The natural centre of chromaticity space is not always achromatic: A new look at colour induction

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Although current theories of colour vision differ in many respects, they all assume the existence of a uniquely defined neutral point in chromaticity space. It is generally assumed that this point satisfies several criteria simultaneously. One of these criteria is that it is perceived as achromatic. A further criterion shared by most theories is the structural assumption that lines in chromaticity space of constant hue converge on the neutral point. The basic assumption that these two criteria coincide is clearly true for isolated spots of light presented in darkness, and it is usually taken for granted that this coincidence generalizes to more complex visual stimuli. Here we show that this is not the case. Our experiments with infields in chromatic surrounds revealed that the point in chromaticity space which appears grey is clearly different from the point on which lines of constant hue converge. A plausible interpretation of this apparently paradoxical finding in terms of colour scission is proposed.

A familiar example of the special role attributed to achromatic colours can be found in the description of three-dimensional colour space along the dimensions of hue, saturation and brightness: In any plane of equal brightness, the achromatic point is assumed to correspond to a natural centre which can be defined alternatively by purely structural criteria. For instance, it is the only point of zero saturation, any closed path around this point contains all possible hues (*enclosure criterion*, see fig. 1a left), and it is the convergence point of all lines of constant hue (*convergence criterion*, see fig. 1a right). The special role of achromatic colours is also acknowledged by opponent-colours theory [1,2] which assumes that an achromatic colour is perceived when both the yellow-blue and the red-green opponent mechanisms are in equilibrium. The abovementioned structural criteria are assumed to hold also within this theoretical framework.

These concepts concerning the structure of colour space and its relation to perceptual variables ultimately have their roots in an experimental paradigm which studies isolated light spots surrounded by complete darkness [3]. In this simple case any light corresponds uniquely to a point in three-dimensional colour space. However, it is well known that the perceived colour of a light spot may change radically if it is surrounded by a coloured region [4,5] (see fig. 1b). The effect of introducing neighbouring stimuli is usually modelled as a context dependent transformation of the coordinates of the isolated light[6-8]. This transformation is thought to preserve both the three-dimensionality and the abovementioned structural properties of colour space. Since the intuition behind this assumption is that the effect of the surround is, in essence, to relocate attributes of colour appearance within a tristimulus space, we will refer to it as the *relocation assumption*. Restricting attention to infields of some fixed luminance presented in a given surround, this ubiquitous assumption implies that the achromatic point and the point of convergence for lines of constant hue should coincide also in this case. We investigated whether this is in fact the case. Our results strongly suggest that it is not.

General methods

In all experiments the stimuli consisted of one or more square infields embedded in an homogeneous rectangular surround. All colours in the display were equiluminant at 10 cd/m^2. The stimuli were presented on a CRT screen (resolution 1024 x 768 pixel, 75 Hz frame rate) in a completely dark chamber. The monitor was controlled by a graphics card with a colour depth of 8 bits per red–green–blue (RGB) channel. This setup was colorimetrically calibrated by means of a colorimeter (LMT C1210) following a standard procedure described by Brainard[9]. All chromaticities are given in *uv*-coordinates (CIE 1976 uniform chromaticity space[3]).

Experiment 1

Experiment 1 consisted of three parts. In experiment 1a we let subjects set the chromaticity of an infield (width: 0.66° visual angle) to achieve an achromatic appearance in three different fixed homogeneous chromatic surrounds (width: 14.25°, height: 10°). The surrounds, which appeared approximately yellow, pink and violet, had the *uv*-coordinates (0.2, 0.49), (0.3, 0.46) and (0.225,0.38), respectively. As is to be expected from the results of previous experiments of a similar kind[6,7], the settings were shifted – relative to the achromatic point for isolated spots of light – in the direction of the chromaticity of the surround (see fig. 2).

