

# A simple model describes large individual differences in simultaneous colour contrast

Vebjørn Ekroll, Franz Faul

*Institut für Psychologie, Christian-Albrechts-Universität zu Kiel, Olshausenstr. 62, 24098 Kiel, Germany*

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## Abstract

We report experimental evidence for substantial individual differences in the susceptibility to simultaneous colour contrast. Interestingly, we found that not only the general amount of colour induction varies across observers, but also the general shape of the curves describing asymmetric matching data. A simple model based on von Kries adaptation and crispening describes the data rather well when we regard its free parameters as observer specific. We argue that the von Kries component reflects the action of a temporal adaptation mechanism, while the crispening component describes the action of the instantaneous, purely spatial mechanism most appropriately labeled *simultaneous* colour contrast. An interesting consequence of this view is that traditional ideas about the general characteristics of simultaneous contrast must be considered as misleading. According to Kirschmann's 4th law, for instance, the simultaneous contrast effect should increase with increasing saturation of the surround, but crispening predicts the converse. Based on this reasoning, we offer a plausible explanation for the mixed evidence on the validity of Kirschmann's 4th law. We also argue that simultaneous contrast, the crispening effect, Meyer's effect and the gamut expansion effect are just different names for the same basic phenomenon.

**Key words:** Simultaneous colour contrast, colour induction, crispening, gamut expansion effect, Meyer's effect, Kirschmann's 4th law, von Kries gain control, individual differences, perceptual transparency

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## 1. Introduction

Despite more than a century of intense and ingenious research efforts, simultaneous colour contrast is still – textbook lore to the contrary – a confusing and ill-understood phenomenon (Valberg, 1975; Shevell, 1978; Kingdom, 2003; Whittle, 2002, 2003). One unresolved question, for instance, is whether simultaneous contrast is to be regarded as a mere perturbation of absolute local colour signals or as a straightforward consequence of fundamental difference-coding principles operating at an early level of the visual system (Whittle, 2003; Arend, 1973). Though lip service is routinely paid to the latter notion, it is often neglected in actual practice.

Over the years, we have also seen an accumulation of novel 'effects', which do not accord with traditional notions about the basic characteristics of simultaneous contrast, such as 'Meyer's effect' (Meyer, 1855), the 'crispening effect' (Takasaki, 1966, 1967; Whittle, 1992) and the 'the gamut expansion effect' (Brown and MacLeod, 1997).

One reason why it has proved difficult to relate the findings from different studies to each other and develop a quantitative model of sufficient general validity is that simultaneous contrast depends on a plethora of different variables (Kingdom,

2008; Shevell and Kingdom, 2008). The effect depends, for instance, on the spatial parameters of the stimulus (Brenner and Cornelissen, 1991), the current state of adaptation (Rinner and Gegenfurtner, 2000), perceptual organisation (Benary, 1924; Gilchrist, 1977; Adelson, 1993, 2000; Anderson, 1997) and observer instructions (Arend and Goldstein, 1987). Even the dependence on purely colourimetric and photometric variables is fairly complex.

In the face of all this complexity, it is quite understandable that most studies have concentrated on studying the dependence on stimulus variables and largely neglected the intimidating possibility of substantial differences across observers. Most studies have been performed with just a couple of observers, mostly the author(s) and perhaps a couple of naive observers. An observation that seems to justify this is that the results from the two or three observers participating in each study tend to agree fairly well.

There is some indication, though, that individual differences can be quite substantial (Takasaki, 1966, 1967; Fairchild, 1999; Cataliotti and Becklen, 2007; Bosten and Mollon, 2007, 2008). Many vision scientists will also probably have had the experience that some members of an audience fail to appreciate a demonstration of simultaneous contrast which the majority experience as striking.

In the present paper, we present the results of an asymmetric matching experiment which yielded substantial individual differences. A particularly interesting aspect of the results is that not only the general amount of colour induction varied across observers, but also the general shape of the individual match-

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*Email address:* vekroll@psychologie.uni-kiel.de (Vebjørn Ekroll)  
*URL:* <http://www.psychologie.uni-kiel.de/psychophysik>  
(Vebjørn Ekroll)

ing curves. Although the data may seem rather complex at first sight, we were fairly successful in modelling the data with a simple model with just three free parameters combining von Kries adaptation (von Kries, 1905) and crispening (Takasaki, 1966, 1967).

In the discussion, we shall argue that the crispening component is likely to describe the general characteristics of *simultaneous* contrast as opposed to temporal adaptation mechanisms. This is interesting because the general characteristics of crispening are in many ways opposite to those traditionally ascribed to simultaneous colour contrast. We will also show that the model can predict the mixed evidence on Kirschmann’s 4th law given the individual differences documented in the present experiment.

## 2. Experiment

### 2.1. Stimuli and methods

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 colour depth of 8 bits. We used a colourimeter (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 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 colour resolution beyond the 8 bits per channel provided by the hardware, we used Floyd-Steinberg error diffusion dithering (Floyd and Steinberg, 1976). The stimuli were pairs of centre-surround stimuli presented side by side on a black screen, with a centre-to-centre distance of 10.7° (see Fig. 1). 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 mean colour of the surround in which the fixed targets were presented was always grey 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 ( $x = 0.3101, y = 0.3162$ ). The mean colour of the surround in which the adjustable target was presented was always violet. It differed from the grey surround only with respect to the  $b$  coordinate, which was raised from 1.16 to 3.5. At surround variance level 0, both surrounds were uniform. In surround variance levels 1-4, both surrounds were variegated ‘Seurats’ (Andres, 1997; Mausfeld and Andres, 2002). As illustrated in Fig. 1, these surrounds consisted 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 at surround variance level  $i$  was

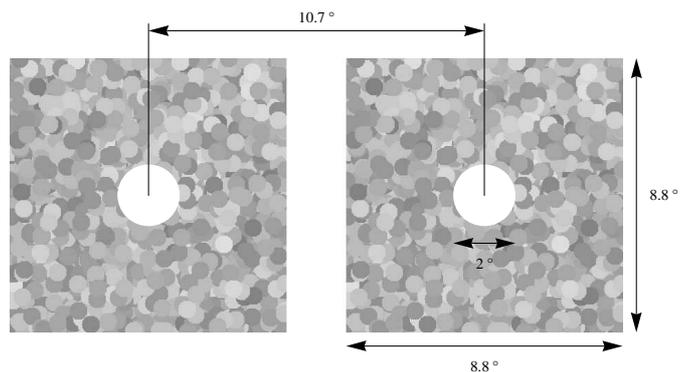


Figure 1: Grayscale version of the stimulus display used in the experiment, here with variegated surrounds. The spatial layout is correctly reproduced except for the absolute size. Note that the actual surrounds used in the experiment were coloured, and that the luminance distribution in this depiction has been manipulated to enhance the visibility of the spatial structure. For the same reasons, the central targets are rendered in white here.

