The peculiar nature of simultaneous colour contrast in uniform surrounds

Vebjørn Ekroll *, Franz Faul, Reinhard Niederée

Institut für Psychologie, Christian-Albrechts-Universität zu Kiel

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Abstract

We present evidence from asymmetric colour matching experiments which strongly suggests that *uniform* surrounds evoke induction effects of a very peculiar nature, *not representative* of colour induction effects in variegated surrounds. Given the widespread use of uniform surrounds in studies of colour vision, this finding is of interest in relation to a number of current research issues, such as contrast coding of colour, functionally equivalent surrounds and colour constancy. A framework that systematises the seemingly complex colour appearance changes induced by uniform surrounds is presented and its implications are discussed.

Key words: Colour vision, Simultaneous colour contrast, Colour induction, Transparency, Scission, Adaptation

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1 Introduction

The well-known phenomenon of simultaneous contrast (Helmholtz, 1911; Kingdom, 1997; Whittle, 2003) may be appreciated in figure 1 (top). Although the two small squares are in fact physically equal, they look rather different, solely due to the fact that they are embedded in differently coloured surrounds. The perceptual effect appearing in this simple stimulus configuration is thought to be a consequence of a general mechanism that also operates in more complex situations and

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* Corresponding author. Tel.: +49-431-880-7534
Email address: vekroll@psychologie.uni-kiel.de (Vebjørn Ekroll).
URL: `www.psychologie.uni-kiel.de/psychophysik/` (Vebjørn Ekroll).

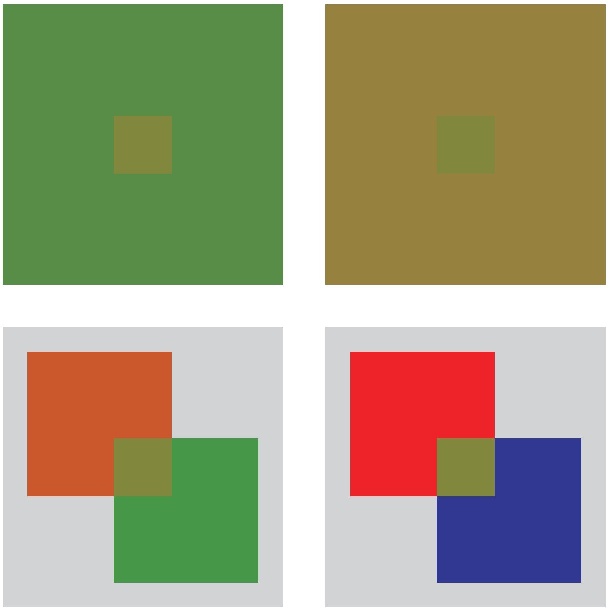

Fig. 1. Top: Simultaneous colour contrast. The two central squares are physically identical, but since they are embedded in different surrounds, they appear rather different. Bottom: Another example of the influence of context on perceived colour. Again, the central squares are physically equal. Beyond the difference in perceived colour, a difference in the perceived opacity of the central squares is notable. In the left configuration one has the impression of seeing a red square behind a green transparent layer, or the converse. In contrast, the central square in the right configuration appears opaque.

plays an important and basic role in human colour vision at large. It has for instance been proposed that the same mechanism which is responsible for simultaneous contrast in simple centre-surround stimuli also plays an important role in human colour constancy, i.e. the approximate invariance of perceived object colour in spite of illumination changes (Walraven, Benzschawel, and Rogowitz, 1987; Lotto and Purves, 2002).

In order to understand a given hypothetical mechanism one usually seeks to identify conditions under which its operation can be observed in its purest and most simple form. In the case of simultaneous contrast at least two considerations may suggest that simple centre-surround stimuli are most likely to make this possible. First, they do not contain any obvious figural cues, such as for instance t-junctions, which are thought to evoke more elaborate scene analyses that may also influence perceived colour (Adelson, 1993; Anderson, 1997). Secondly, since the central patch only borders with one uniform region, the influence of the surround may be expected to be of a particularly simple nature.

In line with such reasoning, uniform surrounds have been employed in the majority of psychophysical investigations of simultaneous contrast. Common methods for quantifying the effect are asymmetric colour matching and grey settings. In either case subjects are asked to compensate the effect of a coloured surround on the perceived colour of the central patch by adjusting the tristimulus co-ordinates of the latter. The appropriateness of this procedure rests on the assumption that the two cone excitation triplets corresponding to the surround and the central patch are conflated into a three-dimensional colour code that determines the perceived colour of the central patch. On this view, which is seldom explicitly formulated (Suppes, Krantz, Luce & Tversky, 1989, chapter 15.4.4, is a notable exception) but nevertheless implicit in most models, the colour appearance changes resulting when the colour of the uniform surround is changed can be appropriately described by a corresponding relocation of the colour code of the central patch in tristimulus space.

However, it is generally acknowledged that not all context effects in colour vision are of this simple kind. Significantly, many context effects appearing in more structured stimuli involve the perception of additional perceptual dimensions such as shadows, highlights and transparency (Arend, 1994; Kanizsa, 1980; Adelson, 1993, 2000; Anderson, 1997). As can be appreciated in figure 1 (bottom), such additional dimensions can make asymmetric matches difficult or even impossible. In this figure, the difference in colour appearance between the two physically identical central squares cannot be compensated by changing the co-ordinates of the central square in the right-hand configuration. One reason is that the left configuration triggers an impression of transparency (Metelli, 1970). Accordingly, the colour in the region of the central square appears to be split into two components, one belonging to a transparent layer, and the other to the background. In the right configuration an impression of transparency is not evident and it would not be possible to reproduce the same dual colour impression in the central square of the other configuration by manipulating the tristimulus co-ordinates of the central square. Consequently, employing an asymmetric colour matching technique is in this case not straightforward.

The distinction between *simple* colour appearance changes occurring in centre-surround stimuli and *complex* colour appearance changes occurring in more structured stimuli seems intuitively appealing and natural, all the more since simultaneous contrast is often thought to have a relatively simple peripheral physiological basis, whereas the dual colour impressions appearing in more complex displays are thought to reflect the action of more complex higher-level processing. This distinction is implicit in much of modern work on colour perception, and can be traced back to the work of Schumann (1921), who formulated it explicitly as a resolution of the controversy between Helmholtz (1911) and Hering (1887a,b,c, 1888) as to whether simultaneous contrast involves the perception of dual colour impressions such as reddish-green and yellowish-blue or not.

There is, however, reason to question whether this theoretical dichotomy is adequate to the nature of the phenomena: Under the assumption that only simple colour appearance changes occur in centre-surround stimuli, recent data from studies of simultaneous contrast (Smith and Pokorny, 1996; Miyahara, Smith, and Pokorny, 2001; Ekroll, Faul, Niederée, and Richter, 2002) would suggest curious or even paradoxical conclusions. If, however, in keeping with previous observations (Masin and Idone, 1981; Mausfeld and Niederée, 1993; Mausfeld, 1998; Niederée, 1998), one admits the possibility that simple centre-surround stimuli may evoke dual colour impressions reminiscent of perceptual transparency, at least the paradoxical conclusions implied by the data of Ekroll et al. (2002) can be avoided (MacLeod, 2003).

Another line of evidence suggesting that complex colour changes may occur in simple centre-surround stimuli stems from research on perceptual transparency. Using achromatic stimuli Masin and Idone (1981) found that the likelihood that a centre-surround stimulus triggers an impression of transparency is inversely related to the luminance contrast between the central patch and its surround. Casual observations (see figure 2 in MacLeod, 2003) indicate that this finding generalises to chromatic contrast: Transparency impressions are most compelling at low chromatic contrast, and absent at high contrast.[1] These findings suggest that the visual system processes centre-surround stimuli in a different manner when they have low contrast. Thus, even for a fixed surround the effect it exerts on a central patch may reflect the action of different perceptual mechanisms, depending on whether the contrast between the central patch and its surround is low or high. The complex and highly non-linear matching data reported by Smith and Pokorny (1996) may be interpreted in this sense.

In line with these observations, the asymmetric matching data obtained in the present study suggest that two quantitatively and phenomenologically distinct types of effect can be observed in centre-surround stimuli with uniform surrounds, whereas in stimuli with variegated surrounds only one of these effects is observed. The effect which is particular to uniform surrounds, is intimately related to contrast coding of colour (Walraven, 1976; Hurlbert, 1996; Shepherd, 1997; Whittle, 2003), whereas the effect common to both types of stimuli can be well described as von Kries scaling (gain control).

In experiment 1 we used uniform surrounds and obtained non-linearities in the matching curves similar to those found by Smith and Pokorny (1996). The special form of these non-linearities and their dependence on the surround chromaticities suggests that the complex total effect is best understood as a combination of two independent simpler effects. This hypothesis is substantiated by the results of experiment 2, which show that when the surround is modified by adding chromatic variance while keeping the space-averaged colour constant, one of these effects is suppressed whereas the other remains unchanged.

As will be outlined in the discussion, this finding has several interesting consequences, which may help to clarify some controversial issues in colour science such as the notion of functionally equivalent surrounds (Valberg and Lange-Malecki,

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[1] Interestingly, artists sometimes seem to use low contrast and transparency synonymously (Koenderink, 2003).

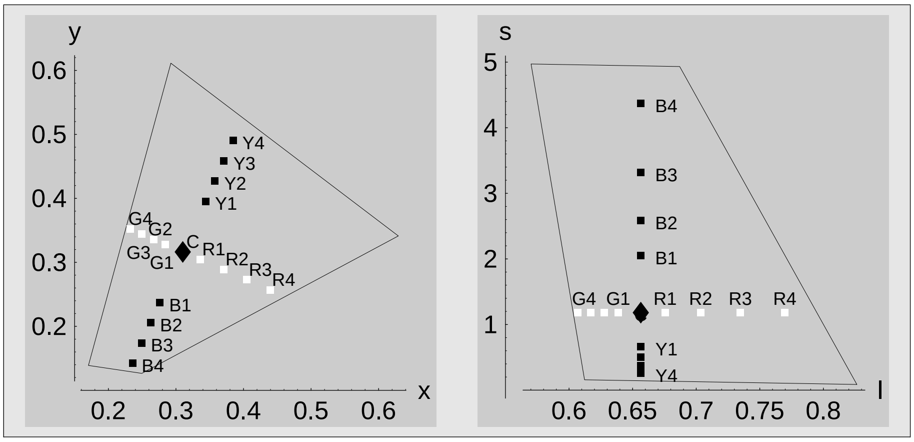

Fig. 2. Chromaticities of the surrounds employed in experiment 1 plotted in the CIE **xy**-chromaticity space (left) and the MacLeod-Boynton (1979) chromaticity space (right). In both cases the polygon represents the gamut of the monitor at the luminance used in the experiment.

1990; Andres, 1997; Brill, 2000), contrast coding of colour (Whittle, 2003) and the colour constancy interpretation of simultaneous contrast.

2 Experiments

2.1 Experiment 1: Uniform surrounds

As mentioned in the introduction, several studies suggest that centre-surround stimuli with low contrast may evoke dual, transparency–like colour impression whereas high contrast stimuli do not. This dual nature of the colour impression can be expected to make true asymmetric matches difficult or even impossible in some situations. We surmised that such problems may be related to or even responsible for the complex and curious pattern of results obtained in the asymmetric matching experiment reported by Smith and Pokorny (1996). Thus, we conducted a similar experiment using stimulus parameters that we expected to be more diagnostic with respect to our hypothesis.

