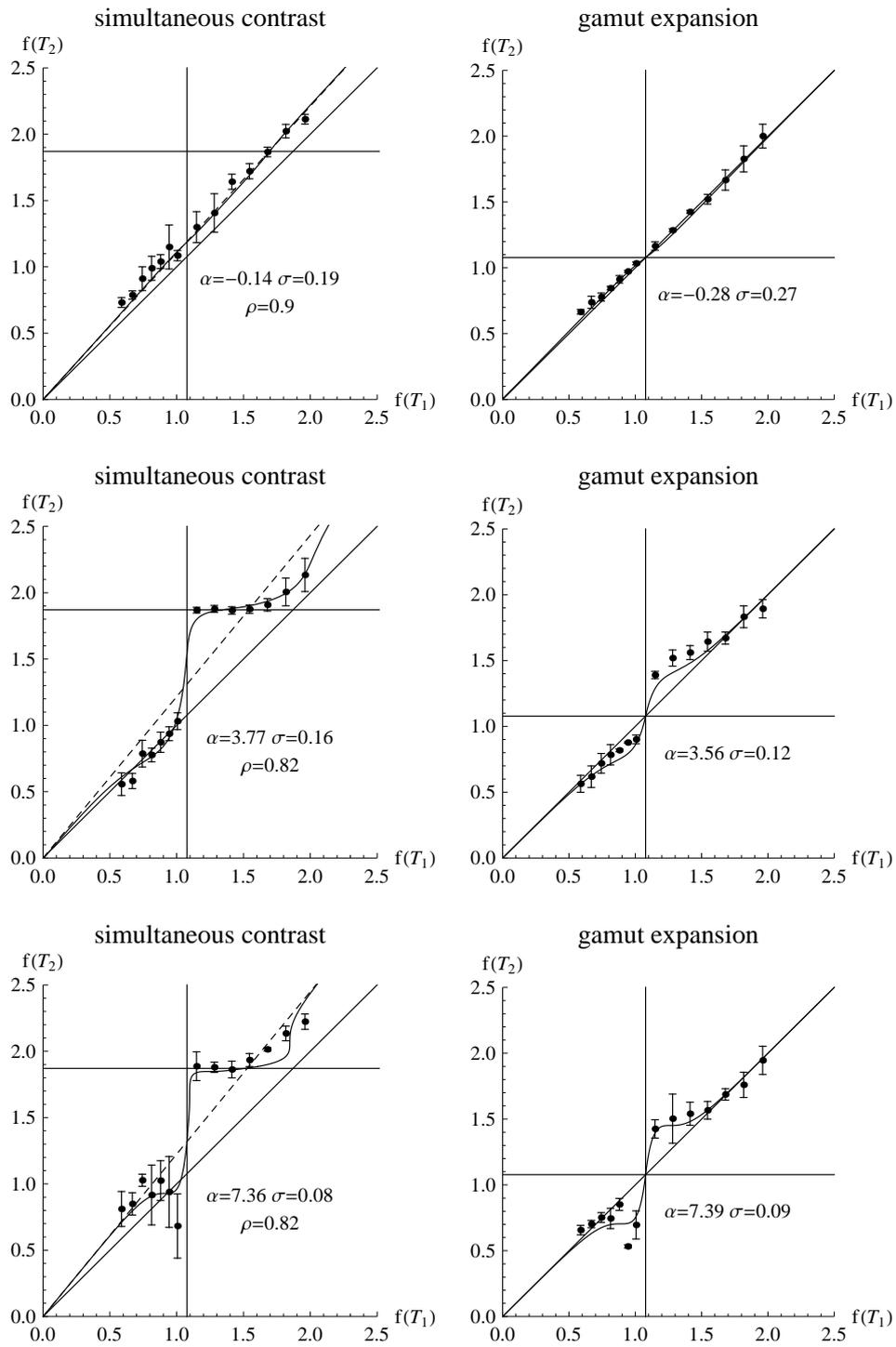
Figure 11: Three selected individual data sets. The left panel in each row shows the data from the simultaneous contrast condition for a single subject, the right panel shows the corresponding data from the gamut expansion condition. The power transformed ($f(x) = x^2$) chromaticity chosen for the adjustable target is plotted against that of the fixed target, and the horizontal and vertical lines indicate the power transformed chromaticities of the surrounds.

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that matching problems may occur and gave them specific instructions regarding what criterion they should rely on (see Section 2.1). To the extent that these instructions were suitable for disambiguating the observers' task, the individual differences would have to be attributed to natural variation in the strength of the underlying visual mechanisms.

While our hypothesis of a common mechanism implies that there should be a correlation between the estimates of the crispening parameters stemming from the two experimental conditions, the converse is not true. In principle, the observed correlation could be due to any other observer-specific factor influencing the results in both conditions. Obvious candidates would be sensory factors other than the postulated crispening mechanism or effects of instruction and criterion problems. This possibilities will have to be more thoroughly considered in future research.