$(i/4) \cdot Cov$ , where

$$Cov = \begin{pmatrix} 0.2621 & 0.1153 & 0 \\ 0.1153 & 0.0551 & 0 \\ 0 & 0 & 0.5184 \end{pmatrix} \quad (1)$$

for both surrounds. As can be seen in Fig. 2, the mean chromaticities of the two surrounds and the 12 different chromaticities used for the fixed target presented in the ‘grey’ 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 12 target chromaticities and the five surround variance levels resulted in 60 different stimuli. Each measurement was repeated four times for some of the observers and two times for the remaining ones. Thus, each subject made either 120 or 240 settings. To balance any effects due to spatial inhomogeneities of the monitor, the horizontal position of the two surrounds were 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. The top/down keys allowed additional adjustments on a very fine scale. The observers were 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 occurring 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

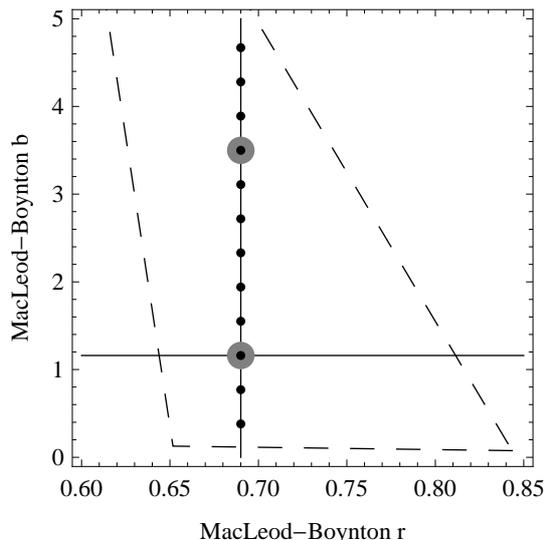


Figure 2: Chromaticities of the stimuli used in the experiments plotted in the MacLeod-Boynton chromaticity diagram (MacLeod and Boynton, 1979). Large grey disks: Surround chromaticities. Black dots: Target chromaticities. The dashed lines show the border of the gamut of our monitor.

than the surround itself, no matter what chromaticity is chosen<sup>1</sup>. Thus, if the surround is violet, targets appearing 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 and 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 subjects were told to view the stimuli in any way they felt natural, but to avoid strict and prolonged fixation. Thus the state of adaptation is likely to depend also on the subject's viewing behaviour and the time taken to establish a match.

The stimuli were presented in random order, and a session with 120 stimuli typically lasted about 2 h. 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 ('Subj. 7') 11 students participating in an advanced course on visual perception served as observers. All were familiar with related subjects in colour perception and informed about the original purpose of the experiment (which was to investigate how the colour induction effect depends on surround variance, not to study individual differences). All subjects were colour normal as tested with the Ishihara plates (Ishihara, 1967).

<sup>1</sup>This effect appears to be most pronounced at equiluminance.

## 2.2. Results

Before analysing the data, we discarded datapoints that may have been influenced by problems due to the restricted gamut of our computer monitor. Specifically, we removed all settings with  $b$ -coordinates above 95% of the highest possible setting ( $b=5.23$ ).

Panel (a) in Fig. 3 shows the individual matching data for the pair of uniform surrounds ('surround variance level 0'). For each subject, the mean chromaticity chosen for the target in the violet surround is plotted against the chromaticity of the target in the grey surround. The data for each subject are connected by a smoothed curve. The dashed diagonal line shows where settings would be located if there were no induction effect at all. The dashed horizontal line marks the chromaticity of the violet surround, the vertical one that of the grey surround. Panels (b)-(e) show the same for surround variance levels 1-4. Considering that the range of these plots corresponds to the whole range of settings possible with our standard computer monitor, it is clear that the individual differences are quite substantial at all variance levels. In panel f), the mean data across observers are shown. Each of the data curves show the mean for one surround variance level. The averaged data are rather similar across variance levels, but the central 'bump' in the data curves is more pronounced at the lower ones.

In Fig. 4 the individual data for surround variance level zero are shown in separate plots. Comparing the individual plots, it can be seen that not only the general amount of induction varies, but also the general shape of the data curves. In order to describe this variation quantitatively we fitted a model based on the notions of von Kries adaptation (von Kries, 1905) and crispening (Takasaki, 1966, 1967) to the data. Fig. 5 replots the data in Fig. 4 with the net inducing effect  $t_2 - t_1$  instead of  $t_2$  on the ordinate.

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 grey to its complementary colour violet (Valberg, 2001). According to the model, the colour appearance of the target is given by the expression

$$C(t) = t + \Delta \cdot \gamma(\Delta) \quad (2)$$

with

$$\gamma(\Delta) := \alpha \cdot e^{-|\Delta|/\sigma}, \quad (3)$$

$t := \rho \cdot T$ ,  $s := \rho \cdot S$ ,  $\Delta := t - s$ ,  $\alpha \geq 0$ ,  $\sigma > 0$ . The scaling of the nominal cone-excitation values with the gain factor  $\rho$  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 term'  $\Delta \cdot \gamma(\Delta)$  in Eqn. 2 stems from the work