Methods and Stimuli All stimuli were presented on a CRT computer monitor, which was colourimetrically calibrated by means of a colourimeter (LMT C1210) following a standard procedure (Brainard, 1989), and controlled by a graphics card yielding a colour resolution of 8 bits per RGB channel. Viewing distance was approximately 90 cm, and the monitor, which was the only source of illumination in the room, was located within a viewing box covered by black velvet on the inside. The subjects viewed two square patches (subtending $1.9°$ visual angle), each

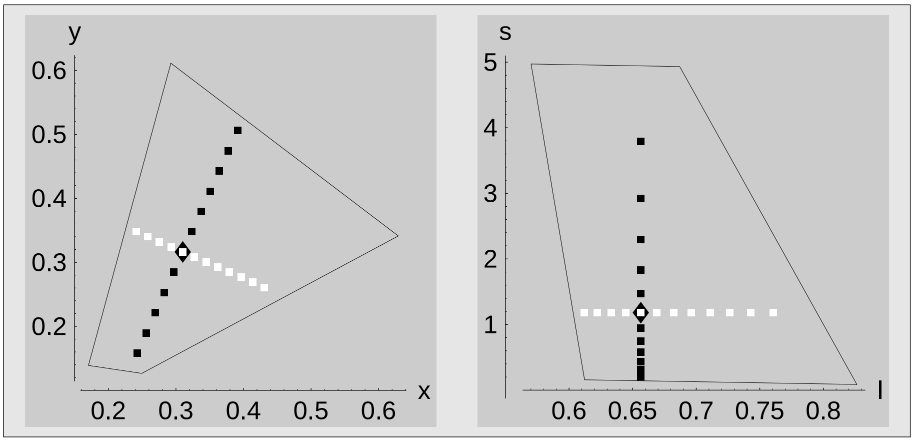

Fig. 3. Chromaticities employed for the fixed patch in experiment 1a (white symbols) and experiment 1b (black symbols) plotted in the CIE **xy**-chromaticity diagram (left) and the MacLeod-Boynton chromaticity diagram (right).

centred in the middle of a square surround ($9.6°$). The centre-to-centre distance between the two centre-surround stimuli was $12.2°$. All parts of the stimuli except the dark general background were equiluminant at 10 cd/m^2. The luminance of the adjustable patch was also restricted to 10 cd/m^2, but the chromaticity could be varied freely within the gamut of the monitor (see fig. 2) by using the arrow keys of a keyboard. For both surrounds and the fixed patch we used chromaticites which were all located on the same cardinal axis (Krauskopf, Williams, and Heeley, 1982). The cardinal axes were defined as the lines through the (**l**,**s**) co-ordinates (0.656, 1.182) of Illuminant C (Wyszecki and Stiles, 1982) in the MacLeod-Boynton (1979) chromaticity diagram with constant **l** and **s** values, respectively. The computation of **l** $:= L/(L+M)$ and **s** $:= c \cdot S/(L+M)$ is based on the cone excitations L, M and S as estimated by Smith and Pokorny (Wyszecki and Stiles, 1982, p. 615). The **s** co-ordinate was scaled by a constant c such that it was 1 for equal energy white. For isolated light spots, the perceived colours corresponding to the chromaticities on the **s**-axis may be said to vary from a reddish blue to a greenish yellow, those corresponding to the chromaticities on the **l**-axis range from red to green. For brevity, and keeping in mind that these axes are not to be confused with the unique hue loci of opponent colours theory (Valberg, 2001), we shall refer to the axes as the blue-yellow and red-green cardinal axis, respectively. All the surround chromaticities used in the present experiments are shown in figure 2. In the left part of the figure the CIE (**x**,**y**)-chromaticities of the surrounds are plotted, and in the right part the corresponding MacLeod-Boynton (**l**,**s**)-chromaticities. In experiment 1a, we used the following pairs of chromaticities (plotted in figure 2) from the blue-yellow cardinal axis for the surrounds of the fixed and the adjustable patch [given in the order (fixed, adjustable)]: (C, B_i), (C, Y_i) and (B_i, Y_i), with $i = 1, 2, 3, 4$; C, B_i, Y_i denote Illuminant C, different blues and different yellows, respectively. For the fixed patch we used the chromaticities from the same cardinal axis which are plotted as black symbols in figure 3. In experiment 1b we chose the pairs (C, R_i), (C, G_i) and (R_i, G_i) from the red-green axis as surround colours and for the fixed patch

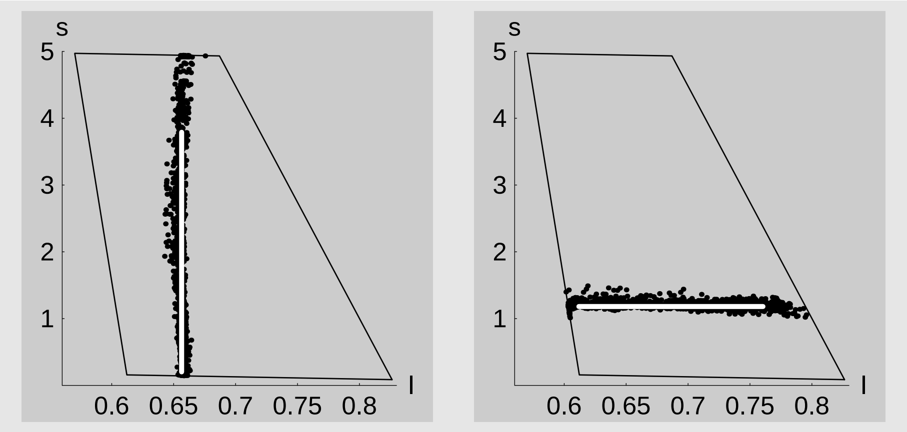

Fig. 4. Complete plot of all the settings chosen by the subjects in experiment 1a (left) and 1b (right) plotted in the MacLeod-Boynton chromaticity diagram.

we used the chromaticites from the same cardinal axis plotted as white symbols in figure 3.

The task of the subjects was to make the perceived colours of the central patches as similar as possible by manipulating the chromaticity of the adjustable patch. In each experimental session matches were made for 12 different fixed patches and one pair of surrounds. Since each match was repeated 3 times for each subject, a single experimental session consisted of 36 single matches.

Three naïve, but experienced psychophysical observers (MK, BS and GW) participated in the experiments. All were colour-normal according to the Ishihara Tests for Colour-Blindness. Author VE also performed the experiment. His data were very similar to those of observer GW and are not reported.

Results and discussion Consistent with previous reports (Wuerger, 1996; Rinner and Gegenfurtner, 2002), the asymmetric matches[2] differed mainly in the same chromaticity co-ordinate (either **l** or **s**) as the surround pairs. Differences with respect to the other co-ordinate were negligible. In figure 4 every single setting made in the experiment is plotted, those for surround pairs differing in the **s** co-ordinate on the left, and those for surround pairs differing in the **l** co-ordinate on the right.

The white lines in figure 4 represent the constant **l** co-ordinate of the fixed patch in experiment 1a (left panel) and the constant **s** co-ordinate of the fixed patches in experiment 1b (right panel). Apart from the small deviations from these lines, plots showing only one of the chromaticity co-ordinates yield a complete representation of the data. In figure 6 the results for the surround pairs differing in the

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[2] In the following we use the term asymmetric match for a best match in the sense of the above instruction. Whenever perceptual identity is implied we shall speak of a *true asymmetric match.*

s co-ordinate are shown. The format of these plots is explained in figure 5. The mean **s** co-ordinate of the subjects' settings (vertical axis) is plotted against the **s** co-ordinate of the fixed patch (horizontal axis). Each data point is based on nine individual settings, three from each of the three subjects, and the error bars represent one standard deviation in each direction. The top four panels represent the data for the surround pairs (C, B_i), $i = 1, 2, 3, 4$, the middle four panels for the surround pairs (C, Y_i) and the bottom four panels for the surround pairs (B_i, Y_i). In each panel, the point where the two white rectangles meet represents the **s** co-ordinates of the surround pair. The projection of this point on the horizontal axis gives the co-ordinate of the surround in which the fixed patch was presented, the projection on the vertical axis gives the co-ordinate of the surround of the adjustable patch. The two white rectangles also show the regions in which data points representing an increment-decrement match with respect to S-cone excitation would fall [3]. A center-surround stimulus is said to be incremental (decremental) with respect to dimension X whenever its center has a larger (smaller) x-value than its surround. The work of Whittle and Challands (1969) and Whittle (2003) suggest that increments can never be matched to decrements, neither with respect to luminance nor with respect to cone excitations (see also Kingdom, 2003).

The induction effects, defined as the difference in the co-ordinates of the fixed and the adjustable patch, is apparent in the plots as the vertical distance between a plot point and the diagonal line, which is where plot points would fall in the absence of any induction effect. Consistent with previous observations (Jameson and Hurvich, 1972; Walraven, 1976; Shevell, 1978), the data cannot be accounted for by simple von Kries adaptation (Kries, 1905). If this were the case, the data in each plot should fall on a single line through the origin, which is clearly not the case. A very conspicious regularity of the data is a step-shaped bump, henceforth referred to as the 'step', where the plot points seem to graze the border of one of the white rectangles. This 'step' gets larger with increasing difference between the **s** co-ordinates of the surround pair, whereas the induction effects outside this region, represented by the plot points which do not graze the white rectangle, are but moderate in comparison. Thus, on a purely descriptive level, it appears that a major part of the induction effects is accounted for simply by stating that the plot points graze the white rectangle. This means that subjects avoid making S-cone increment-decrement matches, consistent with the predictions of relational colour-coding (Whittle, 2003). However, it also reveals more. Referring, for example, to the top panels in figure 6, the horizontal portion of the data curves means that several different **s** co-ordinate increments presented in the neutral surround are matched to the same patch chromaticity in the blue surround, namely to the chromaticity of the blue surround itself.

Casual observations suggest that the reason for this curious pattern of results is that the range of **s** co-ordinate increments presented in the neutral surround, which

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[3] Due to the equiluminance of the stimuli, a S cone increment-decrement match occurs whenever a **s** co-ordinate increment-decrement match occurs.