3.2. Evidence for two distinct mechanisms

According to our hypothesis, two distinct mechanisms contribute to classical simultaneous contrast, namely von Kries adaptation and crispening, while the gamut expansion effect is due to crispening only. The idea that the crispening and adaptation components in our model indeed correspond to two functionally different mechanisms would be strengthend if it can be established that they depend on different stimulus properties. A central tenet of our analysis is that the crispening mechanism depends on the colour variance of the surround, while the von Kries adaptation mechanism depends only on its mean colour. A prediction of the former assumption is that manipulation of the surround variance should lead to changes in the results which mimick those brought about by the individual differences in the strength of the crispening mechanism. This seems indeed to be the case: The rather pronounced nonlinearity in the data curves which tends to occur in side-by-side asymmetric matching experiments such as the present simultaneous contrast experiments and those reported in Ekroll et al. (2004) and Ekroll and Faul (2009) seems to be almost completely absent in some few subjects whose crispening mechanism is presumably less pronounced, but can also be reduced or entirely abolished by replacing the uniform surrounds with strongly variegated ones (Ekroll and Faul, 2009; Ekroll et al., 2004). That the von Kries adaptation mechanism is not influenced by the colour variation in the surround is suggested by the results reported in Ekroll and Faul (2009). There, we found that the estimated von Kries adaptation parameters remained essentially constant when the surround variance was varied.

A thin black outline between the target and its surround is a further stimulus feature which may prove useful for distinguishing between the two putative mechanisms. In a study of the crispening effect in the luminance domain, Whittle (1992) reported that the crispening effect was abolished by adding a black outline as thin as 2' visual angle. Brown and MacLeod (1997) and Faul et al. (2008) found that also the gamut expansion effect is strongly reduced by adding a thin gray or black outline to the target embedded in the uniform surround, suggesting that crispening and the gamut expansion effect are indeed due to the same mechanism. Consistent with the idea that the crispening mechanism contributes both to simultaneous contrast and the gamut expansion effect, and that the crispening mechanism is highly sensitive to thin outlines around the target, it has also been found that simultaneous contrast is strongly reduced by adding thin black borders between target and surround (Brenner and Cornelissen, 1991; Walraven, 1973). This was also pointed out by William James (1890/2007, p.16). An interesting question for future research would be whether the von Kries mechanism is insensitive to this manipulation. This could be tested by checking whether the thin border makes a difference under conditions when no effect of crispening is to be expected, for instance when the surround is variegated or when the contrast between target patch and surround is large. The results of some experiments (Kuriki and Uchikawa, 1998; Brainard, 1998) seem to confirm this prediction.

3.3. Gamut expansion or gamut compression?

The gamut expansion effect was first reported by Brown and MacLeod (1997), who found that coloured patches look more saturated when they are embedded in a uniform surround than when they are embedded in a variegated one. In principle, this may just as well be due to gamut compression in the variegated surround as gamut expansion in the uniform one. The present findings add to previous evidence making the latter interpretation plausible (Faul et al., 2008; Ekroll and Faul, 2009). If the effect were due to compression in the variegated surround, then, contrary to the present results, it should be unrelated to the simultaneous contrast effect occurring when both surrounds are uniform.

3.4. Relation to perceptual transparency

The results of the present study suggest that a mechanism of 'crispening' that is more strongly activated by uniform surrounds than variegated ones is responsible for the gamut expansion effect and also contributes significantly to classical simultaneous contrast in uniform surrounds. The conditions under which crispening seems to produce a large effect seem to be rather similar to those under which impressions reminiscent of perceptual transparency (Metelli, 1970; D'Zmura et al., 1997, 2000; Faul and Ekroll, 2002; Singh and Anderson, 2002) have been reported, namely when the target is similar to the surround (Masin and Idone, 1981; Brenner and Cornelissen, 1991; Mausfeld, 1998; Mausfeld and Niederée, 1993; Ekroll et al., 2002, 2004) and the surround is uniform (Faul et al., 2008). Thus, one may speculate that the crispening mechanism is involved in the perceptual machinery responsible for colour scission (Anderson, 1997; Anderson and Winawer, 2005, 2008; Wollschläger and Anderson, 2009). Pursuing this hypothesis further, it would be interesting to see whether the individual differences in the strength of crispening observed here correlate with individual differences in transparency perception.

3.5. Generality of the present results

In the present study, we observed a link between simultaneous contrast and gamut expansion using stimuli differing in S-cone excitation. Future studies should address the question

whether this finding generalises to other directions in colour space. Considering that the general quantitative relationships indicative of crispening have been observed along other chromatic axes as well, both in studies of simultaneous contrast (Ekroll et al., 2004; Takasaki, 1967) and in studies of the gamut expansion effect (Faul et al., 2008), though, it would be surprising if the relation were restricted to a single direction in colour space.

3.6. The use of individual differences in the study of colour perception

As is well known, the analysis of individual differences played a pivotal role in the development of trichromatic theory. In the further study of colour perception, though, individual differences seem to have been regarded more as minor uninformative noise than as a useful source of insight. Recent work on opponent colour theory, though, shows that the loci of unique hues vary considerably across observers (Kuehni, 2004) and that this variability can be very useful for testing hypotheses about the underlying mechanisms (Webster et al., 2000). The results of the present study suggest that individual differences in the susceptibility to context effects in colour vision are also rather substantial and constitute a valuable source of information.

4. Conclusions

The present experiments show that individual differences in classical simultaneous contrast and the gamut expansion effect are quite substantial. The correlation of the effects across observers suggests that they share a common underlying mechanism. This mechanism seems to be identical with the one responsible for the crispening effect.

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