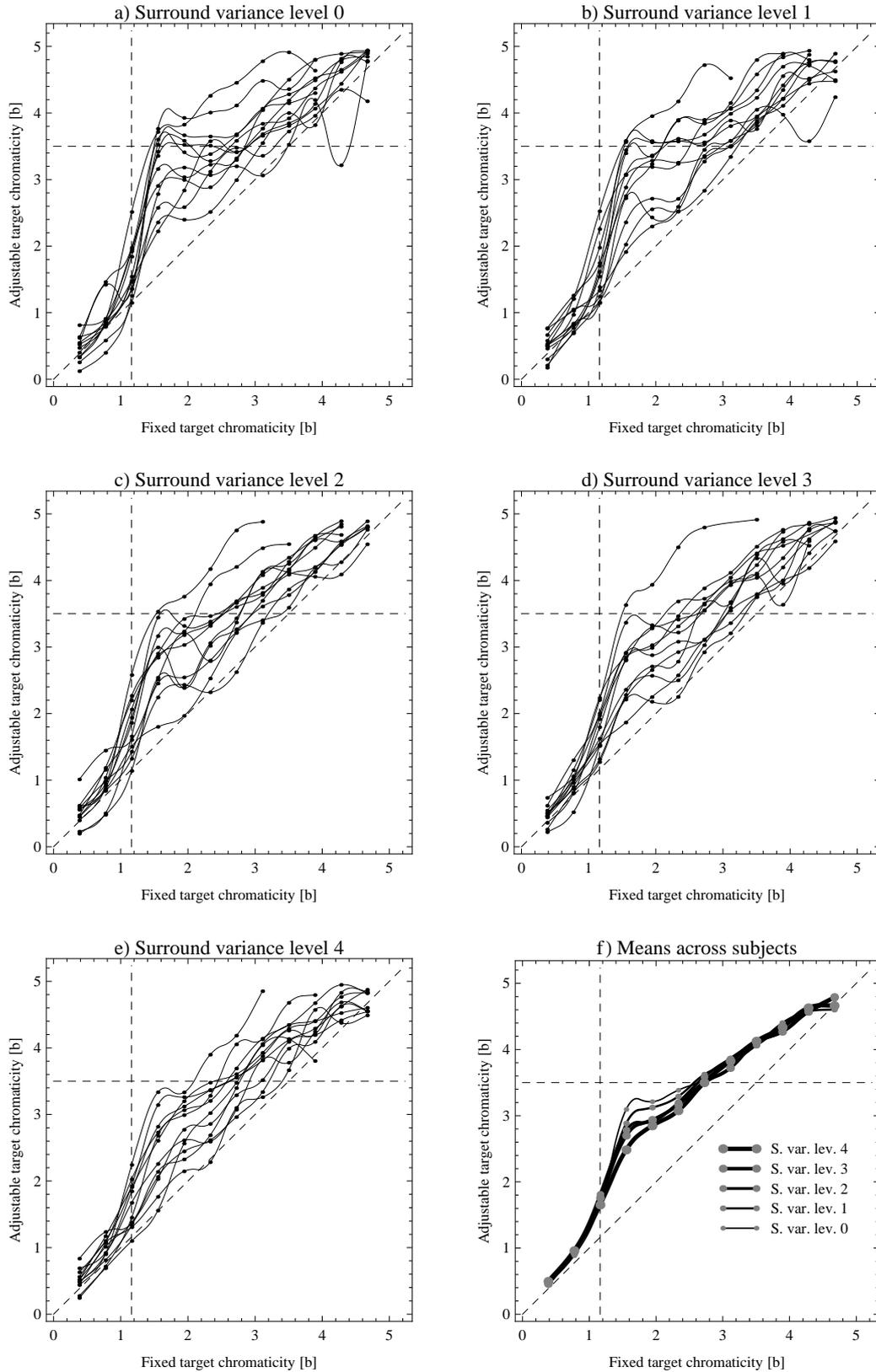


Figure 3: a)-e): Each plot shows the individual matching data for all subjects and one surround variance level. Each data curve represents the mean data of one subject. The mean setting for the target in the violet surround is plotted against the chromaticity of the target presented in the grey surround. The vertical dashed line marks the chromaticity of the grey surround, the horizontal one that of the violet surround. The dashed diagonal line shows where settings would be located in the absence of any induction effect. f): Means of the data pooled across subjects. Each data curve corresponds to one surround variance level.

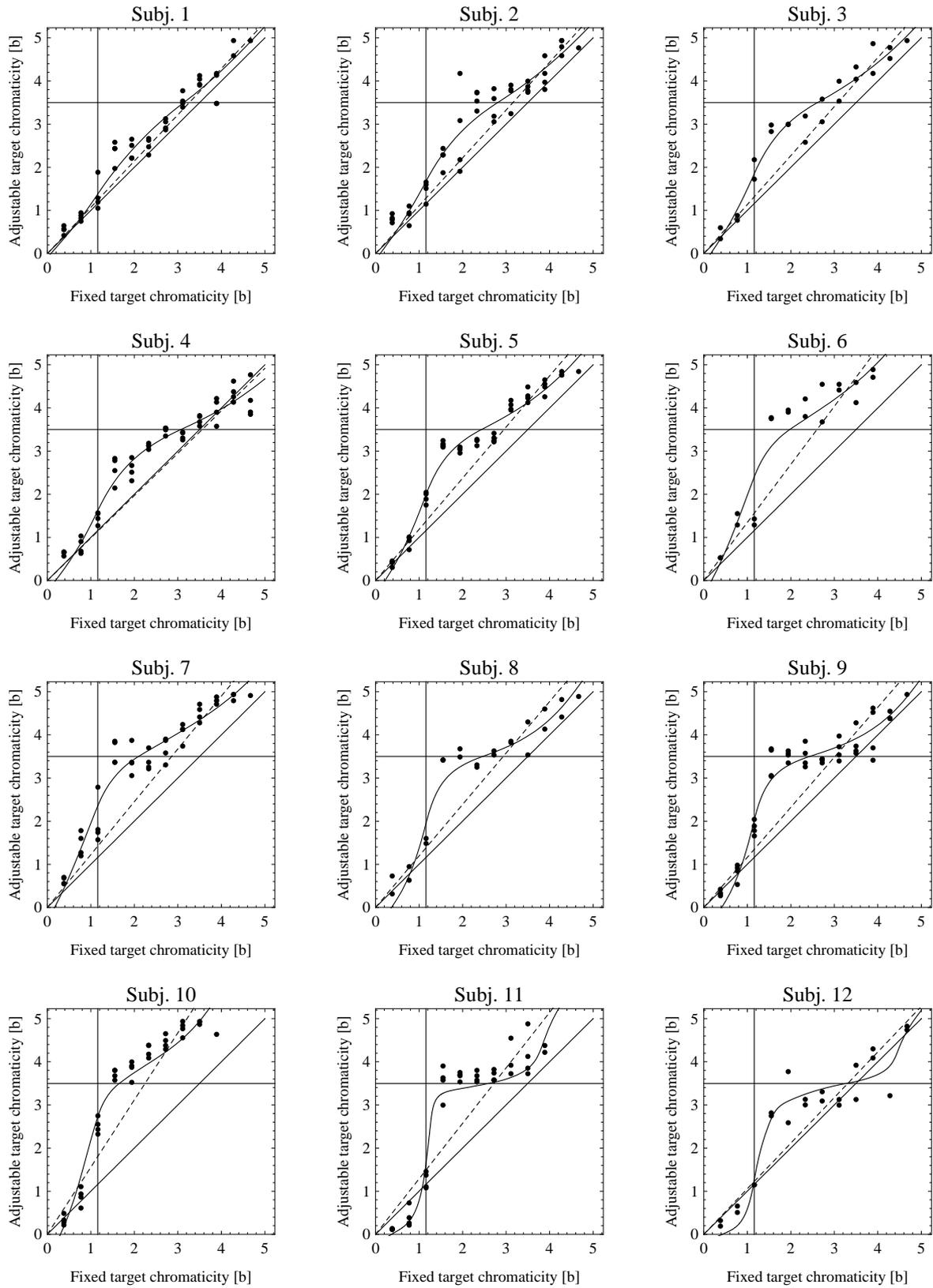


Figure 4: Individual raw data for surround variance level 0. The format of the plots is the same as in Fig. 3. The solid diagonal shows the identity line. The curve fitted to the data is based on the model in Eqn. 2. The dashed line shows the component of the fit attributable to mere von Kries adaptation (see text). The subjects are numbered such that the estimated value of  $\alpha$  increases with subject number.