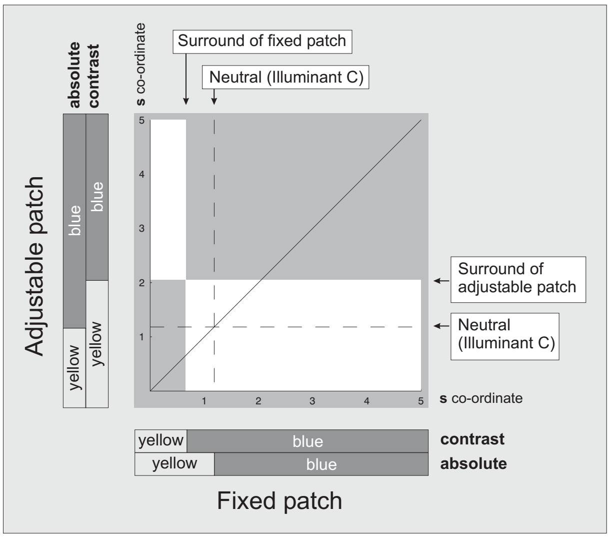

Fig. 5. Explanation of the general format of the data plots. The horizontal and vertical axis represents the **s** co-ordinate of the fixed and the adjustable patch, respectively. The diagonal line shows where the data points would fall in the absence of any induction effect. The dashed lines show the location of a nominally neutral stimulus (Illuminant C) on each axis. In each plot the horizontal co-ordinate of the point where the two white squares meet represents the **s** co-ordinate of the surround of the fixed patch, the vertical co-ordinate that of the surround of the adjustable patch. The white regions show where data points would fall in case of a match between a **s** co-ordinate increment and a **s** co-ordinate decrement. The bars along the axes illustrate where colour impressions should change from blue to yellow assuming either "absolute" coding (relative to Illuminant C) or contrast coding (relative to the surround).

appear less bluish than the blue surround, cannot be reproduced by any possible setting for the patch presented in the blue surround. It is, in other words, not possible to realise blue colour impressions in the blue surround which are less blue than the surround itself: As soon as one has a perceptible **s** co-ordinate decrement in the blue surround, the colour impression of the patch splits into two components having complementary hues: a yellowish contrast component, and a background component of the same colour as the blue surround (Ekroll et al., 2002). Since a true match between the 'pure' blue colour impressions in the neutral surround and the 'yellowish' blue colour impressions in the blue surround is impossible, the subjects can at best try to minimise the differences in the perceived color of the central patches. Depending on which aspect of the colour impression is regarded most important, one can distinguish different strategies.

One strategy ('A') would be to avoid settings for the adjustable patch evoking a colour impression containing a component complementary to a colour component in the fixed patch. This can be achieved by avoiding **s** co-ordinate decrements in the blue surround. However, this strategy has the unfortunate consequence that the patch in the blue surround now appears too blue, a discrepancy which is the more evident and disturbing the more saturated the blue surround is. An alternative strat-

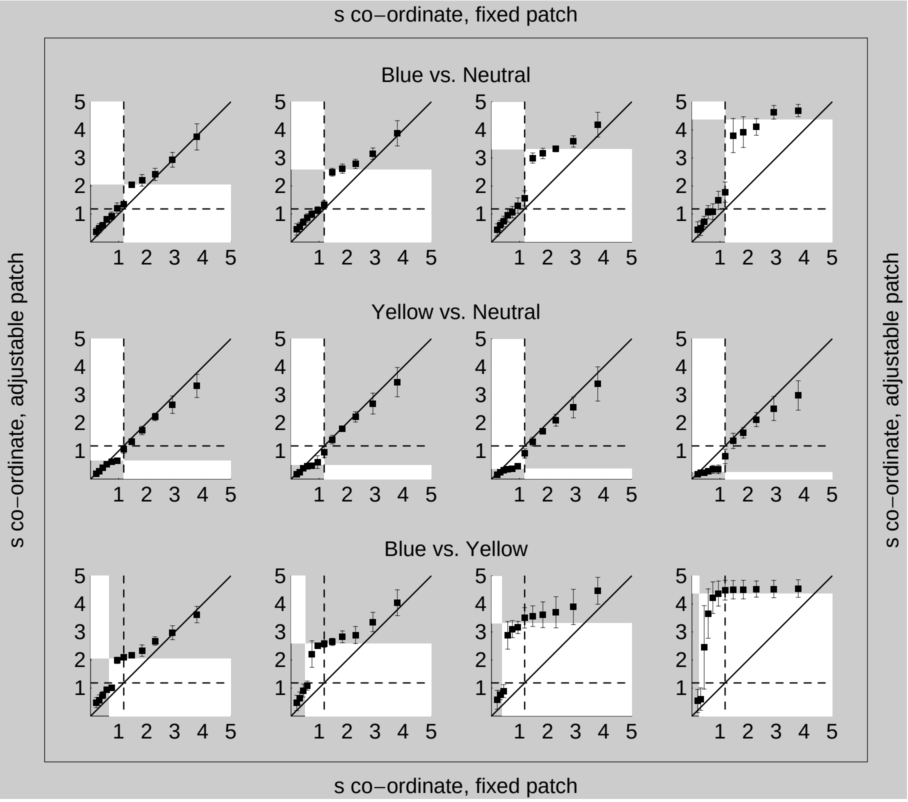

Fig. 6. Results from experiment 1a. Each data point represents the mean of 9 settings (3 repetitions for each of the 3 subjects). Error bars represents one standard deviation in each direction. See fig 5 for further explanations.

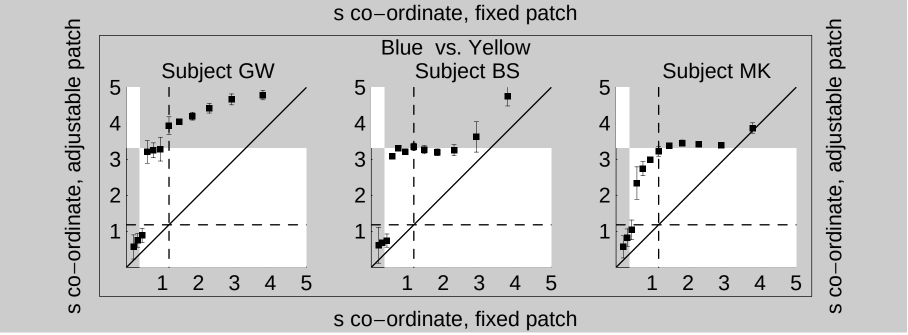

Fig. 7. Individual plots for the surround pair $(B3, Y3)$ for the observers GW (left), BS (middle) and MK (right). Each data point is based on 3 individual settings. See caption of figure 6 for further explanations.

egy (‘B’) would be to accept complementary colour impressions in the two central patches, in order to avoid the differences in blueness which would result under strategy A.

Consistent with this reasoning, there were marked inter-observer differences evident in the data which may be attributed to different strategies. In figure 7 individual plots for one of the surround pairs differing in the **s** co-ordinate are shown. Ob-

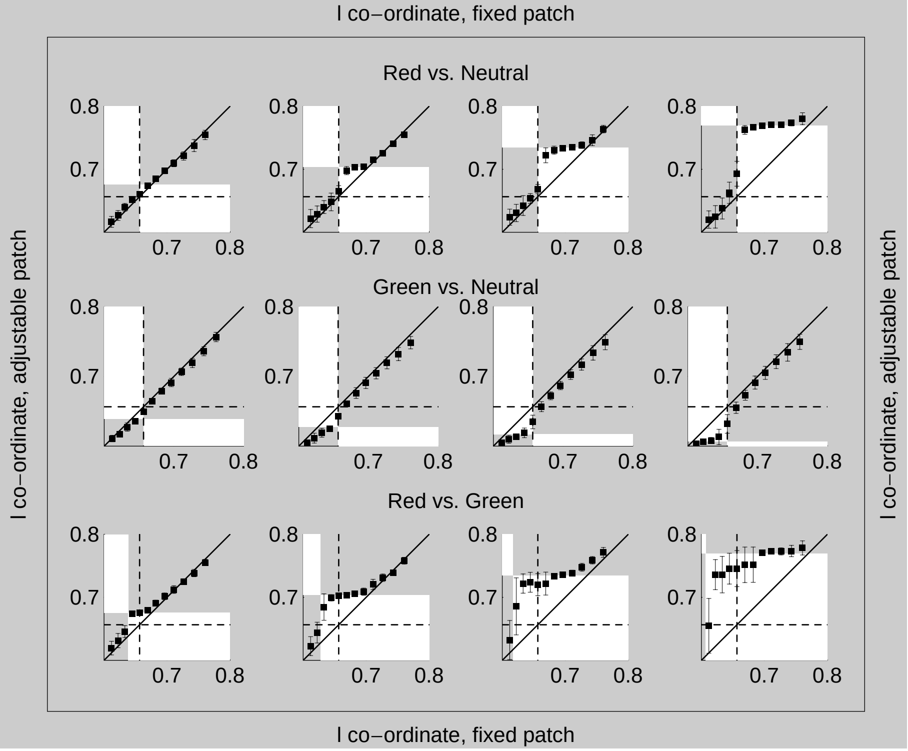

Fig. 8. Results from experiment 1b. The plots show the results for the **l** co-ordinate. The caption of fig. 6 applies analogously by substituting '**s** co-ordinate' by '**l** co-ordinate'.

servers GW and BS almost always avoided increment-decrement matches, whereas observer MK sometimes did not. These data suggest that when confronted with the dilemma outlined above, our subjects made their settings according to different strategies: Observers GW and BS seem to prefer strategy A, whereas observer MK seems to switch from strategy A to strategy B when the perceived differences in blueness of central patches would get very large if one were to stick to strategy A. All of the abovementioned patterns in the data for surrounds differing in the **s** co-ordinate are also evident in the data for the surrounds differing in the **l** co-ordinate. Figure 8 shows the pooled data for these surround pairs, and figure 9 shows individual plots for one of the surround pairs demonstrating analogous inter-observer differences.

The data of experiment 1 show a rather complex pattern of results for each surround pair. However, the plots for all of the surround pairs share a characteristic 'step' which is associated with subjective matching problems and a general trend towards avoiding increment-decrement matches. Visual inspection of the plots in figures 6 and 8 suggests that the subset of data points which do not graze the border of the white 'increment-decrement' rectangles represent smaller induction effects. Furthermore, this subset of data points can in many cases be fairly well described by a line through the origin, which would be consistent with a simple von Kries mechanism. This idea is illustrated by the exemplary plot in figure 10. The open symbols represent data points grazing the white increment-decrement border rectangle. The

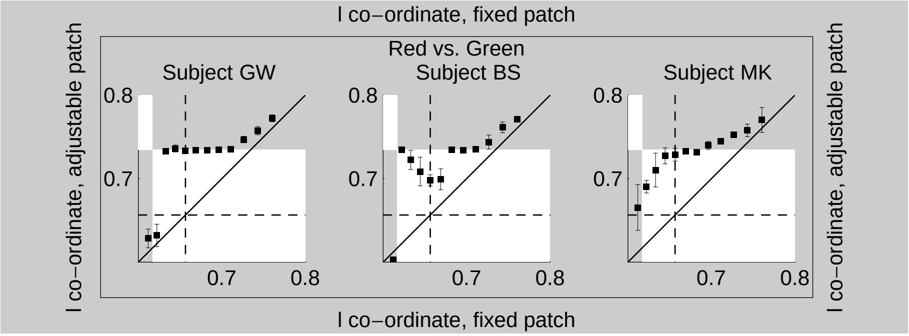

Fig. 9. Individual plots for the surround pair $(R3, G3)$ for the observers GW (left), BS (middle) and MK (right). Each data point is based on 3 individual settings. See caption of figure 8 for further explanations.