In experiment 1b we used a novel method, inspired by an informal demonstration described by Whittle[4], to determine the neutral point indirectly by employing the above-mentioned structural criteria of enclosure and convergence: Two sets of 16 coloured patches (width: 0.33° each) arranged on two circles ("*spatial circles*", radii 1,38° and 2.06°) were displayed in the same surrounds as in experiment 1a (see fig. 1c left). The chromaticities of these patches were equally spaced on two concentric circles ("*chromaticity circles*") in the CIE uniform chromaticity space[3]. The radius of the inner chromaticity circle was set at a relatively small value (0.015 Euclidian distance in the *uv* plane). The outer chromaticity circle had the same centre as the inner one, its radius being twice as large (see fig 1c right). The chromaticity of each patch on the screen was set to the that point of the chromaticity circles which corresponds to its location on the spatial circles (see fig. 1c). If one rigidly translates the two chromaticity circles in chromaticity space (i.e. the relative positions of all infield chromaticities are unchanged), one finds a uniquely defined setting where each pair of patches on the screen with the same angular position appear to be of the same hue. Furthermore, the otherwise almost uniform collection of colours unfurl rather impressively into a set of colours spanning a full gamut of hues as soon as this particular point is reached[4]. According to the enclosure and the convergence criterion this is exactly what one would expect to happen when the circles of infield chromaticities are centred around the neutral point. The task of the subjects in this part of the experiment was to find this point.

In experiment 1c, only one circle of patches was presented in the surround. Thus subjects could not rely on the convergence criterion, and had to rely on the enclosure criterion only. The only difference in procedure compared to experiment 1b was that the subjects also controlled the radius of the circle of chromaticities. The task of the subjects was to find the point which enabled the perception of a full hue circle[*] with the least possible radius setting.

The results from all three parts of experiment 1 are plotted in figure 2. It can be seen that the cluster of the achromatic settings is clearly distinct from that of the settings made using the structural criteria. Furthermore, the means of the latter settings for each surround coincide almost perfectly with the surround chromaticities. This result suggest

[*] As a criterion for the perception of a full hue circle subjects were instructed to ascertain that shades of all four unique hues red, green, blue and yellow were visible.

that already in simple infield-surround stimuli the lines of constant hue do not converge on the achromatic point, but instead on the background chromaticity.

Since this finding challenges a basic assumption of most colour theories it is natural to ask whether the above result may be due to artefact. Indeed, it may be argued that the settings for the achromatic point cannot be compared with the hue convergence settings: The first were made with only one single "infield" whereas the latter were made with effectively 32 "infields", and thus the observed difference of the settings may be due to a difference in the complexity of the stimulus. Our second experiment was designed to address this issue.

Experiment 2

In experiment 2 subjects matched the hue of only two infields (width: 0.66°, centre-to-centre distance: 1.38°) in the same surround (width: 14.25°, height: 10°). The chromaticity of one of these patches was fixed to one of 16 equidistant points on a circle in *uv*-chromaticity space. The chromaticity of the second infield could be adjusted continuously along a smaller concentric circle in chromaticity space in the search for the hue match. The centre of both chromaticity circles was located at the point halfway between the background chromaticity and the achromatic point, which was determined experimentally using the same procedure as in the first part of experiment 1. The radii of these chromaticity circles were 1.5 times and 3 times the distance between these two points, respectively (see fig. 3). Since the radii of the chromaticity circles depend on the grey settings of the subject, it often happened that the outer chromaticity circle extended beyond the monitor gamut. In these cases the surround colours, which were initially set to the same values as in experiment 1, were made slightly less saturated and the entire procedure repeated.

The convergence criterion implies that straight lines drawn through the standard infield chromaticity and the chromaticity of the hue match intersect at the neutral point of chromaticity space. Since both the achromatic point and the background chromaticity were located symmetrically with respect to the centre of the inner chromaticity circle and well within it (see fig. 3), it was a priori equally possible for the lines of constant hue to converge on either one of these points.

Typical results from this experiment are presented in figure 3. To estimate the neutral point for a subject and a given surround, we searched for the chromaticity X which minimized the mean absolute angular deviation between the line from fixed chromaticity to the subjects' settings and the line from the fixed chromaticity to the neutral point X. It can be seen that the estimated neutral points lie very close to the background chromaticity, and much farther away from the mean achromatic settings. Thus the results from experiment 1 can be confirmed also in this more rigorous test.

Experiment 3

A central assumption underlying our use of the convergence criterion in the above experiments is that lines of constant hue are approximately straight. If, however, contrary to this assumption, the lines were strongly curved, for instance as depicted in figure 4 (left panel), the results of experiment 2 may be compatible with the standard assumption that lines of equal hues converge on the achromatic point. Although only relatively small deviations from linearity have been reported previously[3], the possibility that large deviations may occur under the present experimental conditions cannot be ruled out a priori. We therefore conducted a third experiment in which we addressed this possibility explicitly.