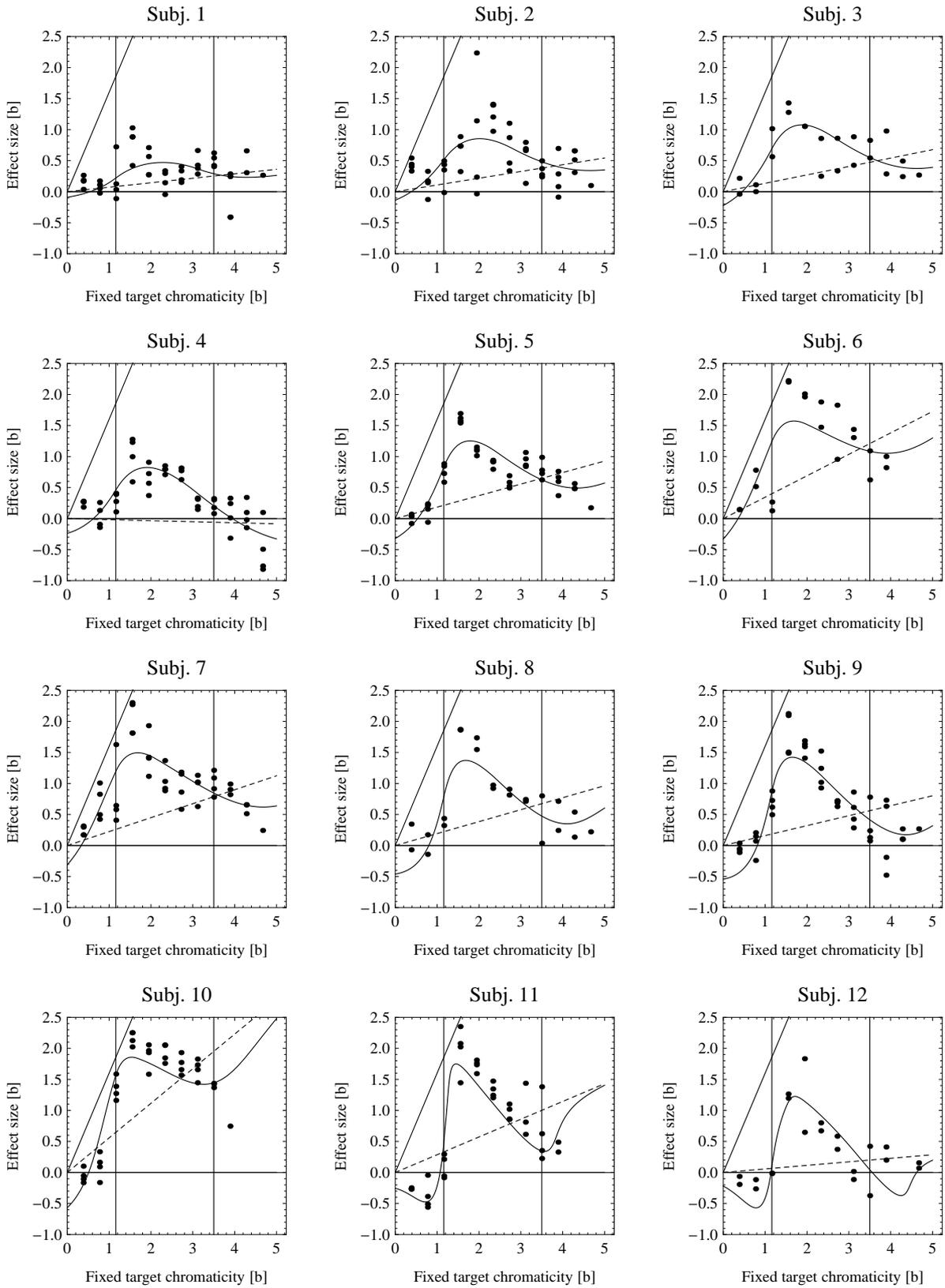


Figure 5: Replot of the individual raw data for surround variance level 0 from Fig. 4. Here, the size of the effect  $t_2 - t_1$  is plotted on the ordinate. The two vertical lines represent the chromaticities of the surrounds. The curve fitted to the data and the dashed line correspond to fits and the von Kries component in Fig. 4. The solid oblique line shows the prediction for complete von Kries adaptation (i.e.  $t_2 = (s_1/s_2)t_1$ ).

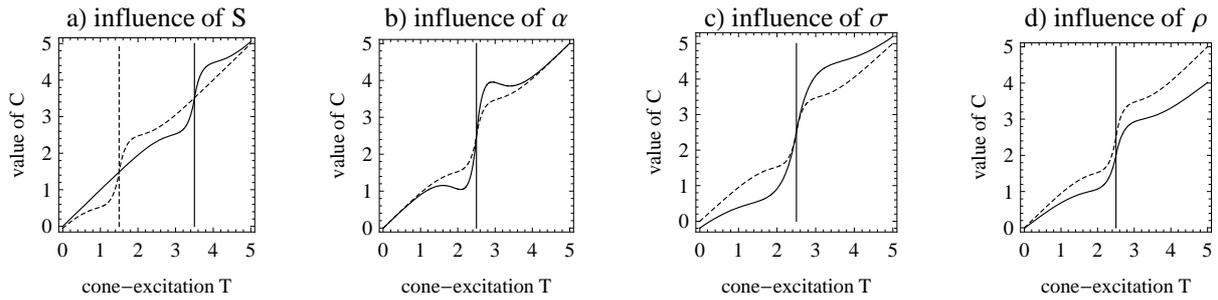


Figure 6: Illustrations of how the relationship between the cone excitation value  $T$  of the target and the expression  $C$  changes with changes in the model parameters (Eqn. 2). a) Different values of the surround cone excitation value  $S$ , given by the vertical lines. b) Large value of  $\alpha$  (solid curve) and smaller value (dashed curve). c) Large value of  $\sigma$  (solid) and small value (dashed). d)  $\rho = 1$  (dashed line) and  $\rho < 1$  (solid line).

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. Note that since  $\Delta$  changes its sign at  $s$  and  $\gamma(\Delta)$  is a non-negative function, adding  $\Delta \cdot \gamma(\Delta)$  as in Eqn. 2 leads to an expansion around the surround colour  $s$ . Fig. 6 illustrates how  $C$  plotted against the target cone-excitation value  $T$  changes with a) the surround cone-excitation value  $S$ , b) the ‘crispening amplitude parameter’  $\alpha$ , c) the ‘reciprocal crispening sharpness parameter’  $\sigma$  and d) the ‘von Kries adaptation parameter’  $\rho$ .

In the model outlined above, we assume that von Kries adaptation occurs prior to crispening. Our main motivation for doing so was that this order of operations yields predictions, which seem plausible in light of previous findings. In particular, the model is compatible with a linear matching curve  $T_2 = (\rho_1/\rho_2)T_1$  under conditions of full adaptation, that is, when  $\rho_1/\rho_2 = S_2/S_1$ .

A target  $T_1$  embedded in the ‘grey’ surround  $S_1$  should match a target  $T_2$  embedded in the ‘violet’ surround  $S_2$  whenever the corresponding expressions for  $C$  in Eqn. 2 have the same value. We assume that the crispening parameters  $\alpha$  and  $\sigma$  are identical for both target-surround stimuli, whereas the adaptation parameter  $\rho$  depends on the surround. Presuming that  $\rho$  reflects local receptor adaptation it would, under strict fixation, depend only on the target itself. Under the free viewing conditions of the present experiments, we make the simplifying assumption that the influence of the small target is small compared to the influence of the local surround and can therefore be neglected. Thus, to model our matching data we have to solve the equation

$$\begin{aligned} \rho_1 T_1 + \alpha(\rho_1 T_1 - \rho_1 S_1)e^{-|\rho_1 T_1 - \rho_1 S_1|/\sigma} = \\ \rho_2 T_2 + \alpha(\rho_2 T_2 - \rho_2 S_2)e^{-|\rho_2 T_2 - \rho_2 S_2|/\sigma} \end{aligned} \quad (4)$$

for  $T_2$ . An analytical solution is not known to us, so in order to model the data we solved it numerically. We arbitrarily set  $\rho_1 = 1$ , and estimated the values of  $\alpha$ ,  $\sigma$  and  $\rho_2$  that best fit the data for each subject and surround variance level. A least squares criterion and a numerical search method (MATHEMATICA’s FindMinimum function) was used, with the constraints  $\alpha \geq 0$  and  $\sigma > 0$ .

The solid curves in Fig. 4 are the resulting fits for surround variance level 0 (the results for the other variance levels were similar). The dashed lines show the component of the model fit which is attributable to von Kries adaptation only, i.e. the matching equation  $T_1 = \rho_2 T_2$  with the estimate of  $\rho_2$  obtained from the full model fit. The full model’s deviation from this line is due to the crispening component. It can be seen that the model accommodates the variation between subjects fairly well. The crispening non-linearity is almost absent in the data of subject 1, for instance, while it is very pronounced in the data of subject 11. The slope of the dotted line in each plot is  $1/\rho_2$ . Thus, a slope of 1 would mean that there is no von Kries adaptation, and the amount of adaptation increases with slope. The amount of adaptation also varies across observers. The data of subject 10 indicate a substantial amount of adaptation, while those of observers 4 and 12 indicate that there is as good as no adaptation.