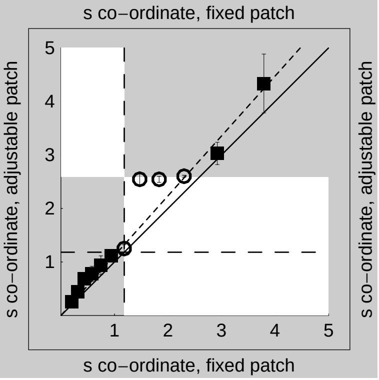

Fig. 10. If those matches which graze the border of the white rectangle representing increment-decrement matches (open symbols) are disregarded, the remaining data points (filled symbols) can be well accounted for by simple von Kries scaling (dashed line). Data for surround pair (C, B_2), observer BS.

rest of the data points (filled symbols) are well fitted by a straight (dashed) line through the origin, which is consistent with von Kries adaptation. Based on the phenomenological and quantitative differences between these two subsets of the data we surmised that different perceptual mechanisms might be responsible for different subsets of the matching data.

2.2 *Experiment 2: Uniform vs variegated surrounds*

The results of experiment 1, as well as previous observations (Smith and Pokorny, 1996; Miyahara et al., 2001), show that the *quantitative* pattern of colour appearance changes evoked by centre-surround stimuli with uniform surrounds is complex. Furthermore, phenomenological observations also indicate that the *qualitative* nature of these colour appearance changes is more complex than one would expect merely on the basis of sensitivity regulation and opponent recoding (Katz, 1911; Gelb, 1929; Evans, 1964; Mausfeld and Niederée, 1993; Niederée, 1998; Whittle, 2003). One aspect of this complexity is that dual colour impressions reminiscent of perceptual transparency may occur. This is particularly obvious at low contrasts between centre and surround (Masin and Idone, 1981; Mausfeld, 1998; Ekroll et al., 2002).

These observations suggest that stimuli with uniform surrounds, which are indeed very simple in terms of a *physical description*, are far from simple in terms of the *internal semantics* of the visual system (Mausfeld, 2003). Considering that—as noted by Evans (1974, p. 210)—spatially uniform surfaces come “close to being contrary to the laws of nature”, this is not entirely unexpected. Indeed, natural scenes seldom give rise to uniform retinal stimulation. One rare exception, however, is the case of dense fog. Hence one may surmise that an extended uniform stimulus may serve as a fairly reliable cue for fog, which is a translucent medium. Indeed, a low variance of colour codes in the stimulus has been proposed by Brown and MacLeod (1997) as a cue for the presence of haze or fog. Since a uniform stimulus may be regarded as the limiting case of low variance, one could surmise that it also gives rise to this interpretation.

If it is really the low variance that triggers an interpretation in terms of fog or haze, then, conversely, a high variance surround should make such an interpretation improbable, and any influence that may result from such an interpretation would be missing. Hence, by comparing the induction effects appearing in uniform surrounds with those appearing in variegated surrounds of high variance it should be possible to isolate the ‘transparency effect’, provided that both types of stimuli are comparable with respect to other possible mechanisms. Seurat-type stimuli (see figure 11), previously investigated in a number of studies (Andres, 1997; Golz and MacLeod, 2002; Mausfeld and Andres, 2002; Webster, Malkoc, Bilson, and Webster, 2002), appear to be well-suited as such a ‘base-line stimulus’: For any uniform surround, a high-variance Seurat surround can be found which is functionally equivalent with respect to visual mechanisms which adapt to the spatial mean of the distribution of cone excitations.

In accordance with these deliberations we decided to compare the induction effects appearing in uniform surrounds with those appearing in corresponding high-variance Seurat surrounds having the same spatial average of cone-excitations.

Methods and stimuli Display apparatus and calibration technique were the same as in experiment 1. The CIE 1931 2° XYZ measurements made with a colourimeter were however converted to the presumably more realistic cone excitation values based on the Stockman-MacLeod-Johnson (1993) 2° fundamentals according to a procedure recently proposed by Golz and MacLeod (2003). Specifically, our XYZ measurements were multiplied with the matrix

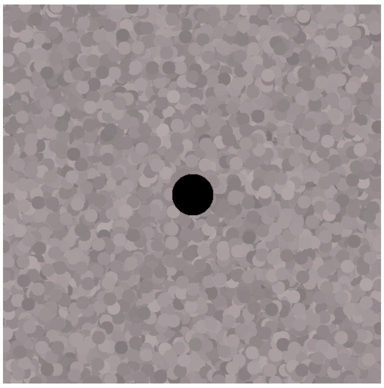

Fig. 11. An achromatic Seurat surround (Andres, 1997; Mausfeld, 1998; Mausfeld and Andres, 2002). The figure represents the geometry of the actual surrounds used in our experiments correctly, but the Seurats actually employed in our experiments were isoluminant with purely chromatic variance.

$$M := \begin{bmatrix} 0.18772 & 0.60445 & -0.02517 \\ -0.14014 & 0.43056 & 0.03773 \\ 0.02017 & -0.04189 & 1.08472 \end{bmatrix}$$

in order to obtain LMS cone excitation values. The MacLeod-Boynton (1979) chromaticity co-ordinates given in this section are based on these values, i.e. $\mathbf{l} := L/(L+M)$ and $\mathbf{s} := S/(L+M)$. Luminance was defined as $L+M$. Again, the **s** co-ordinate is scaled to be 1 for equal energy white.

The subjects viewed two circular patches (subtending $1.4°$ visual angle), each centred in the middle of a square surround ($9.8°$). The centre-to-centre distance between the two centre-surround stimuli was $11.7°$. The surrounds were either uniform or variegated (Seurats); only surrounds of the same type were used together in a given stimulus presentation. All surfaces except the dark general background were equiluminant at $L+M = 10.97$.[4] The luminance of the test infield was also restricted to $L+M = 10.97$, but the chromaticity could be varied freely within the gamut of the monitor (see fig. 12) by using the arrow keys of a keyboard. For the two surrounds and the fixed patch we used combinations of chromaticites which were all located on the same cardinal axis (Krauskopf et al., 1982). Since our main objective in this experiment was to compare the effects of uniform and variegated surrounds, we only used chromaticites from the ’blue-yellow’ cardinal axis (with a constant **l** co-ordinate at 0.692) for two surrounds and the fixed patch, thus keeping the experimental effort within reasonable bounds.

The MacLeod-Boynton chromaticities of the two uniform surrounds employed were $(0.692, 3.203)$ and $(0.692, 1.149)$, which appeared approximately violet and white, respectively. In order to avoid cumbersome language, violet and its complementary,

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[4] For CIE-illuminant C this value of $L+M$ corresponds to a luminance of 10 cd/m^2.

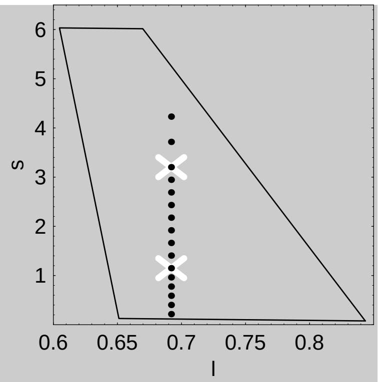

Fig. 12. Chromaticites used in experiment 2 for the two uniform surrounds (white X's) and the fixed patch (black dots), plotted in the MacLeod-Boynton chromaticity diagram. The Seurat surrounds had the same *mean* chromaticities as the corresponding uniform surrounds.

a yellowish-green, will henceforth be referred to as ‘blue’ and ’yellow’, respectively. To each of the uniform surrounds, a corresponding variegated surround was constructed which had the same spatial average of MacLeod-Boynton co-ordinates. For both variegated surrounds, the variance of the **l**, **s** and luminance co-ordinates were 0.000484, 0.256036 and 0 respectively (with zero covariance between **l** and **s**). Since parts of the surround having a common contour with the central patch may potentially be more important in determining its perceived colour than more remote parts of the surround, we ensured that the spatial mean and variance of chromaticity co-ordinates was equal for several narrow ring-shaped regions around the central patch.

The chromaticities of the 16 fixed patches are plotted together with the chromaticites of the surrounds in figure 12. All had the same **l** co-ordinate as the surrounds, and the **s** co-ordinates ranged from 0.216 to 4.230.

On a standard account it should not matter which member of a given pair of surrounds is chosen for presenting the fixed patch and which of them is used as a surround for the adjustable patch. However, the characteristic ‘step’ evident in the data from experiment 1 suggests that presenting the fixed patch in only one of the surrounds yields an incomplete picture. Hence, for the pair of uniform surrounds employed, both surrounds were used for presenting the fixed patch, yielding a double, complementary data set. Preliminary experiments showed that when a pair of variegated surrounds were used, the data curves were much less complex, so that the use of only one of the surrounds for presenting the fixed patch yielded a sufficiently clear picture.

The 5 subjects were colour normal as assessed by the Ishihara Tests for Colour-Blindness and naïve as to the purposes of the experiments. All of the subjects were instructed to set the chromaticity of the adjustable patch such that it appeared as similar in colour to the fixed patch as possible, and in order to avoid possible misunderstandings, they were also told that if achieving the best possible match should require setting the chromaticity of the adjustable patch equal to that of its surround, they should not hesitate to do so merely because the central patch would then become indistinguishable from the surround.

As mentioned in the discussion of the results of experiment 1, true colour matches are sometimes impossible to make, and in these cases subjects seemingly revert to different strategies (A or B). In order to elucidate this point, two of the subjects (MH and GH) were told that if they experienced problems in establishing a perfect match and were uncertain how to proceed, they should at least satisfy the criterion that the two central patches should not contain traces of complementary colours, i.e. if one patch contained a shade of blue, the other should not contain a shade of yellow, and vice versa. Under the hypothesis that perfect colour matches can be established, this auxiliary instruction should of course not have any effect on the behaviour of the subjects. Based on the results of experiment 1, however, we expected that subjective problems should occur and that when confronted with them, this instruction would make the subjects pursue strategy A.

Results The results for those 3 subjects (AD, OS and SZ) who *did not* receive the auxiliary instruction are plotted in figure 13, those of the 2 subjects (MH and TG) who did, in figure 14 . Each row in the figures represents the data of one subject. In the leftmost panels, the matching data for the pair of variegated surrounds are shown. For each subject, these data were fitted by a line through the origin (dotted line). These fits describe the data rather well, with values of R^2 between 0.94 and 0.97 for the 5 subjects. Furthermore, the individual slopes are rather similar, ranging from 1.21 to 1.26.

The simplicity of these data curves are contrasted by the more complicated data curves obtained with the corresponding pair of uniform surrounds (middle and right hand panels). The filled symbols in the middle panels represent the data obtained when the fixed patch was presented in the ’blue’ surround, and those in the right-hand panels represent the data obtained when it was presented in the ’neutral’ surround. To ease comparison with the data from the variegated surrounds, the dotted regression lines of the left-hand panels are redrawn in these panels. Data points which fall within the white regions in the plots represent a match between a **s** co-ordinate (i.e, S-cone) increment and a **s** co-ordinate decrement. The data for the uniform surrounds (middle and right-hand plots) are in general rather similar to the data for the variegated surrounds (left-hand plot) except that the white increment-decrement regions appear to be avoided, resulting in a ‘step’ in the data curve: the data curves appear to ‘get stuck’ at the left hand (middle panels) and upper (right-hand panels) borders of the (lower) white rectangle. This feature of the data is most pronounced in the data of the subjects who received the auxiliary instruction (figure 14). In the right hand panels of figure 14, none of the data points are within the increment-decrement region, and in the middle panels only one data point for each observer is clearly within, namely the data point immediately below the horizonal border between the two white rectangles. A possible reason for this exception is that the contrast between the fixed patch and its surround was so low that the observers occasionally did not recognize the central patch at all, and instead perceived a uniform field of the same colour as the surround. In these cases, one would expect a setting closer to the diagonal in the plots. The high variances of the data points in question support this interpretation.