The results of experiment 2 show that if lines of equal hue are curved and may thus still converge on the achromatic point, some of them should have strongest curvature (see figure 4, left panel) and we focused on these cases. We used a method with fixed stimuli instead of the adjustment procedure employed in experiment 2. The subjects viewed two infields (width: 1.27°, centre-to-centre distance: 2.64°) in a common surround (width: 27.6°, height: 19.2°). The surrounds, which may be roughly described as yellow, pink and violet, had the *uv*-coordinates (0.2, 0.53), (0.3, 0.46) and (0.22,0.35), respectively. In a 4-alternative forced choice procedure, the subjects were asked to indicate whether the left (test) infield a) had the same hue as the right (standard) infield, b) had a hue different from that of the standard, c) was invisible against the surround, or d) appeared achromatic. They were instructed to use a strict criterion for a hue match.

For each surround, the chromaticities for the test infield were chosen from a triangular region in *uv*-space spanned by the chromaticities A, B and S of the achromatic point, the surround, and the standard infield, respectively. All different chromaticities inside this triangle realisable at 8-bit colour resolution were used for the test infields. The achromatic point was – just as in experiment 2 – determined for each subject in a preliminary experiment. The individually determined mean A over 8 achromatic settings for a surround together with the surround chromaticity B defines a line AB in chromaticity space. For the standard infield we used a chromaticity S which (in *uv* chromaticity space) had a Euclidian distance of 0.04 units from this line, and was equally far away from A and B (see figure 4, right panel).

The results for one of the surrounds is plotted for two subjects in figure 5 (the results of an additional subject were similar to those of subject MK and are not shown). It can be clearly seen that the equal hue lines for subject MK, which extend all the way down to threshold detectability of the infield against the surround, are approximately straight and converge on the surround chromaticity. This equal hue line and the achromatic locus are separated by an extended region which is neither classified as achromatic nor as a hue match. The equal hue lines of observer BS look like "amputated" versions of those of subject MK. After the experiment subject BS reported that he had experienced a pronounced impression of transparency when the infield was similar to the background and that he, in view of the instruction to apply a strict criterion, had not classified these cases as hue matches. Similar reports of perceptual transparency were also made by the other subjects (see discussion). The general pattern of results apparent in figure 5 is equally clear in the data for the other surrounds (not shown).

The results of experiment 3 clearly rule out non-linearities of equal hue loci as a possible explanation for the dissociation of the achromatic point and the convergence point for lines of equal hues observed in experiment 1 and 2. Furthermore, since in this experiment judgements of achromaticity and hue equality were made under the exact same conditions, any artefact due to slight differences in context can also be ruled out.

Discussion

The results of all three experiments support the conclusion that there is a dissociation between the perceptual criterion of achromaticity and the structural definition of the neutral point in chromaticity space in terms of the convergence criterion. Lines of equal hue converge on the background chromaticity, and not on the achromatic point. Therefore, contrary to common intuitions, the chromaticity of the background should be regarded as a more natural centre of chromaticity space than the achromatic point. Interestingly, a similar dissociation of the achromatic point and a functionally relevant neutral point has been found in a study[10,11] on contrast adaptation. Here, the experimentally determined centre of contraction in contrast adaptation was not the achromatic point but the mean of a temporally modulated adapting stimulus.

The present finding appears paradoxical if one tries to understand it in terms of classical notions of colour space with *three* dimensions such as hue, saturation and brightness[12]. In this view, if brightness and hue are constant, the only variable attribute of colour is saturation, whereby desaturation is taken to mean a (perceptual) mixture with white. Consequently, lines of constant hue should converge on white. This should not change if a chromatic surround is introduced, since according to the relocation assumption only the *position* of the white point should move.

Contrary to this, the results of our experiments show that lines of constant hue converge on a chromatic colour, namely that of the background. This means that colours on this line must contain, in addition to the hue that should be matched, varying amounts of the background colour, which seems to be at odds with the fact that the subject found it easy and natural to make complete hue matches, and were never uncertain about which point to choose. A parsimonious way to resolve this apparent paradox is to assume that the visual system performs a decomposition of the proximal stimulus into two simultaneously perceived colour components – a common background component, and a contrast component[4] defined relative to the background (see figure 1d). The critical assumption one has to make is that even though both are perceived simultaneously, the subjects base their hue-matches in an immediate and effortless way only on the contrast component and can – in this regard – be said to discount the common background component. This interpretation makes the observations that lines of equal hue converge on the background chromaticity and that the smallest possible full colour circle encloses the background chromaticity intelligible.