For purely illustrative purposes, the subjects have been numbered such that the estimated value of  $\alpha$  in the zero variance condition shown in Fig. 4 increases with subject number. Note that the size and shape of the non-linearity in the plots does not only depend on the amplitude parameter  $\alpha$ , but also on the width parameter  $\sigma$ , and the adaptation parameter  $\rho_2$ . The dependence on  $\rho_2$  may be appreciated by verifying that the linear matching equation  $T_2 = (\rho_1/\rho_2)T_1$  is a solution to Eqn. 4 if  $\rho_1/\rho_2 = S_2/S_1$ .

The estimates of the model parameters for all surround variance conditions are summarised in Fig. 7. The mean parameter estimates are averaged across surround variance levels in the top row and across subjects in the bottom row. The error bars represent 95% confidence intervals. As can be seen in the top panels, the mean estimates of each of the three model parameters are reliably different across observers. In the bottom panels it can be seen that the mean crispening amplitude  $\alpha$  decreases with surround variance level, while the mean reciprocal crispening sharpness parameter  $\sigma$  and adaptation parameter  $\rho_2$  seem to be constant across surround variance levels.

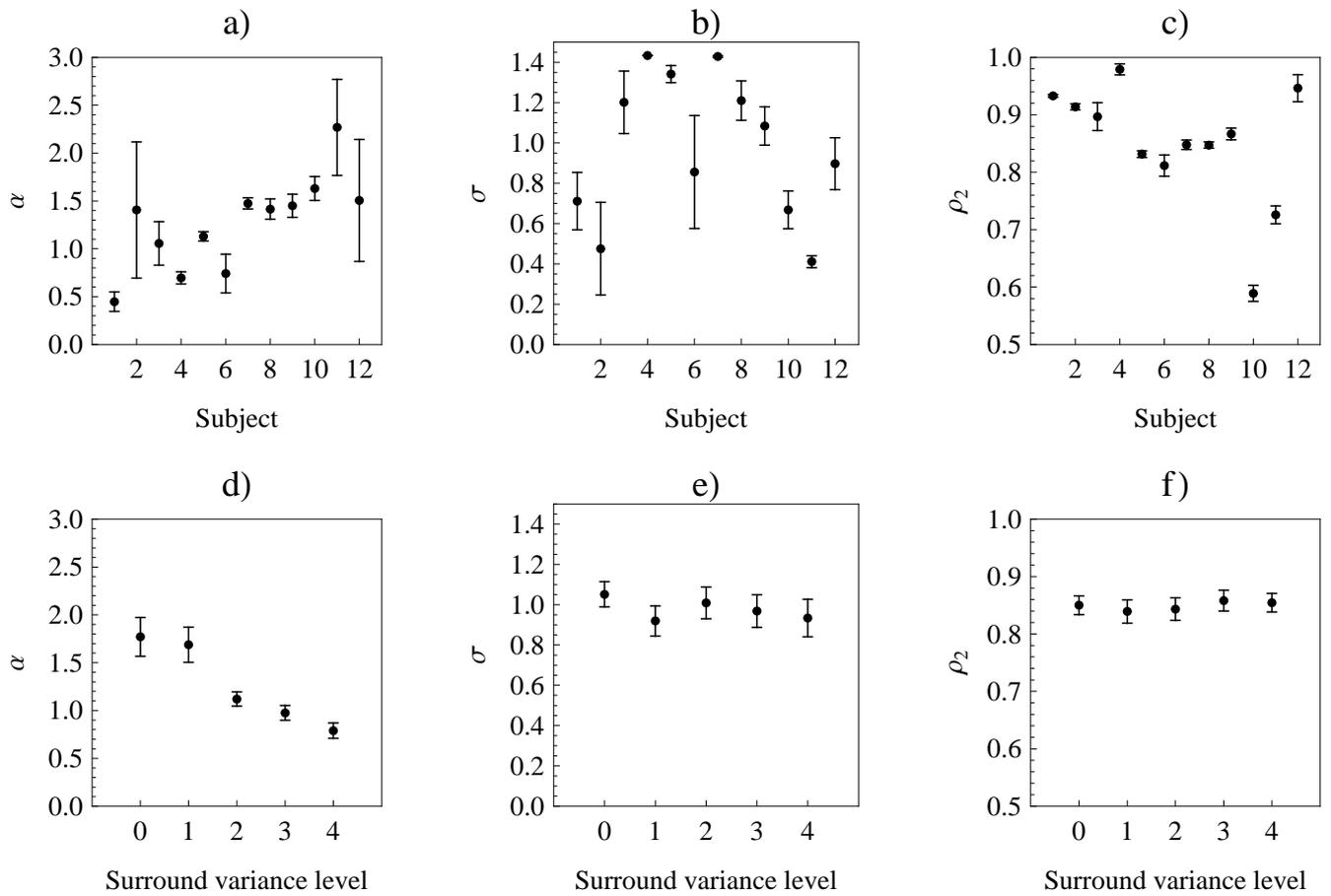


Figure 7: Top row: Subject-wise estimates of the model parameters averaged across surround variance levels. a) Estimates of the crispening amplitude  $\alpha$ . b) Estimates of the reciprocal crispening sharpness  $\sigma$ . c) Estimates of the von Kries adaptation parameter  $\rho_2$ . Bottom row: The same parameter estimates averaged across subjects and plotted against surround variance level. The error bars represent 95% confidence intervals in all panels.

### 3. Discussion

The main findings of the present investigations are the following:

- There are substantial individual differences in the susceptibility to simultaneous colour contrast.
- Not only the general amount of simultaneous contrast varies across observers, but also the shape of the matching curves (Fig. 4).
- The data can be fairly well accounted for by a model (Eqn. 2) based on von Kries adaptation and crispening when all three parameters of this model (crispening amplitude  $\alpha$ , reciprocal crispening sharpness  $\sigma$  and von Kries adaptation  $\rho_2$ ) are regarded as observer specific.
- The crispening amplitude decreases with increasing surround variance, while crispening sharpness and the amount of von Kries adaptation seem to be independent of surround variance (at least for the limited range investigated here).

The crispening non-linearity and the individual variation found in the present experiments were also evident in the findings of Takasaki (1967). The present replication makes it seem less likely that the individual variation reported by Takasaki is an artifact due to the somewhat cruder technical apparatus used in his study (matching of Munsell chips). Presumably related crispening non-linearities are evident in the data from several studies of simultaneous colour and brightness contrast using asymmetric matching (Takasaki, 1966; Smith and Pokorny, 1996; Schirillo, 1999; Miyahara et al., 2001; Ekroll et al., 2004). A crispening non-linearity has also been reported in a number of scaling and discrimination studies, where it shows up as enhanced discrimination for targets of low contrast relative to the surround (Whittle, 1986, 1992, 1994; Krauskopf and Gegenfurtner, 1992; Ovenston, 1998).

#### 3.1. The absence and presence of crispening in different studies

As discussed by Whittle (1992), many early researchers failed to notice the crispening effect in studies that would seem to be similar to his own, which produced clear evidence of crispening. There may be three different reasons for the failure of crispening to show up in a given study. As we shall discuss in the following, the crispening may be absent due to a) interindividual differences in the susceptibility to crispening, b) stimulus properties and c) cancelling of crispening under conditions of complete von Kries adaptation.

*Individual differences:* One possible reason for crispening effects failing to show up in some studies might be individual differences such as the ones documented in the present study. Some observers, such as for instance Subj. 1 in the present study (see Fig. 4) may be practically ‘immune’ to the crispening effect.