The ‘step’, i.e. the vertical and horizontal portion of the data curves obtained with uniform surrounds shown in figures 13 and 14, means that several different chromaticities of the fixed patch were matched by the same chromaticity of the adjustable patch. This finding is *a priori* open to two interpretations. Either the asymmetric matches made by the subjects do not fulfill the requirements of an equivalence relation, which means that they cannot be taken to reflect perceptual identity, i.e. they cannot be true matches, or, alternatively, the physically different standard chromaticities which were matched to the same test chromaticity were perceptually indistinguishable. [5]

The open symbols in the middle and right hand plots of figure 13 and 14 represent *symmetric* matches with either the blue uniform surround used on both sides (middle panels) or the neutral uniform surround used on both sides (right panel). Since a pair of identical surrounds is used in both cases these matches should be colourimetric and hence fall on the diagonal of the plots, which is indeed the case. For our purposes, the interesting feature of these data is however not their veridicality, but their precision. The fact that these data points are well-ordered and monotonic indicates that the different fixed patches are readily discriminable. Since the set of chromaticities used for the fixed patch in these symmetric matches include those that were matched to the same chromaticity of the adjustable patch when the other uniform surround was used, we can conclude that the original asymmetric matches do not fulfill the requirements of an equivalence relation, and thus cannot, in general, be considered true colour matches.

Subjective matching problems in our data related to colour scission phenomena In order to understand the abovementioned quantitative findings it is necessary to consider the complex phenomenology of the colour impressions evoked in stimuli with uniform surrounds used in our experiments. First we will describe the colour impressions which occur in a single centre-surround stimulus. We will

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[5] Let $(a, A) \equiv (b, B)$ denote the empirical statement that the central patch a in the surround A is matched by the central patch b in the surround B. Formally, our empirical finding means that there are two physically different central patches a and a' such that $(a, A) \equiv (b, B)$ and $(a', A) \equiv (b, B)$. If $\equiv$ is an equivalence relation, it follows that $(a, A) \equiv (a', A)$. Obviously, if this is not the case, $\equiv$ is not an equivalence relation and hence cannot be taken to represent perceptual identity.

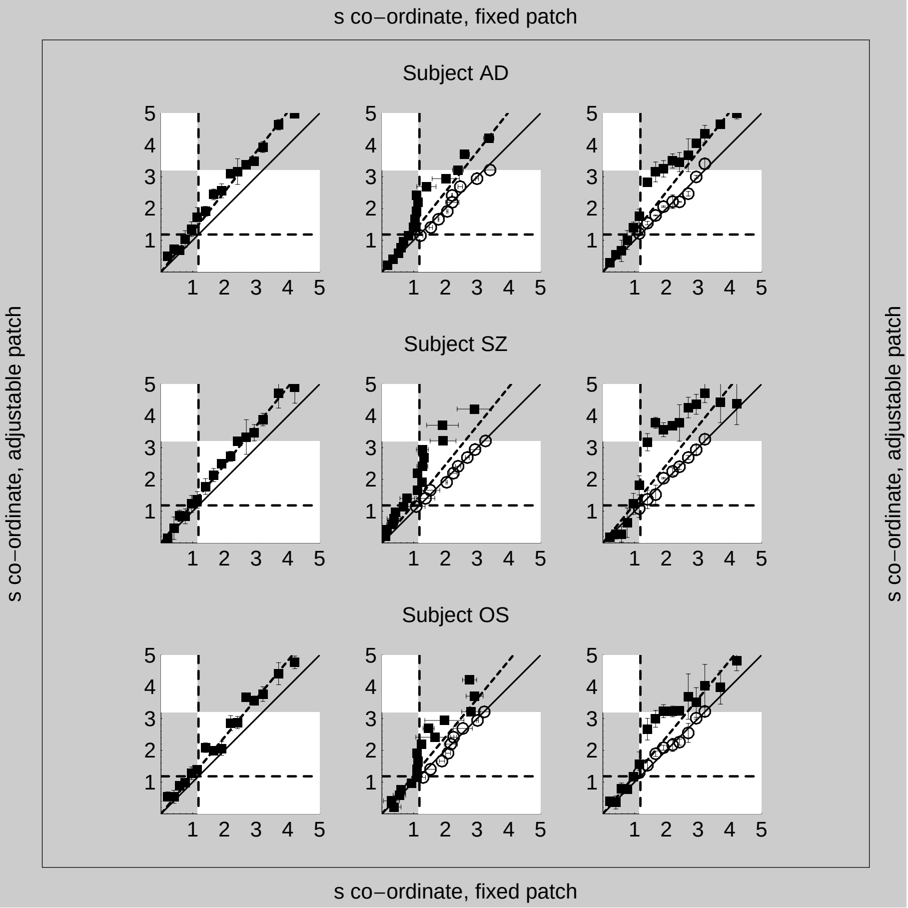

Fig. 13. Results from experiment 2 for the subjects AD (top), SZ (middle) and OS (bottom). In the left and right panel the horizontal axis represents the **s** co-ordinate of the fixed patch and the vertical axis the **s** co-ordinate of the settings for the adjustable patch. In the middle panel the axes are interchanged. Each plot point represents the mean based on three individual settings, error bars represent one standard deviation in each direction. As in figure 6, the point where the white rectangles meet represents the **s** co-ordinates of the surrounds and the white rectangles the region where increment-decrement matches would be located. Left panels: Results obtained with *variegated* surrounds are well fitted by von Kries scaling (dashed line). Middle and right-hand panels: Results obtained with corresponding *uniform* surrounds show a characteristic 'step' which is associated with the avoidance of the white region which represents increment-decrement matches. Outside of this region, the matches fall close to the dotted line representing the von Kries scaling obtained with the variegated surrounds. The middle panels represents the data obtained when the fixed patch was presented in the neutral surround, the right-hand panel represents the data obtained when it was presented in the blue surround. Open symbols represent *symmetric* matches with a pair of identical neutral surrounds (middle panels) or with a pair of identical blue surrounds (right-hand panels).

then consider how these observations can be related to matching problems which are sometimes experienced when trying to establish an asymmetric match between two central patches embedded in *different* uniform surrounds.

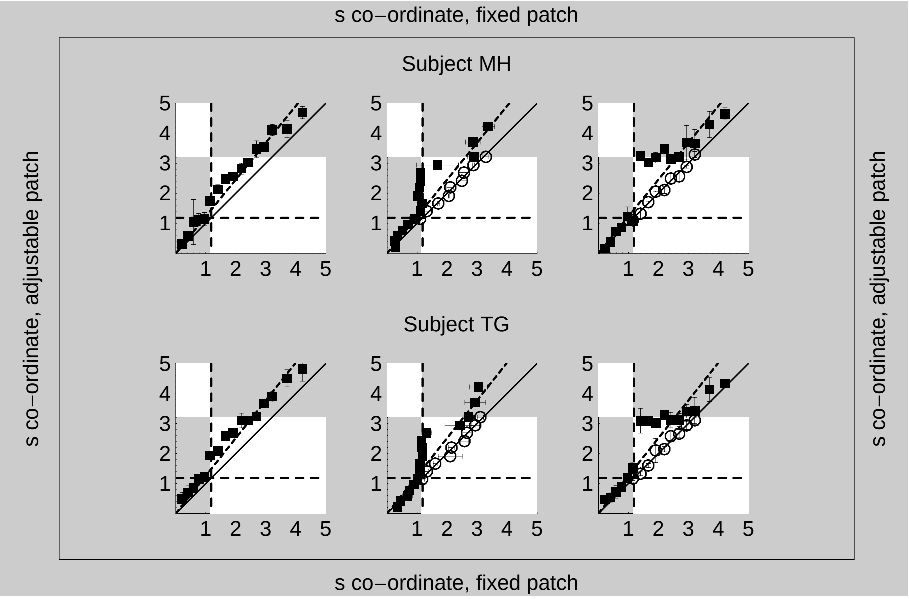

Fig. 14. Results from experiment 2 for the subjects MH (top) and TG (bottom). See caption of figure 13 for further explanations.

As reported in Ekroll et al. (2002), equiluminant centre-surround stimuli with low chromatic contrast between centre and surround evoke impressions of transparency in which two simultaneously perceived colour components can be distinguished, namely a contrast component and background component. The background component always appears in the same colour as the surround, whereas the perceived colour of the contrast component depends on the direction of the chromatic contrast between centre and surround.

Consider a neutral uniform surround. Which colour impressions can then be evoked in central patches differing from this surround only in the **s** co-ordinate? Not surprisingly, **s** co-ordinate decrements appear yellowish, whereas increments appear bluish. The larger the contrast the more ‘colourful’ the patches appear. In the case of isolated light spots this variation in ‘colourfulness’ would be referred to as a change in saturation, i.e. as a variation of the similarity to an achromatic colour impression. In our case this description is inappropriate. The reason for this is that as the chromaticity of the central patch approaches that of the neutral surround, the colour impression of the patch splits into two components or ‘layers’, whereby the entire achromatic content of the central patch seems to be ‘absorbed’ by the background component. The remaining contrast component, which is the more prominent part of the percept, is therefore devoid of any greyness. Accordingly, one may say that the central patch, as it becomes more similar to the surround, becomes less colourful or less pronounced but *not less saturated*. This means that the contrast component cannot be made arbitrarily similar to white.

Let us now consider the case of a blue uniform surround. Just as in the case of the neutral surround, **s** co-ordinate decrements appear yellowish and increments appear blueish. However, there are two important differences. First, when contrast is low and the colour splits into two components, the background component is now blue instead of white. Second, the set of incremental and decremental colour impressions demonstrate a remarkable difference. In the case of low contrast **s** co-ordinate decrements the entire *blueness* of the central patch is 'absorbed' by the background component. The remaining contrast component appears yellowish and can, at low contrast, appear much more whitish, i.e. less saturated, than any yellow colour impression that can be produced in a neutral surround. In the case of **s** co-ordinate increments, the situation is radically different. In this case one perceives a bluish contrast component which however small the increment is, appears at least as colourful as the surround and therefore more colourful than many of the low–contrast blue impressions which can be produced in the neutral surround. Analogous statements can be made with respect to any arbitrarily coloured uniform surround.

As is evident from the above description, there is always a set of colour impressions that can be evoked in a neutral uniform surround but not in a coloured uniform surround and vice versa. In fact, as is easily deduced, this statement holds for any pair of surrounds of different hue. From these phenomenological observations alone it is clear that true asymmetric colour matches may sometimes be impossible to make, and they also account for the most prominent feature of our data curves, namely the 'step'. The horizontal part of the step simply means that low contrast **s** co-ordinate increments presented in the neutral surround, which are perceived as blues which are less colourful than the blue surround, are matched to the colour of the blue surround itself in lack of a better alternative, since blues less colourful than the surround cannot be evoked. The vertical part of the step means that several **s** co-ordinate decrements presented in the blue surround, which appear as various 'desaturated yellows' veiled with a weak bluish background component, are matched to the colour of the neutral surround in lack of a better alternative, since any yellow colour impression that can be evoked in the neutral surround is more colourful.