Interestingly, however, the above account of our results in terms of colour scission suggests that true achromatic settings should actually be impossible to make, for also in this case two chromatic colour components should be simultaneously perceived. Indeed, it has already been observed by others that it is impossible to find grey infields in different surrounds that appear truly identical[13]. According to the scission account this could be explained by assuming that in such a situation the two colour components present are both faint and that the background component can be balanced – but not cancelled – by a complementary contrast component such that the total impression is close – but not identical – to a true grey (see figure 1d).

The scission interpretation outlined above is not only supported by our data, but also by the phenomenological observation that, especially at low chromatic contrast, the colour component of the infield seems to be covered by a 'veil' which has the same colour as the background. The perceptual impression is reminiscent of perceptual transparency[14-16]. Hence, Hering's description of 'desaturation' as a 'veiling with white'[1] seems to be appropriate in a literal sense *provided* that 'white' is replaced by 'background colour'.

In more complex stimuli, similar phenomena of 'laminar segmentation'[17] or 'scission'[18] of colour, such as the simultaneous perception of illumination and surface colour[19], or of background colour and a transparent overlay are well known. Our finding strongly suggest that such a dual coding of colour occurs even in simple infield-surround stimuli, albeit in an embryonic form[8,17].

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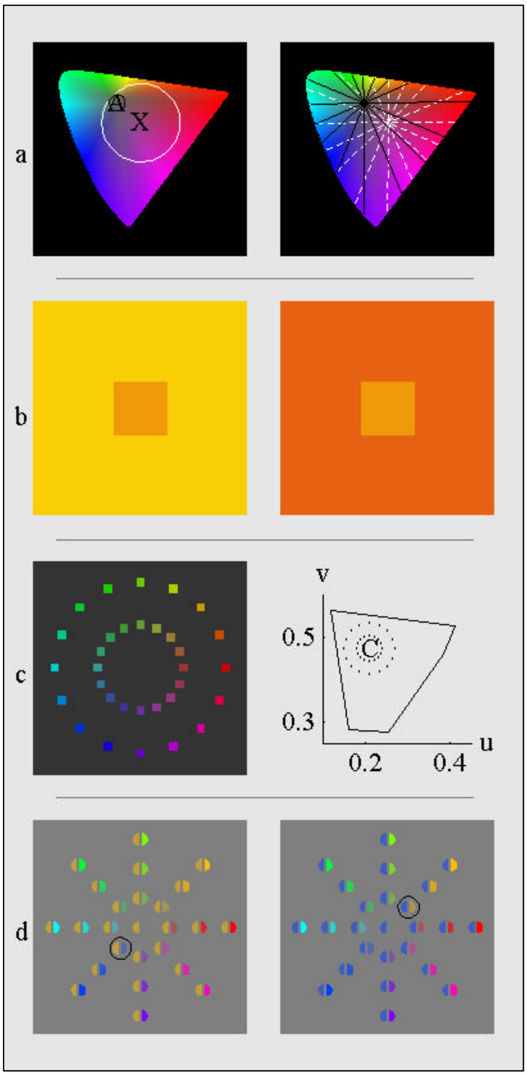

Figure 1: **a)** Two properties of the achromatic point shown in the *uv* chromaticity space. Left: If the small black circle around achromatic point A is the smallest circle around this point containing all hues (albeit at low saturation), then the larger white circle is the smallest circle around the chromaticity X which contains all hues, since if it is made smaller, the greens will be missing. Right: the straight lines emanating from the achromatic point are of approximately constant hue with increasing saturation. The straight lines emanating from any other point, such as the white dashed ones, can not all be of constant hue. **b)** Simultaneous colour contrast. Although the two small rectangles are physically identical, they look different due to the different inducing effects of the surrounds. The effect is even stronger when centre-surround stimuli are viewed in a surround of complete darkness. **c)** Left: Schematic picture of the display used in experiment 1 with a black surround. The surrounds in the experiment were chromatic and equiluminant to the patches. Right: Chromaticities of the patches for a centre C, which in this case is equal energy white, and an inner circle radius of 0.03. The polygon is the border of the monitor gamut at the luminance used in our experiments. **d)** Schematic illustration of the scission account of our results outlined in the discussion. The left and right panel correspond to the situation of a yellow and a blue surround respectively. The left half of each disk represents the colour of the common background component, the right half the colour of the "contrast component". A feature which is not clear from this figure is that the salience of the background component increases as the infield chromaticity approaches that of the surround. The figure illustrates the impossibility of making true achromatic settings and the best alternative choice (black circles).