*Stimulus properties:* As shown by Whittle (1992) the crispening can be strongly reduced or even abolished by rather subtle stimulus manipulations. Adding a thin black outline to the targets was found to be very effective in reducing the crispening in the brightness domain<sup>2</sup> (but less so in the chromatic domain (Ovenston, 1998)). Also, the brightness crispening of achromatic targets was abolished by using saturated chromatic surrounds instead of an achromatic one (Whittle, 1992). If the model in Eqn. 2 is formulated in terms of cone excitation vectors this sort of result is to be expected since the crispening term would be effectively zero at larger vector differences between target and surround. Previous findings of ours (Ekroll et al., 2004; Faul et al., 2008), as well as the present ones, demonstrate that the amount of crispening is reduced or even abolished by using variegated surrounds instead of uniform ones. Thus, the stimulus conditions under which substantial amounts of crispening occur seem to be rather limited.

*Cancelling of crispening under conditions of complete von Kries adaptation:* Under conditions of complete von Kries adaptation, i.e. when  $\rho_i = 1/S_i$  or more generally  $\rho_1/\rho_2 = S_2/S_1$ , the predicted matching curve is linear with  $T_2 = (\rho_1/\rho_2) \cdot T_1$  regardless of the amount of crispening. Intuitively, this is because the von Kries-corrected cone-excitation values of the two physically different surrounds are equal, so that the crispening – which operates on the von Kries-corrected cone-excitation values – cancels out in the asymmetric matching task. That is, under conditions of full von Kries adaptation, crispening still occurs, but it does not influence the results of asymmetric matching experiments. This feature of the model is particularly interesting since the available evidence from asymmetric matching experiments may appear rather contradictory in the sense that many studies have produced essentially linear matching data (Whittle and Challands, 1969; Wuerger, 1996; Richter, 2002) although the present one and many others have produced highly non-linear matching data (Takasaki, 1966, 1967; Smith and Pokorny, 1996; Schirillo, 1999; Miyahara et al., 2001; Ekroll et al., 2004). In terms of the present model, this would simply be because von Kries adaptation was essentially complete in the former kind of study, while it was not in the latter. The results reported by Beer and MacLeod (2001) are in good agreement with this idea. Their asymmetric brightness matching experiments produced matches fitting the linear equation  $\rho_1 \cdot T_1 = \rho_2 \cdot T_2$  with  $\rho_i = 1/S_i$  very well under conditions which presumably favour full adaptation ( $\rho_i = 1/S_i$ ) and non-linear, more variable data under conditions which do not. In general, it would seem that approximately linear matches are reported in studies where stable adaptational states were produced by minimising spatial and temporal transients.

#### 3.2. Relation to the gamut expansion effect

Brown and MacLeod (1997) showed that coloured targets looked more saturated when they were presented in a grey uniform surround than when they were presented in a variegated

<sup>2</sup>Incidentally, this might be the simple factor responsible for the results reported by Nundy and Purves (2002).

one that was also grey on average. Highlighting the fact that this effect differs radically from traditional descriptions of simultaneous contrast as a translatory shift in colour space they coined the term ‘gamut expansion effect’. There is good reason to believe that the ‘gamut expansion effect’ and the ‘crispening effect’ are identical. In experiments similar to those of Brown and MacLeod (1997), we previously obtained data showing that the gamut expansion effect is highly non-linear (Faul et al., 2008). For targets with low contrast to the surround the expansion is maximal, and—in much the same way as the crispening term in Eqn. 2—it decreases rapidly towards zero as the difference between target and surround increases. Thus, if we assume that a sufficiently variegated surround produces essentially no crispening, the data on the ‘gamut expansion effect’ would simply reflect crispening in the uniform surround.

It is instructive to consider how the matching equation in Eqn. 4 can be adapted to the experimental paradigm in which the gamut expansion effect has been studied. In this case, the asymmetric matching is made between a grey uniform surround  $S_2$  and a variegated one  $S_1$  with the same grey mean. According to a classical idea (Valberg and Lange-Malecki, 1990), adaptation depends only on the mean surround colour. Hence, with the convention that  $\rho = 1$  for a surround with a grey average colour, we have  $\rho_1 = \rho_2 = 1$ . Assuming further that there is no crispening in the variegated surround, i.e.  $\alpha_2 = 0$ , Eqn. 4 reduces to

$$T_2 = T_1 + \alpha \cdot (T_1 - S) \cdot e^{-|T_1 - S|/\sigma}, \quad (5)$$

where  $S = S_1 = S_2$  is the mean cone-excitation value of the grey surrounds. In Faul et al. (2008) we presented our data on the gamut expansion effect by plotting Brown and MacLeod’s (1997) relative richness measure  $(T_2 - S)/(T_1 - S)$  against  $T_1$ . This can also be regarded as a plot against  $\Delta := T_1 - S$  by translating the origin on the horizontal axis. Hence, the function shown in our plots should be given by

$$f(\Delta) = \alpha \cdot e^{-|\Delta|/\sigma} + 1. \quad (6)$$

Thus, if the above assumptions are correct, asymmetric matching in the gamut expansion paradigm can be considered as providing a direct measure of the crispening function  $\alpha \cdot e^{-|\Delta|/\sigma}$ .

This poses an interesting question for future research, namely whether the individual differences in the sensitivity to crispening suggested by the present studies are mirrored by corresponding individual differences in the sensitivity to the ‘gamut expansion effect’. If the sensitivity to crispening indeed varies across observers, we would expect that the estimates of the crispening parameters from a ‘simultaneous contrast experiment’ and a ‘gamut expansion experiment’ should correlate.

The above-mentioned hypothesis according to which Valberg and Lange-Malecki’s (1990) functional equivalence of surrounds with equal mean colours holds with respect to von Kries adaptation but not with respect to crispening seems to be supported by the finding that the crispening parameters  $\alpha$  and  $\sigma$  depend on the surround variance level while  $\rho_2$  does not (see Fig. 7).

### 3.3. Relation to Kirschmann’s 4th law and Meyer’s effect

According to Kirschmann’s (1891) 4th law, the simultaneous contrast effect observable with a grey patch embedded in a chromatic surround increases with the saturation of the surround. This statement may be thought of as general prediction of most models of simultaneous contrast. A number of important models, for instance, which are specifications and elaborations of Jameson and Hurvich’s (1961) dual process model (Walraven, 1976; Shevell, 1978, 1980; Mausfeld and Niederee, 1993; Chichilnisky and Wandell, 1995), would in general predict results in accordance with Kirschmann’s 4th law because their two main constituents do (von Kries adaptation and background discounting).

The general empirical validity of Kirschmann’s 4th law is questionable. Kinney (1962) and Bosten and Mollon (2007) agree in finding that the postulated increase is very modest. Critically, some of the results from both studies even indicated a *decrease*. Such a decrease is also evidenced by the phenomenon known as Meyer’s effect or ‘tissue contrast’ (Meyer, 1855; Hering, 1887b; von Helmholtz, 1911; Perls, 1932; Krauss, 1949; Walls, 1960; Brown, 2003; Mausfeld, 2003). The basic observation is that the simultaneous contrast effect that occurs when a grey target is embedded in a chromatic surround can be enhanced by viewing the stimulus through a piece of white transparent tissue. Since the transparent tissue will reduce the saturation of the surround, this would contradict Kirschmann’s 4th law.

While it is difficult to account for Meyer’s effect on the basis of models based on von Kries adaptation and background discounting, it is naturally accounted for in terms of crispening. Fig. 8a shows how the induction effect in a grey target should depend on surround saturation according to the crispening term in the present model (Eqn. 2). Each curve represents the predictions based on the parameter estimates for one of our subjects. As surround saturation increases the induction swiftly reaches a maximum at the point where the surround saturation (defined as the difference between the surround and the grey target) equals the inverse crispening sharpness parameter  $\sigma$  and then decreases towards zero.