We shall refer to these subjective matching problems, which lead to the 'step' in the data curve, as the problem of 'missing colours'. Apart from this kind of problem a second, less severe kind of subjective discontent was observed in cases in which the data point was outside but close to the step. In these cases one of the patches had a low contrast to its surround, and was therefore perceived as transparent, whereas the other patch, with a higher contrast, generally did not. This kind of discontent, however, does not, like the 'missing colours' phenomenon, correspond to any easily identifiable feature of the data curves. Thus, altogether a fairly large part of the matches involved subjective discontent. In fact, the only matches which were subjectively satisfying were those corresponding to points well outside the step in the data curves.

Our observations may be summarized as follows: (1) An achromatic uniform surround prohibits, for all hues, the perception of central patch colours of arbitrarily low ‘colourfulness’, with the singular exception of the case when the central patch is indistinguishable from the surround, where it obviously has zero saturation. (2) Compared to this situation, using a uniform surround of a given hue prohibits the perception of even more colours of the same hue in the central patch but also allows the perception of more colours of the complementary hue in the central patch.

3 General Discussion

Based on the results of the present experiments, we may draw the following conclusions, which we will discuss in more detail below:

(1) There are fundamental quantitative and qualitative differences between the colour changes induced by uniform surrounds and those induced by variegated surrounds.
(2) In the case of **uniform** surrounds, we conclude that:
  - At low chromatic contrast between centre and surround, transparency-like impressions are evoked, involving a background and a contrast component.
  - For any pair of different uniform surrounds there is a specific set of colour impressions that cannot be realized in *both* surrounds.
  - If one surround induces a colour impression that cannot be realized in the second surround, a true asymmetric match is impossible. In this case, matches made by subjects are merely a best choice among poor alternatives.
  - If the quantitative data obtained in these problematic cases are misinterpreted as true matches, they may erroneously be thought to indicate a particularly large induction effect.
(3) In the case of **variegated** surrounds the abovementioned matching problems are absent or at least dramatically reduced. This is reflected in a much simpler data curve.
(4) A difference between the empirical matching curves for uniform and corresponding variegated surrounds only occurs in cases where a true match is impossible in uniform surrounds. The data curves are almost identical in the other cases, suggesting a basic common mechanism and a second mechanism which is particular to uniform surrounds.

The most important conclusion which can be drawn based on our findings is that uniform surrounds evoke induction effects of a very peculiar nature, which are, contrary to widespread and seemingly innocuous assumptions, *not representative* of colour induction effects at large. This observation is of central importance, given the widespread use of uniform surrounds in studies of colour vision.

Before we discuss the implications of this observation for the interpretation of previous findings, we will present a framework which systematises the colour changes induced by uniform surrounds. This framework allows to predict which colour matches should be possible and which not, and thus yields a principled account of the matching data.

3.1 The nature of simultaneous contrast in uniform surrounds

In the results and discussion section of experiment 2, we described sources of subjective discontent with asymmetric matches. The ‘missing colours’ problem is experienced as particularly disturbing, and suggests that we need to develop new intuitions about the nature of the colour changes induced by a uniform surround in order to account for the empirical findings. Taking the ‘missing colours’ phenomena at face value, we would like the reader to consider a simple descriptive model which, although it certainly does not capture the full complexity of the phenomenon under investigation, makes it comparatively easy to understand the major features of our findings and captures crucial aspects of the phenomena under consideration. As a simplification we shall use the term ‘saturation’ throughout to describe how colours of constant hue and luminance may vary if presented in a uniform equiluminant surround. It should be kept in mind, though, that this involves using the term in a simplistic manner. To be specific, the variations in ‘saturation’ we refer to often only involve a mere variation in ’colourfulness’ without any variation in grey content. Furthermore, in cases where a transparency-like impression is evoked, we apply the term only to the contrast component, which is the dominant part of the colour impression and can therefore be assumed to be the major determinant of the subjects’ settings.

3.1.1 Saturation scale truncation and extension

Consider—in the equiluminance plane—a line of chromaticities through equal energy white, ranging from, say, blue to yellow. We then have a scale of colour impressions which is divided into a saturation scale of yellows and a saturation scale of blues at the chromaticity of the neutral point. In a graphic representation of the colour impressions on this line, we may think of each of these two half-axes as a wedge, whereby the thickness of this wedge represents the saturation of the colour impression represented. Thus we obtain a blue wedge and a yellow wedge which abut at the neutral point (see figure 15 left middle panel). It is obvious from this representation that the line of chromaticities in question allows for colour impressions of arbitrarily low saturation for both hues, in accordance with classical assumptions. In our descriptive model, however, we depart from this assumption, and posit that it is not possible to produce colour impressions of arbitrarily low saturation when the patch is embedded in an equiluminant uniform neutral surround. This feature of our descriptive model, which we shall refer to as ‘pretruncation’, is accommodated in the graphic representation by using wedges which have their tips

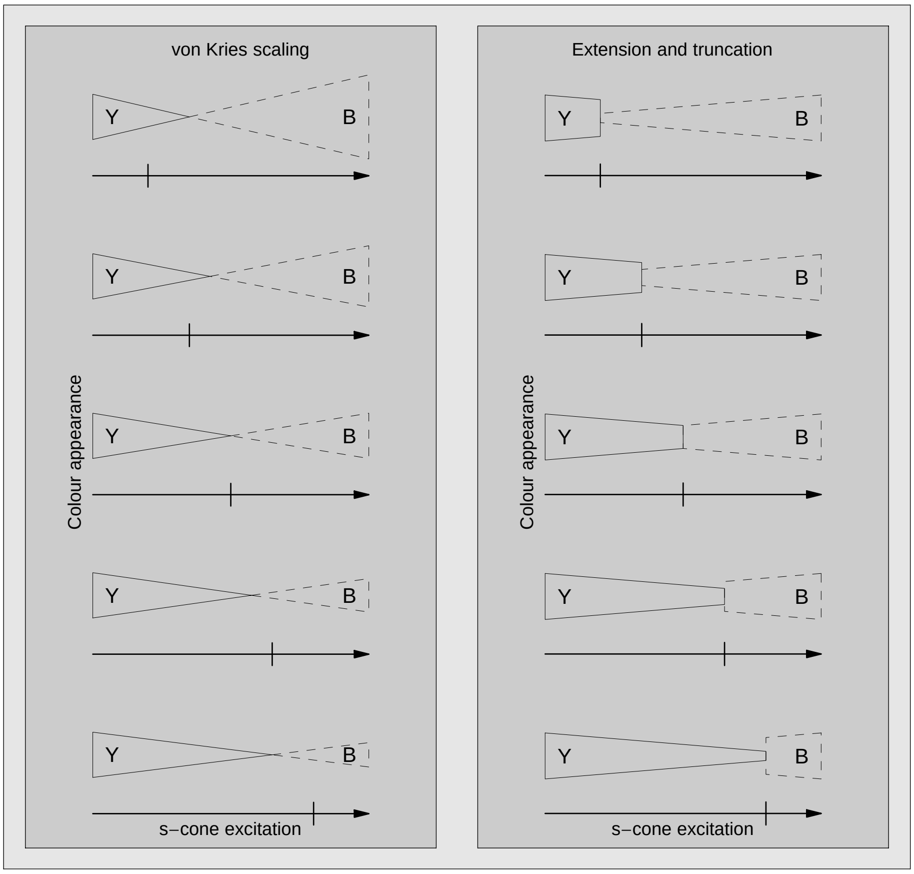

Fig. 15. Classical (left) vs. truncation-extension (right) view of how colour impressions should vary along a line from yellow to blue in chromaticity space for patches embedded in surrounds of different colours. In each sub-panel a pair of wedges represents the perceived colours of the opponent hues blue and yellow. The thicker the wedge the more saturated the colour impression. Below each pair of wedges a scale representing S cone excitation is shown with a vertical tick mark at the location of the surround. From top to bottom the illustrations refer to yellow, neutral and blue surrounds. A crucial difference between the classical and the truncation-extension view is that, in the latter case, the saturation never approaches zero.

cut off (see figure 15, right middle panel). We further posit that when a coloured surround is used, the wedges representing the colour impressions for the central patches remain essentially *unchanged*. The graphic representation is merely modified in the following way: the wedge which represents colours of the same hue as the surround is truncated at the location of the surround colour, and the wedge representing colours of the complementary colour impression is correspondingly extended (see figure 15, right panel). This feature of the descriptive model will be referred to as saturation scale extension and truncation.

The main assumptions of our descriptive model, namely ‘pretruncation’ for the neutral surround, and ‘saturation scale extension and trunctation’ for coloured surrounds are motivated by, and correspond closely to, the observations we referred to as ‘missing colours’ in the results and discussion section of experiment 2.

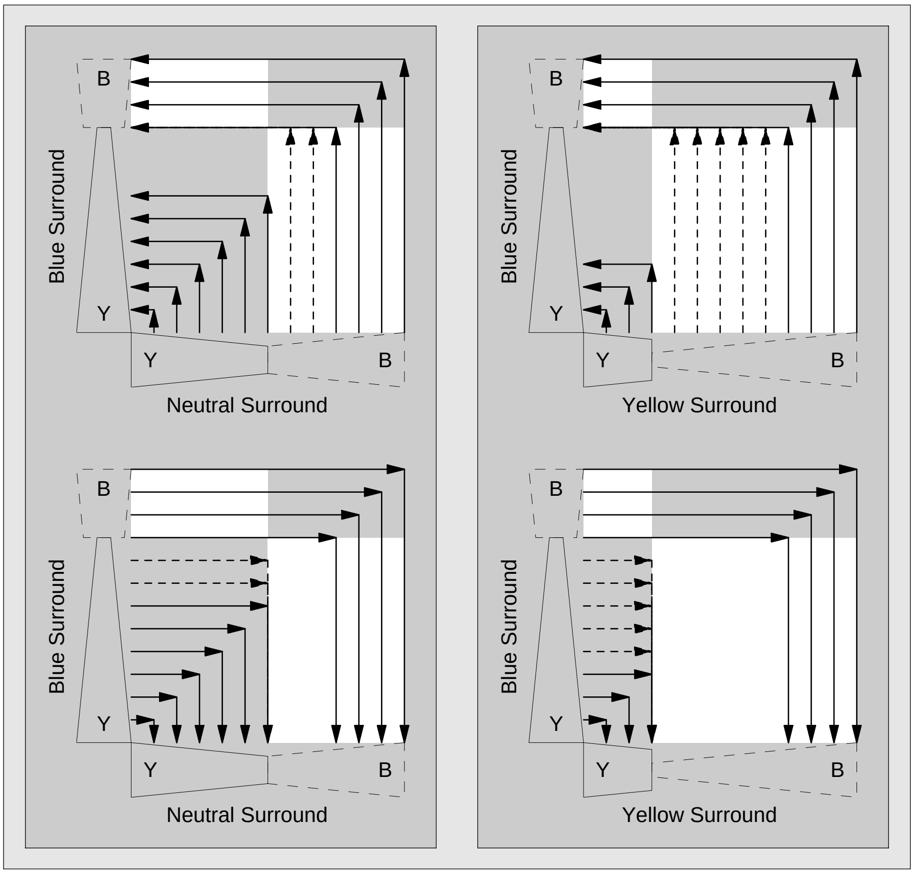

Fig. 16. Top left panel: The matches which may be expected based on extension and truncation when fixed patches are presented in neutral surrounds, and the settings are made in a blue surround. Lower left panel: Expected matches when the fixed patches are presented in the blue surround. Right-hand panels: Analogous expectations derived for matches made with a yellow and a blue surround.