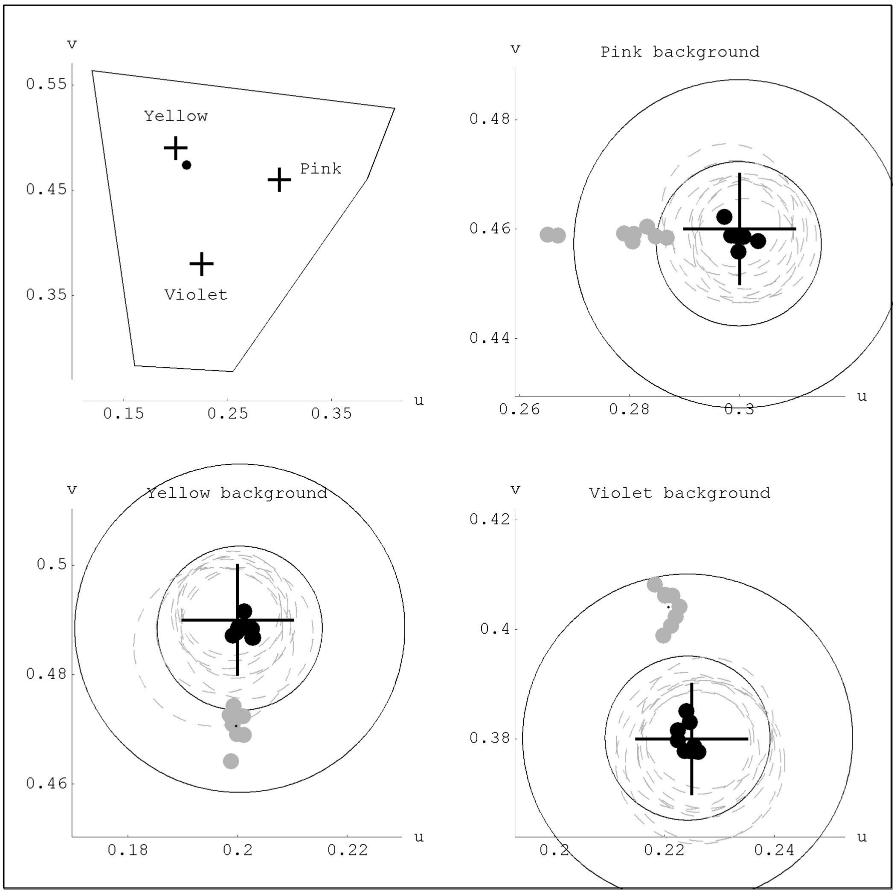

Figure 2: Typical results from experiment 1 (Subject VE). Upper left: The crosses represent the three background chromaticities investigated. The black point represents the chromaticity of equal energy white. The surrounding polygon is the monitor gamut at the luminance used in our experiments (10 cd/m^2). The other graphics represent scaled up portions of this space. (Background chromaticity crosses are correspondingly scaled in size.) The grey dots represent the achromatic settings (experiment 1a), and the black dots the settings made in experiment 1b. Around the mean of these settings two black solid circles are drawn with the fixed radii used. Each of the dotted grey circles represent one single setting from experiment 1c.