It is less straightforward to derive predictions based on von Kries adaptation, since most models do not make specific commitments as to exactly how the von Kries parameters  $\rho$  decrease with the cone-excitation values of the surround. The predictions shown in panel b) of Fig. 8 are based on the convention that  $\rho = 1$  for a grey surround and the assumption that it decreases linearly with the cone-excitation value of the surround. Again, each curve is based on the parameter estimate ( $\rho_2$ ) for one of our subjects. Panel c) shows corresponding predictions based on the full model (Eqn. 2) which combines crispening and von Kries adaptation. The interesting point to be noticed is that whether the predictions are in accordance with Kirschmann’s 4th law or its antithesis Meyer’s effect depends on the individual combination of model parameters  $\alpha$ ,  $\sigma$  and  $\rho_2$ . It is also noteworthy that the qualitative shape of the predictions in panel c) is rather similar to the empirical data curves obtained by Bosten and Mollon (2007). Note that they also reported large individual differences.

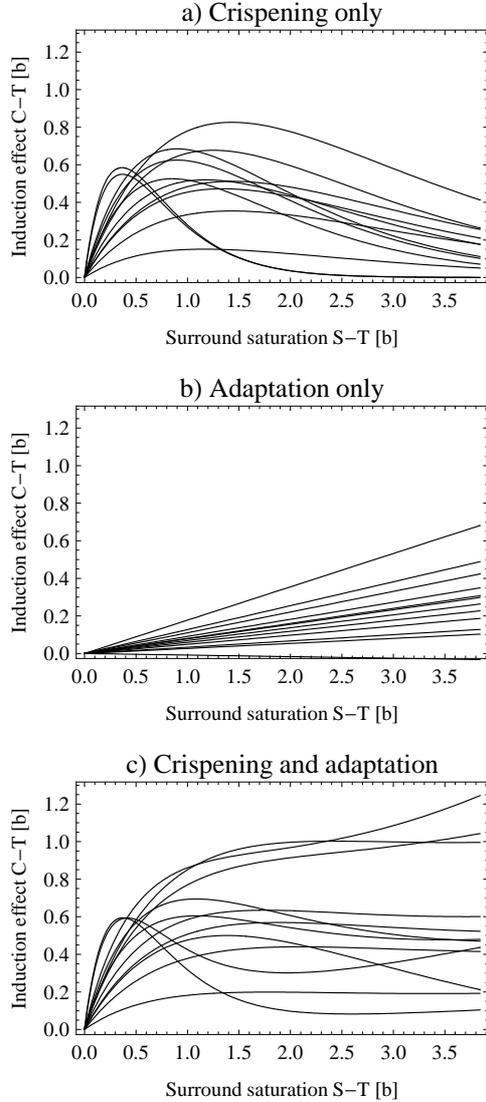


Figure 8: Plots of how the induction effect in a grey target  $T$  should depend on surround saturation  $S - T$  according to the present model (Eqn. 2). Each curve represents the prediction based on the parameter estimates for one of our subjects. a) Here, the influence of crispensing only is shown by neglecting von Kries adaptation ( $\rho_2 = 1$ ). In this case the induction effect  $C - T$  should equal  $\alpha(T - S)e^{-|T-S|/\sigma}$ . b) Here it is assumed that only von Kries adaptation takes place, i.e.  $C - T = \rho_s T - T$ . We assume that  $\rho_s = 1$  for a white surround and  $\rho_s = \rho_2$  for the violet surround used in the present study. The values of  $\rho_s$  for other surround colours are determined by linear interpolation/extrapolation. c) Predicted induction effect using the full model, that is,  $C - T = \rho_s T + \alpha(\rho_s(T - S))e^{-|\rho_s(T-S)|/\sigma} - T$ .

Cornelissen and Brenner (1991) have shown that colour induction increases under conditions favoring adaptation (such as strict fixation and prolonged viewing). In the present model, such manipulations would lead to lower values of the adaptation parameter  $\rho_2$ . Thus, the critical balance between crispensing and adaptation that determines whether Kirschmann's 4th law is violated or not, is likely to depend not only on individual differences, but also on viewing conditions. Specifically, we expect less violations of Kirschmann's 4th law under conditions favouring adaptation.

### 3.4. What is the essence of simultaneous colour contrast?

According to received wisdom, the colour induced in a target is roughly complementary to the colour of its surround. Furthermore, the strength of the induction effect is assumed to increase with the saturation of the surround (Kirschmann's 4th Law). The majority of models of simultaneous colour contrast, such as for instance the dual process models incorporating von Kries adaptation and background discounting (see above) are compatible with this gross qualitative description. Over the years, though, a number of phenomena have been documented which *a priori* may qualify as simultaneous colour contrast in the sense that they seem to be instantaneous changes in the perceived colour of a target induced by the surround, but do not fit the above-mentioned qualitative description, namely Meyer's *effect*, the crispensing *effect* and the gamut expansion *effect*. Rather than regarding these observations as anomalies suggesting that common conceptions about the essential characteristics of simultaneous colour contrast need to be revised, though, the trend in the literature has been to regard these phenomena as additional separate '*effects*'.

In light of the above discussion, it seems reasonable and parsimonious to regard Meyer's effect, the gamut expansion effect and the crispensing effect as just different names for the same basic phenomenon. The terms 'gamut expansion' and 'crispensing' aptly describe different essential characteristics of the phenomenon described by the crispensing term in Eqn. 2. The former term is adequate in the sense that we are dealing with an expansion instead of a translation. The expansion is not linear, though, and as a consequence we get a maximum of discriminability at the point where the target equals the surround. This aspect is better captured by the latter term '*crispensing*'.

The model used to describe the present data consists of the two components von Kries adaptation and crispensing. The former component is compatible with traditional descriptions of simultaneous contrast as a unidirectional transform, while the latter is not. One may ask, though, whether it is not actually the crispensing term that is most appropriately conceived of as *simultaneous* colour contrast. It is quite reasonable to assume that most actual measurements, including the present ones, are due to a combination of time-dependent adaptation mechanisms and purely spatial mechanisms of true simultaneous contrast which occurs instantaneously (Rinner and Gegenfurtner, 2000). The component in the present model most naturally associated with time-dependent mechanisms is von Kries adaptation, and the component most naturally conceived of as an instantaneous spatial mechanism is crispensing. Some arguments can be made in

favour of this view. First, the von Kries scheme was originally developed to account for temporal adaptation effects, and it is traditionally associated with the notion of receptor fatigue (von Kries, 1905). Second, phenomena characteristic of crispening, such as the gamut expansion effect or Meyer's effect are typically observable immediately upon inspection of a demonstration. The suggested identification of true simultaneous colour contrast with crispening certainly needs to be investigated more thoroughly in formal experiments. At present, though, it suggests itself as an interesting and parsimonious hypothesis, and it is compatible with the available evidence. If the hypothesis is true, it would mean that traditional notions of simultaneous colour contrast as a unidirectional transform instead of as a non-linear expansion are fundamentally misleading. In this connection, it should be noted that it is quite easy to confuse an expansion with a unidirectional transform such as background discounting (Jameson and Hurvich, 1961; Walraven, 1976; Shevell, 1978, 1980; Mausfeld and Niederée, 1993; Chichilnisky and Wandell, 1995) if one investigates only a limited range of target colours which do not span the centre of expansion. Experiments with unique hue and grey settings would be a case in point.