3.1.2 Features of the data captured by the notions of extension and truncation

From our descriptive model we may indeed derive expected data curves for asymmetric matches that closely resemble the actual data. This is illustrated for asymmetric matches between a neutral and a blue surround in the upper left panel of figure 16. In this case it is assumed that the fixed patches are presented in the neutral surround. As in our data plots, the axes in these figures represent the chromaticity of the fixed and the adjustable patch, respectively. Along the horizontal axis a schematic representation of expected perceived colour for these chromaticities is drawn, given that the central patch is presented in a neutral surround. Along the vertical axis a corresponding representation for expected perceived colour for central patches presented in a blue surround is shown. Any point in this ‘plot’ which projects to locations on the two axes representing the same colour impression, as indicated by the schematic saturation scales drawn along them, represents an expected match. The tips of the *solid* vertical arrows represent such expected matches. It will be noted, however, that the scale drawn at the horizontal axis contains blues of low saturation which have no *identical* counterpart in the scale drawn at the vertical axis. For these colours a true match should not be possible. The tips of the *dotted* vertical arrows drawn in the figure represent the best possible settings that can be expected under the assumption that any two colour impressions which have the same hue are more similar than two complementary colour impressions. [6] If the same pair of surrounds is used, but the fixed patch is presented in the blue surround (figure 16, lower left panel), an analogous construction can be made. In this case we observe that the scale drawn at the vertical axis contains yellows of low saturation which have no identical counterpart in the scale drawn at the horizontal axis. The tips of the horizontal arrows represent the expected matches, whereby those arrows which are drawn as dotted lines again represent imperfect, but best possible matches. In the right-hand panels of figure 16 analogous expected matching curves have been derived for a blue and a yellow surround, exhibiting the same general features.

It should now be clear that the somewhat unorthodox notions of saturation scale truncation and extension, which are based on the observation that some low-saturation colour impressions do not appear in certain surrounds, allow for an elegant and parsimonious description of a very prominent feature of our results, namely the ‘step’ in the data curves which arises because several different chromaticities of the fixed patch are matched to the same chromaticity of the adjustable patch. An obvious but unimportant and easily remediable shortcoming of this description is that it predicts colourimetric matches outside the region of the ‘step’: A closer correspondence to this subset of the actual data can be achieved by including a simple von Kries scaling operation prior to truncation and extension. In the above we refrained from doing so merely for reasons of expositatory simplicity. Furthermore, the amount of von Kries scaling necessary to account for the actual data points in our plots would be rather small.

3.2 Relation to previous work

Our findings, which inspired the notion of saturation scale extension and truncation, have interesting implications for a number of current research issues, which we will consider in turn.

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[6] As discussed in the results section of experiment 1, subjects may pursue two different strategies (A or B) when confronted with this lack of a true match: either ensure that hue is correct, or that saturation differences are minimised. The derived expectations are based on the assumption that strategy A is pursued.

3.2.1 Do grey settings yield representative measurements of colour induction?

Many studies on colour induction rely on achromatic settings or equilibrium hue settings to measure the strength of the effect (Walraven, 1976; Werner and Walraven, 1982; Nerger et al., 1993; Chichilnisky and Wandell, 1996, 1999; Ekroll et al., 2002). Although achromatic settings have the advantage of making it possible to study colour induction without an external reference stimulus, which may distort the settings, this method has the limitation that only the effect on central patches which look achromatic can be directly measured. It is tempting to regard these measurements as representative of colour induction effects in general. Clearly, however, this would only be possible if the patches which appear achromatic are subject to the same general principles of colour induction as patches of other colors (Speigle and Brainard, 1999). How realistic is this in the light of the present findings?

The notion of saturation scale truncation and extension, which captures our findings with uniform surrounds very well, implies that measuring the transition point between complementary hues should, as a result, yield the point corresponding to the corner of the 'step' in the data curve. It is clear that the transition point will never actually be chosen as a grey setting, since it corresponds to the chromaticity of the surround. Nevertheless, available data suggest that actual grey settings fall rather close to the chromaticity of the surround (Werner and Walraven, 1982; Chichilnisky and Wandell, 1999; Ekroll et al., 2002), which means that they are located well within the region of the 'step'. As can be seen in the schematic representation in fig. 16 as well as in our data plots, interpreting any point within the 'step' as a representative measurement, would lead to an overestimation of the overall induction effect. This overestimation is at its largest and most misleading for points close to the transition point.

Thus, from our findings we may conclude that, when uniform equiluminant surrounds are used, grey settings can be expected to overestimate the general induction effect. We would like to emphasize that this reasoning only applies to stimuli which evoke saturation scale extension and truncation. That the situation may be different with other kinds of stimuli is illustrated by the results of a study by Speigle and Brainard (1999). They used more naturalistic stimuli and obtained asymmetric matching data which could be well described by simple von Kries scaling. This suggests that saturation scale extension and truncation was not evoked by their stimuli. Thus the fact that their asymmetric matching data could be predicted from achromatic settings is not at odds with the present conclusions.

3.2.2 How basic is contrast-coding of colour?

Traditionally one has sought to understand colour induction in terms of photoreceptor sensitivity regulation, i.e. von Kries scaling. According to more modern theoretical developments, perhaps most forcefully advocated in the works of Whittle (1994, 2003) and Walraven (1976), the phenomenon of simultaneous contrast reveals a more fundamental property of basic colour coding, namely that the colour of a patch is computed relative to the colour of the surround.

Although the main psychophysical evidence for contrast coding stems from studies using uniform surrounds (Whittle and Challands, 1969; Walraven, 1976; Werner and Walraven, 1982; Whittle, 1992; Mausfeld and Niederée, 1993; Nerger et al., 1993; Chichilnisky and Wandell, 1995, 1996; Niederée and Mausfeld, 1997; Shepherd, 1997, 1999; Ekroll et al., 2002; Richter, 2002), it has been proposed that contrast coding is a general and fundamental property of the visual system. Whittle (2003) for instance argues that "contrast colors [...] reflect a stage of early visual processing through which all color information passes" (p. 116). Despite the compelling psychophysical evidence for contrast coding, the colour science community at large has been somewhat reluctant to give up the traditional idea of absolute colour coding (e.g. Irtel, 2003). As discussed by Whittle (2003), this reluctance "is not without reason, for the idea that colour is always perceived relative to the background is contradicted by the everyday observation that if you move an object against a *variegated* background, it is often hard to see any changes in its colour at all" (p. 116, our emphasis).

Our findings yield an interesting perspective on the role of contrast coding in colour perception. They suggest that the colour induction effects appearing in uniform surrounds are a combination of two distinct effects that may be understood as resulting from "absolute" and "contrast" coding, respectively, namely simple von Kries scaling and saturation scale truncation and extension. The critical observation is that the von Kries effect is common to both uniform and variegated surrounds whereas the presumably contrast-based truncation and extension seems to be specific to low contrast stimuli with uniform surrounds. This suggest that not only contrast coding can be observed in a "pure form" (e.g. Whittle and Challands, 1969; Wuerger, 1996; Shepherd, 1997; Beer and MacLeod, 2001) but also absolute, von Kries coding. It may therefore be premature and potentially misleading to attribute a more fundamental role to contrast coding than to absolute coding. We find it more reasonable to assume that both codings schemes play specific functional roles in visual processing that may be triggered by different stimulus conditions. Such a "dual coding" could for instance be implemented as two parallel channels of colour information (Arend, 1973, p. 391).

3.2.3 Is the notion of functionally equivalent surrounds tenable?

It is often assumed that the colour induction effects appearing in uniform and variegated surrounds are basically of the same nature. A prominent theoretical concept reflecting this general notion is that of *functionally equivalent surrounds*.

Functional equivalence can be defined both on a theoretical level and on a performance level. From a theoretical point of view, the concept of functionally equivalent stimuli is defined with respect to a *particular mechanism*: Two stimuli are functional equivalent whenever the output of this particular mechanism is the same for both stimuli. On the level of psychophysical performance, functional equivalence is understood with respect to a *behavioral criterion*: Two stimuli are regarded as functional equivalent in this sense, if they lead to indistinguishable experimental results. Failures of functional equivalence on the behavioral level can only be taken as an unequivocal indicator of functional equivalence with respect to a specific mechanism if the behavior of the subjects depends exclusively on this mechanism. If, on the other hand, a further mechanism also plays a role, failure of functional equivalence on the behavioral level could result even if functional equivalence with respect of one of the mechanisms holds.

In the colour vision literature, functional equivalence is often discussed with reference to mechanisms of colour constancy. If, for instance, the colour of the illuminant is estimated based on the average colour, all stimuli, variegated or uniform should be functionally equivalent whenever they have the same mean colour code. In order to test the viability of this theoretical concept, it has been translated into the empirical question whether it is possible to find, for any arbitrary surround A, a corresponding uniform surround A' such that A and A' induce the "same colour shifts" (Valberg and Lange-Malecki, 1990), in the sense that *any* conceivable central patch should look the same whether it is embedded in A or A' (Andres, 1997; Brill, 2000). A number of previous studies (e.g. Schirillo and Shevell, 1996; Brown and MacLeod, 1997; Shevell and Wei, 1998; Barnes et al., 1999), suggest that this is not possible. The present findings also speak strongly against the possibility of finding a uniform surround which is functionally equivalent to a given variegated surround in this behavioral sense: The data curves obtained in our asymmetric matching experiment with pairs of variegated surrounds are approximately linear and consistent with simple von Kries scaling. If there exists a pair of corresponding functionally equivalent uniform surrounds, it should be possible to obtain the same simple data curve with this pair of uniform surrounds. This does not appear feasible, however, since all of our data curves obtained with pairs of uniform surrounds demonstrate strong non-linearities.

However, our data questions the assumption that colour induction effects can be ascribed to a single unique mechanism. Instead, the data curves obtained with uniform surrounds seem to be due to two distinct mechanisms, namely one yielding a simple and weak von Kries scaling and another leading to saturation scale extension and truncation. It seems that the former mechanism operates in the same simple manner both in the case of uniform and variegated surrounds, whereas the latter only plays a role in uniform surrounds. These findings suggest that even seemingly simple stimuli may trigger more than one colour coding mechanism. Accordingly, failures of functional equivalence found in previous as well as the present study should be interpreted cautiously; they do not preclude the possibility of functional equivalence with respect to specific contributing mechanisms.

3.2.4 Are gamut expansion and 'pretruncation' related phenomena?

Based on our findings we were led to assume that there is a range of colour impressions of low saturation that cannot be produced in a patch embedded in a uniform neutral surround. We referred to this phenomenon as 'pretruncation'. This assumption implies that when we shift the chromaticity of the central patch slightly away from that of the neutral surround, it should appear rather saturated as soon as it is distinguishable from the surround. Since 'pretruncation' does not occur in variegated surrounds, a higher purity of the central patch should be necessary to obtain the same colour impression if it is embedded in a variegated surround of the same average colour.