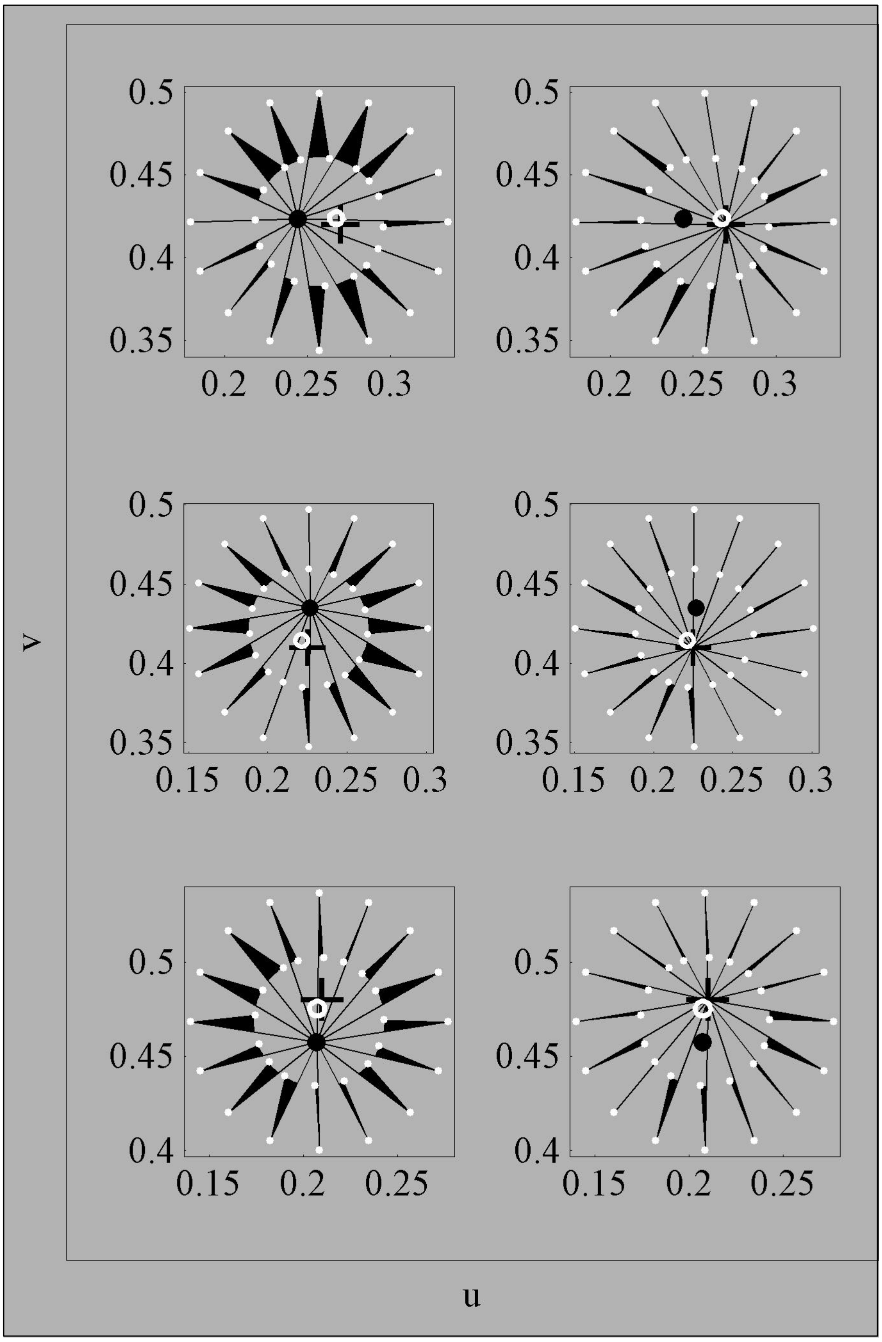

Figure 3: Typical results from experiment 2 in *uv* chromaticity coordinates (Subject GW). Row 1 is for the pink background, row 2 is for the violet background and row 3 is for the yellow background. The results of three additional subjects were almost identical. In the left column the data are plotted together with lines predicted by the hypothesis that lines of constant hue converge on the achromatic point (black filled circle). Shorter lines are drawn from the chromaticities of the fixed patches (small white dots on the outer circle) to the corresponding mean settings (small white dots on the inner circle), and the angular deviation from the predicted lines are filled out in black. The white ring represent the best-fitting point of convergence, the black cross represents the background chromaticity. In the right column the same data is plotted, except that the lines predicted by the hypothesis that lines of constant hue converge on the background chromaticities are given.