Assuming that simultaneous contrast is essentially identical to crispening, one would expect that the dependence on spatial variables is the same in both cases. Experiments with simultaneous contrast (Walraven, 1973; Brenner and Cornelissen, 1991) agree with our experiments on crispening/gamut expansion (Faul et al., 2008) in indicating a rather local effect. Increasing the width of an annular surround beyond  $1^\circ$  adds but very little to the effect and a gap between target and surround of less than  $1^\circ$  degree abolishes the effect almost completely.

### 3.5. Relation to perceptual transparency

Interestingly, it has repeatedly been noticed that centre-surround stimuli tend to evoke an impression reminiscent of perceptual transparency (Metelli, 1970; Anderson, 1997; D'Zmura et al., 1997, 2000; Kasrai and Kingdom, 2001; Robilotto et al., 2002; Singh and Anderson, 2002; Faul and Ekroll, 2002) or haze when the contrast between target and surround is low (Masin and Idone, 1981; Brenner and Cornelissen, 1991; Brown and MacLeod, 1997; Mausfeld, 1998; Ekroll et al., 2002, 2004; Faul et al., 2008). Since both simultaneous contrast *qua* crispening and perceptual transparency in simple centre-surround stimuli occur primarily at low target-surround contrast, it is natural to speculate that the two phenomena may be related. This would be consistent with the growing body of work suggesting an intimate connection between colour/brightness induction effects and transparency-like layered scene representations (Adelson, 1993; Anderson, 1997; Adelson, 2000; Anderson and Winawer, 2005, 2008; Wollschläger and Anderson, 2009)

### 3.6. Possible causes of the individual variation

We now consider how the variation in the individual estimates of model parameters  $\alpha$ ,  $\sigma$  and  $\rho_2$  may be interpreted.

*Sensitivity to colour difference signals and simultaneous contrast.* It is clear from Eqn 4 that the crispening parameter  $\alpha$  is a measure of how strongly colour difference signals contribute to colour appearance. Our results suggest that  $\alpha$  depends on both stimulus properties and characteristics of the observer. As can be seen in Fig 7 a, the individual estimates of  $\alpha$  (averaged across the surround variance levels) vary by a factor of about 5 (from 0.45 to 2.27). In section 3.4 we argued that crispening and simultaneous colour contrast are just two sides of the same coin. From this perspective individual variations in  $\alpha$  would constitute different degrees of susceptibility to simultaneous contrast.

*Crispening sharpness vs. receptor gain.* In the model fitted to the data there is an ambiguity with respect to the absolute size of the parameters  $\rho_i$  and  $\sigma$ : In the matching equation (Eqn. 4), multiplying  $\rho_i$  with a factor  $x$  can always be compensated exactly by multiplying  $\sigma$  with the same factor. In modelling data we have used the convention  $\rho_1 = 1$  and all parameters were estimated relative to that.

Thus, the variability in the individual parameter estimates for  $\sigma$  is open to two different interpretations: The variance in  $\sigma$  may reflect variance in the inverse crispening sharpening, the absolute cone sensitivity of the observer or a combination of both. The interpretation in terms of absolute cone sensitivity is compatible with the finding that the mean estimate of  $\sigma$  is about the same for all surround variance levels (Fig. 7 e).

*Variations in time-dependent adaptation.* As we have already mentioned, it appears natural to identify the von Kries adaptation parameter  $\rho_2$  with time-dependent adaptation mechanisms. Thus, since subjects were free to use as much time as they needed to establish a match, the variation in the individual estimates may equally well reflect differences in viewing time as true individual variation. Since the experiments were made under free viewing conditions, differences in viewing strategies may also have contributed to the variance in the estimates of  $\rho_2$ .

*Criterion problems.* Several authors have pointed to the fact that the colour appearance of a target has more than three degrees of freedom when also the colour coordinates of the surround are free to vary (Gelb, 1929; Katz, 1935; Evans, 1964, 1974; Heggelund, 1993; Niederée, 1998; Niederée, In Press; Mausfeld and Niederée, 1993; Mausfeld, 1998, 2003, In Press; Whittle, 2003; Ekroll et al., 2002, 2004; Logvinenko and Maloney, 2006; Vladusich et al., 2007), which could be attributable to the above-mentioned+6 occurrence of layered, transparency-like colour impressions. Thus, in asymmetric matching experiments, where the subject can only vary three parameters (the nominal cone-excitation values of the adjustable target), one may expect that it shall be impossible to establish a true match. Confronted with this impossible task, subjects may adopt different criteria for deciding what constitutes the best possible match (Arend and Goldstein, 1987; Arend and Spehar, 1993a,b). As mentioned in the experimental section, we took pains to ensure that the subjects adopted the same criterion. These precautions need not necessarily have been as effective as intended, though,

so it cannot be ruled out for certain that criteria problems may have contributed to the individual variation in the data. However, the first author (Subj. 7), for instance, is quite confident that he would never accept the almost veridical matches made by Subj. 1 (see Fig. 4). Thus, at least a part of the individual variation seems to reflect true perceptual differences.

In any event, we do not believe that the matches made in our experiments represent perceptual identity in all cases. Consequently, the model we used to describe the ‘matches’ should not be thought of as predicting when two targets in different surrounds appear equal. Rather, it merely describes the subjects’ matching behaviour.

### 3.7. Other evidence for substantial individual differences

Investigations of simultaneous contrast are typically performed with just a couple of observers, often just the author(s) and perhaps one or two naive observers. As a consequence, it is difficult to estimate how much individual variation there is based on the existing literature. Results from experiments with just two or three observers often tend to suggest that the interobserver consistency is quite good. Some reports with a somewhat larger sample of observers, though, suggest that the individual variation actually may be rather substantial (Barbur et al., 2004; Cornelissen and Brenner, 1995; Pungrassamee et al., 2005). Interestingly, Cataliotti and Becklen (2007) recently reported that one of their subjects was practically immune to simultaneous brightness contrast. They called this observer a ‘superseer’. Similarly, Subj. 1 in the present study seems to be well-nigh immune to simultaneous colour contrast (See Fig. 4). Anecdotal evidence suggests that such an ‘immunity’ to simultaneous contrast effects may be not all that seldom in the general population. In personal communications, many colleagues have related similar observations.

*Limitations of the model.* The colour appearance of a target embedded in a uniform surround depends on six parameters, namely the cone excitation triplet of the target and that of the surround. The model used to describe the data implicitly assumes that the colour appearance of a target embedded in a coloured surround nevertheless can be described by a triplet. This implies that – barring gamut limitations – a perfect asymmetric match should always be possible. As already mentioned, however, several lines of evidence suggest that this is not the case. Therefore the model cannot possibly capture all aspects of colour appearance. Instead it can at best represent what the observer considers the best choice among imperfect alternatives.

## 4. Conclusions

The present study documents substantial individual variability in the susceptibility to simultaneous colour contrast. The variability could be well described using a model based on von Kries adaptation and crispening. While the variability in the reciprocal crispening sharpness parameter  $\sigma$  and the von Kries adaptation parameter  $\rho_2$  are open to rather simple explanations, such as variations in absolute cone sensitivities and variable viewing time, the variability in the crispening amplitude  $\alpha$

may be taken to suggest that the relative sensitivity to difference signals and absolute signals varies across observers. We have also argued that simultaneous contrast, crispening and the gamut expansion effect are just different terms for the same basic phenomenon. This would mean that common assumptions about the basic characteristics of simultaneous colour contrast are misleading. Viewed in conjunction with the individual variation among our observers, this may account for the mixed evidence for Kirschmann’s 4th law.

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