In an experiment realising the abovementioned conditions, Brown and MacLeod (1997) obtained results which are in accordance with this prediction. These authors coined the term 'gamut expansion' to describe the observed effect. It appears natural to understand 'gamut expansion' as a re-scaling of the contrast signal coding the saturation of the central patch. Given this interpretation, 'gamut expansion' and 'pretruncation' make different predictions regarding how the effect changes with increasing purity of the central patch. As illustrated in the left panel of fig. 17, 'gamut expansion' would imply that the matching curve relating the purity of the central patch in the uniform surround to the purity of the central patch which appears equally saturated in the variegated surround is a *continuous* curve through the origin of the co-ordinate system representing zero purity. In contrast, as illustrated in the right panel of fig. 17, 'pretruncation' would predict a discontinuous[7] step in the matching curve at the location of the origin.

Based solely on the data of Brown and MacLeod one cannot discriminate between these two alternative predictions, since only a single purity of the central patch was investigated for each direction in the chromaticity space. However, recent data from a study by Wendt (2003), who investigated several different purities, are in clear favour of the predictions based on 'pretruncation'. Thus, it appears that 'pretruncation' is also supported by independent data gathered in a different theoretical context.

3.2.5 Saturation scale extension and truncation can account for Meyer's effect

An effect related to simultaneous contrast which has received little attention in modern colour science, but was often discussed in the earlier literature is Meyer's

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[7] Since the notion of 'pretruncation' only refers to the contrast component of colour impressions which appear transparent and ignores the background component, this does not imply that the total colour impression is also discontinuous.

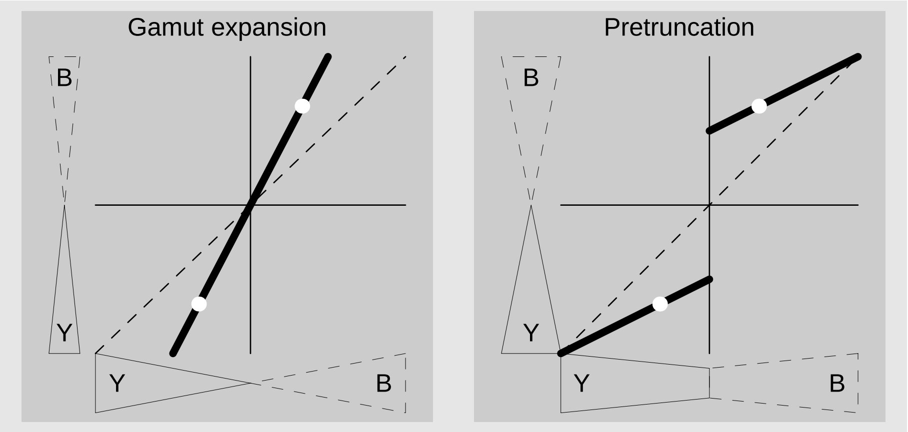

Fig. 17. Predictions based on ‘gamut expansion’ (left) and ‘pretruncation’ (right). The wedges on the horizontal axis represent perceived saturation for central patches with chromaticities from the blue-yellow axis in chromaticity space when presented in a uniform neutral surround. In the case of ‘pretruncation’ the wedges would have their tips cut of (right panel). The wedges on the horizontal axis represent the perceived saturation for the same central patches when embedded in a variegated neutral surround. The different steepness of the horizontal and vertical wedges in the left panel represents gamut expansion. The locations of expected matches are drawn as thick lines. The white dots demonstrate that the result of measuring the effect for only one purity of the test patch is compatible with either hypothesis.

effect, which is also known as *tissue contrast* (German: ‘Florkontrast’, Meyer, 1855; Hering, 1887b; Helmholtz, 1911; Perls, 1932; Walls, 1960; Brown, 2003; Mausfeld, 2003). The basic observation is that the inducing effect a coloured uniform surround has on a central patch which appears grey when viewed in isolation may appear equally impressive when the centre-surround stimulus is viewed through a transparent tissue although this generally reduces the purity of the surround in terms of the proximal stimulus. The interesting feature of this demonstration is that it is at odds with the conventional wisdom that more saturated surrounds have a stronger inducing effect. Meyer’s effect, or at least a very similar and equally interesting phenomenon can easily be observed without using an actual transparent tissue, but instead simulating it by simply reducing the saturation of the surround, as was done in an experiment by Kinney (1962). Her results are replotted in fig 18. It can be seen that the strength of the induction effect, which is present already with surrounds of very low purity, remains remarkably stable in spite of large increases of surround purity. In fact, Kinney reported that for some of her subjects the induction effect even *decreased* with increasing surround purity.

This observation – *almost constant colour impression* in spite of large changes in surround purity – may appear to be in conflict with the well-established finding that the balance point between complemenatry hues traces the surround chromaticity, suggesting *large changes in perceived colour* with variations of surround purity (Ekroll et al., 2002; Whittle, 2003).

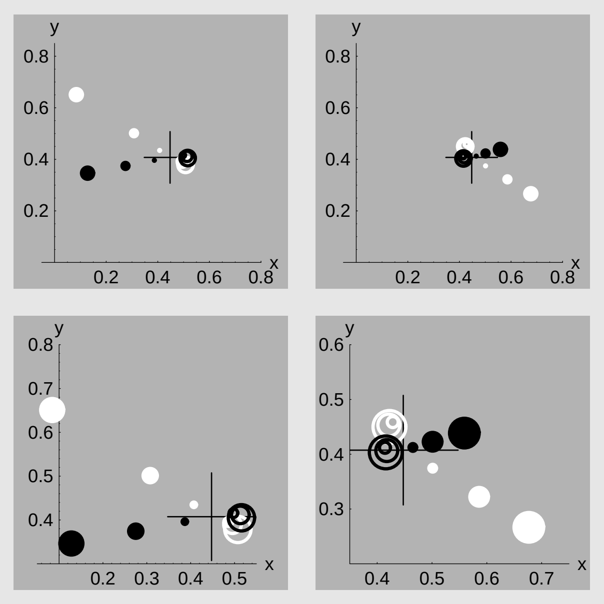

Fig. 18. Matching data from Kinney (1962), replotted in the CIE 1931 **xy**-chromaticity diagram. A patch with the chromaticity of illuminant A (large cross) was presented in surrounds with different purity (filled circles). Subjects adjusted the colour of an isolated patch in order to establish a match with the embedded patch. The mean results from four observers are shown as open circles. Correspondence between surround condition and subjects' settings is denoted by size and colour of the disks and circles, respectively. The lower graphs are blown-up versions of the upper ones. Obviously, the subjects' settings change but marginally with large changes in the purity of the surround.

To our knowledge, no extant model of simultaneous contrast accommodates for both of these observations, but as illustrated in figure 19, they are in excellent agreement with the notion of saturation scale truncation and extension. Actually, with respect to Meyer's effect, truncation and extension predicts that the perceived colour of the central, nominally grey patch should appear the same yellow when presented in a blue surround, however saturated the surround is, and the same blue when presented in a yellow surround, whatever its saturation. Smaller deviations from this prediction, in the sense that more saturated surrounds enhances the effect slightly can be attributed to stronger von Kries scaling in more saturated surrounds.

3.2.6 Colour constancy interpretation of simultaneous contrast

As mentioned in the introduction, it has been proposed that the phenomenon of simultaneous contrast can be understood as "a misdirected attempt to obtain colour constancy" (Walraven et al., 1987, p. 269). While the general idea does not seem unreasonable, our findings suggest that one should be cautious about interpreting the induction effects obtained in uniform surrounds in terms of colour constancy: Saturation scale extension and truncation, which seems to be responsible for the strong effects obtained with equiluminant uniform surrounds, appears to be a fea-

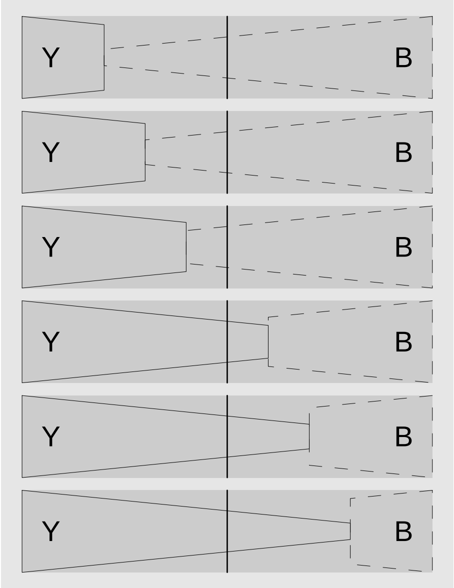

Fig. 19. Prediction of Meyer's effect based on saturation scale extension and truncation. The three upper scales represents the expected colour impressions for central patches from the blue-yellow axis in chromaticity space when viewed in three yellow surrounds of different saturation. The three lower scales shows the same for three blue surrounds. The vertical lines denote the chromaticity of a nominally grey central patch. As evident from the illustration, such a neutral patch should appear the same blue (yellow) when presented in any of the yellow (blue) surrounds.

ture which is particular to this type of stimuli. Therefore the results obtained with uniform surrounds may not be representative of induction effects occurring in stimuli that resemble natural situations more closely. Since it is difficult to conceive of a sensible functional role in mechanisms correcting for illuminations changes for the distinguishing feature of saturation scale truncation and extension, namely the 'missing colours' phenomenon, it appears more natural to regard it as an additional effect, that is not directly related to a basic colour constancy mechanism. In the light of our findings, a more plausible candidate for such a mechanism is simple von Kries scaling which is consistent with the full data set obtained with variegated surrounds, and also seems to play a basic role in uniform surrounds.

3.2.7 Is there a link between perceptual transparency and saturation scale extension and truncation?

While the extension-truncation-notion has the virtue of accounting for the major features of our findings in a reasonably simple and coherent manner, it is at present unclear what the functional role of the mechanisms underlying this phenomenon might be. However, as mentioned in the introduction, a number of previous observations suggest that mechanisms of colour scission (Anderson, 1997) similar to those that subserve the perception of transparency are intimately related to the observed phenomenon (Masin and Idone, 1981; Adelson, 1993; Brown and MacLeod, 1997; Mausfeld, 1998; Ekroll et al., 2002).

Also observations made in the present investigation suggest a connection between colour scission and saturation scale extension and truncation: (a) Both phenomena appear to be particular to uniform surrounds, since only in such stimuli a clear transparency impression was observed, (b) whenever saturation scale extension and truncation occurred, i.e. in the region of the ‘step’, also perceptual transparency was perceived, and (c) impressions of transparency were also—at least partially—responsible for the subjective matching problems occurring in the region of the ‘step’ in the data curve obtained for uniform surrounds.

3.3 Conclusions

We have introduced the notion of saturation scale extension and truncation to describe the major features of colour induction in uniform surrounds. This effect appears to be absent in the more general case of variegated stimuli. It is therefore likely that induction effects observed in uniform surround are not representative of induction effects at large. Failure to recognise the special status of uniform surrounds may in part be responsible for the confusing and seemingly contradictory pattern of results obtained in previous studies, which has prevented the emergence of a commonly accepted and reasonably general quantitative model of colour induction. As we have shown, analysing the induction effects in uniform and variegated surrounds in terms of common and distinct mechanism makes it easier to understand the complete range of effects.

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