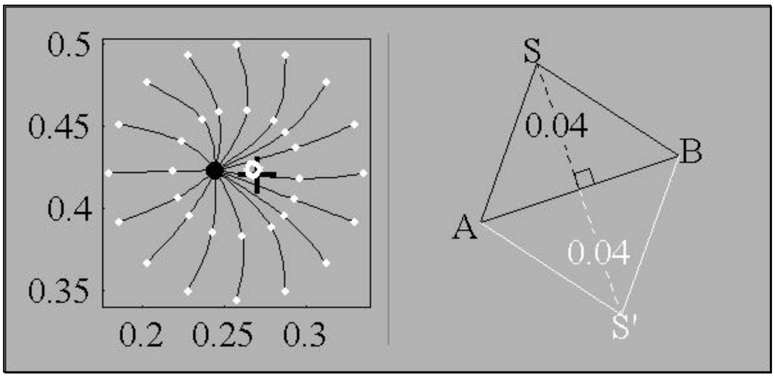

Figure 4: Left: A possible alternative interpretation of the data in experiment 2 (here for the pink background, cf. figure 3, top panel) in terms of curved lines of constant hue. Right: Illustration of the choice of infield chromaticities in experiment 3 (see text for details). The black and white lines correspond to two different conditions used for each surround.

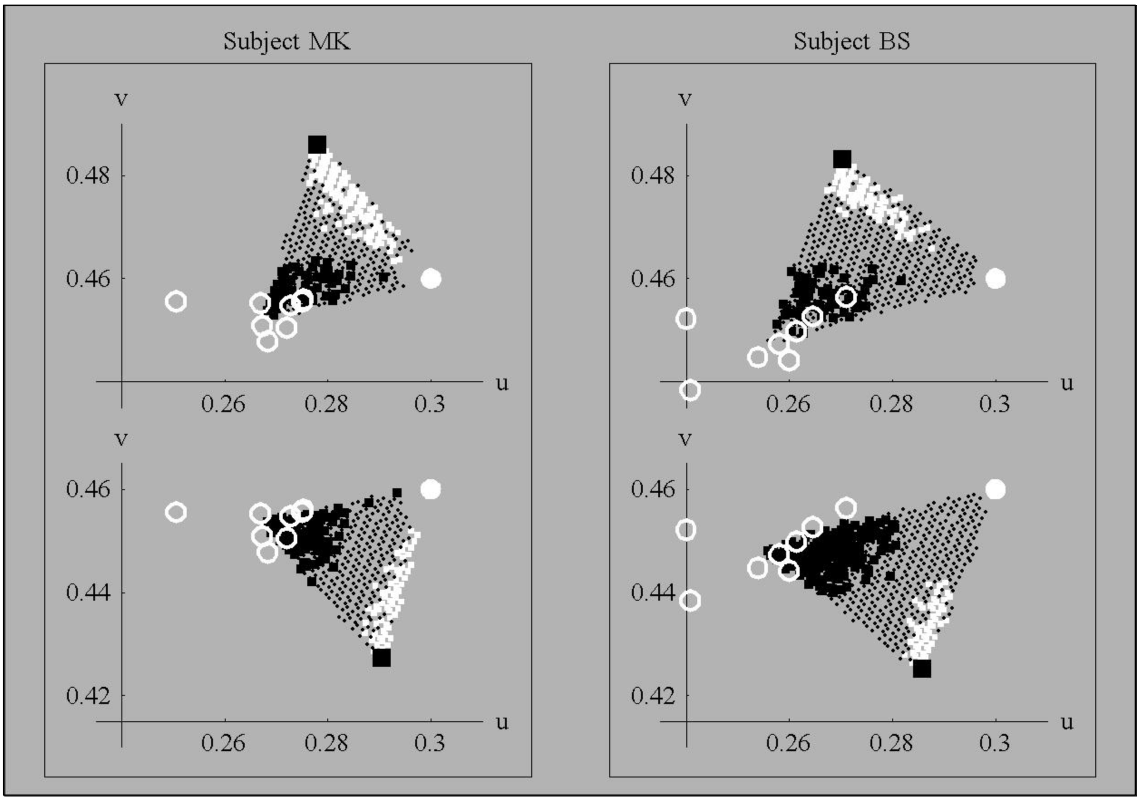

Figure 5: Typical results from experiment 3 in *uv* chromaticity coordinates. Filled white circle: background chromaticity. Open white circles: gray settings from preliminary experiment. Large black square: standard infield chromaticity. Each point within the triangle represents one of the test chromaticities. Points plotted as white squares represent test infields which appear equal in hue to the standard infield, those plotted as small black square represent test infields which appear achromatic, and those plotted as small black dots represent test chromaticities that are judged neither to be achromatic nor a hue match. Chromaticity points for those test infields which appeared indistinguishable from the surround are omitted in the plot, yielding an empty region close to the white filled circle.