Colour constancy for an unseen surface

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Summary

The illumination of a scene strongly affects our perception of objects in that scene - the pages of a book illuminated by candlelight will appear quite yellow relative to other types of artificial illuminants. Yet at the same time, the reader still judges the pages as white, their surface-colour unaffected by the interplay of paper and illuminant. It has been shown empirically [1] that we can indeed report two quite different interpretations of 'colour': one dependent on the constant surface spectral reflectance of an object (*surface*-colour), and the other on the power of light of different wavelengths reflected from that object (*reflected*-colour). How then are these two representations related? The common view, dating from Aristotle, is that our experience of surface-colour is derived from reflected-colour or, in more familiar terms, that colour perception follows from colour sensation [2-4]. By definition, colour constancy requires that vision 'discounts the illuminant'; thus it seems reasonable that vision begins with the colour of objects as they naively appear and that we infer from their appearances their surface-colour. Here we question this classic view. We use metacontrast-masked priming and, by presenting the unseen prime and the visible mask under different illuminants, dissociate two ways in which the prime matched the mask: in surface-colour or reflected-colour. We find that priming of the mask occurs for when it matches the prime in *surface*-colour, not reflected-colour. It follows that colour perception can arise without prior colour sensation.

Results

Experiment 1

The aim of this experiment was to determine whether the colour of an unseen object is represented in terms of its reflected-colour or its surface-colour. That is, can colour constancy be computed for an object that elicits no experience? Metacontrast-masking [5], which extinguishes the experience of a briefly presented stimulus through the use of a subsequent mask, was used to render a coloured prime invisible. Success of this method depends upon the inter-stimulus delay, plus the spatial, temporal and chromatic properties of the stimuli. The colour of the prime speeds colour recognition of the mask, but only when the prime and mask match in colour. In this experiment, the prime and mask were presented under different illuminants, one resembling direct sunlight (CIE D50) and the other resembling average daylight (CIE D65). Two mask colours were chosen so as to match either the prime’s surface-colour (blue mask) or the prime’s reflected-colour (green mask). See Figure 1, Table S1 and Supplemental Experimental Procedures for information on chromaticities. Figure S1 illustrates the spectral properties of the two illuminants.

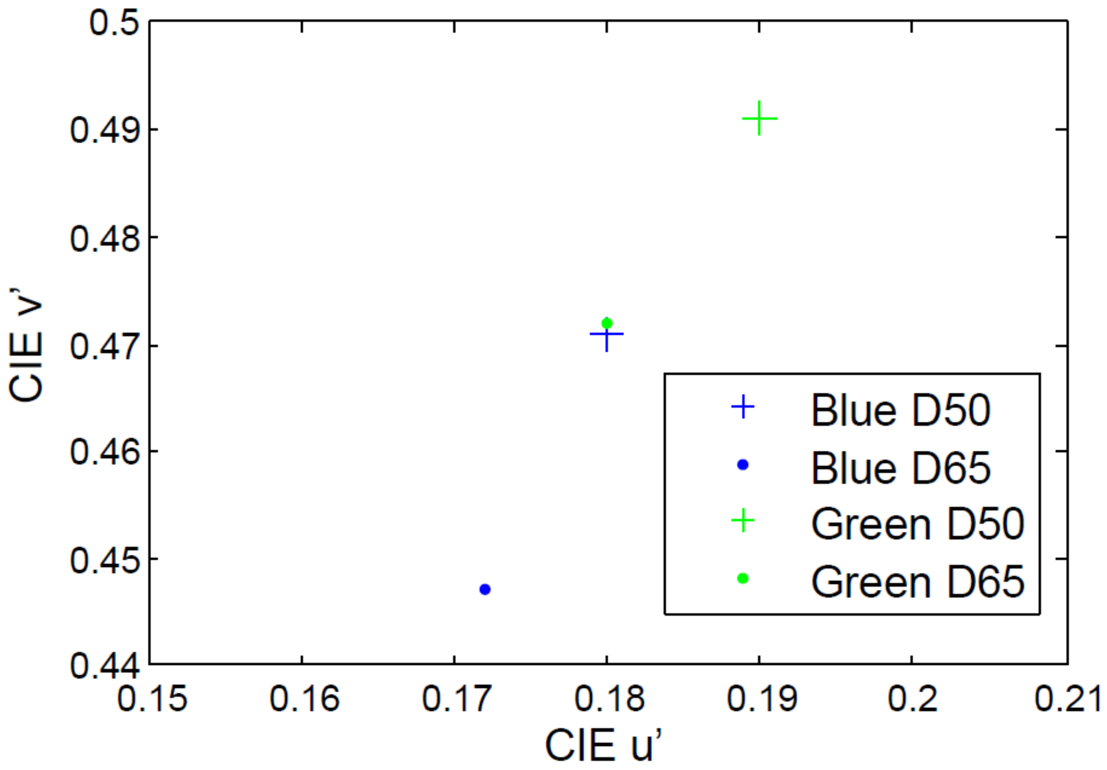

Figure 1. Chromaticities for the blue and green surfaces when illuminated by D50 or D65, specified in CIE u' v' space. The blue and green filled dots in the plot represent the chromaticities of the blue and green masks, respectively, seen under D65. The crosses represent the same surfaces seen under D50. The prime display is illuminated by D50 and the prime is identical in chromaticity to that of the blue mask under the prime's illuminant (surface-colour match) but is nonetheless physically identical to the green mask in terms of reflected-colour (reflected-colour match). See figures S1 and S3 for further details and modelling of the effects of adaptation to the stimuli.

The experiment consisted of two separate phases. In the first phase, the priming phase, participants completed three sessions in which they identified the colour of the mask as quickly as possible. The prime was presented 50ms before the onset of the mask for durations of either 12.5ms or 37.5ms. The prime was absent in half of the trials – we refer to these as having a 0ms prime presentation time. See Figure 2 for an illustration of the sequence of events in a single trial (see Figure 2 legend and Supplemental Experimental Procedures for details on how the illuminant was changed). We quantify a single measure of the prime's effect by taking the difference between its effect on response times (RTs) for masks matched in reflected-colour (measured relative to when the prime is absent) and the same measure for masks matched in surface-colour. The resultant measure is the surface priming advantage (SPA) - when positive, this implies that the colour of the prime was congruent in terms of surface-colour and, when negative, implies it was congruent in reflected-colour. The SPA was significantly above zero at both prime duration levels (mean SPA = 25.8ms for short prime duration and 31.4ms for long prime duration; $t_{(9)}$=4.801, p=0.001 and $t_{(9)}$=5.120, p=0.001, respectively). All results are shown in Figure 3.

In the second phase of the experiment, the detection phase, participants completed three sessions in which they judged whether the prime was present or not on a confidence scale of 1 to 8 (the nature of the prime was demonstrated to them in a much slowed presentation of stimuli prior to beginning this phase). The discriminability index d_a was calculated using the software RScorePlus [6] to fit a Gaussian unequal-variance signal detection model to these data. Overall, d_a did not differ significantly from zero for either level of prime duration (mean d_a = -0.006 for short and 0.186 for long prime duration; $t_{(9)}$ = 0.162, p = 0.875 and $t_{(9)}$ = 1.823, p = 0.102, respectively) which indicates very strongly that participants had no experience of the prime. The individual signal detection results indicate that just two participants could detect the presence of the long duration primes. No participants were able to detect the short duration primes.

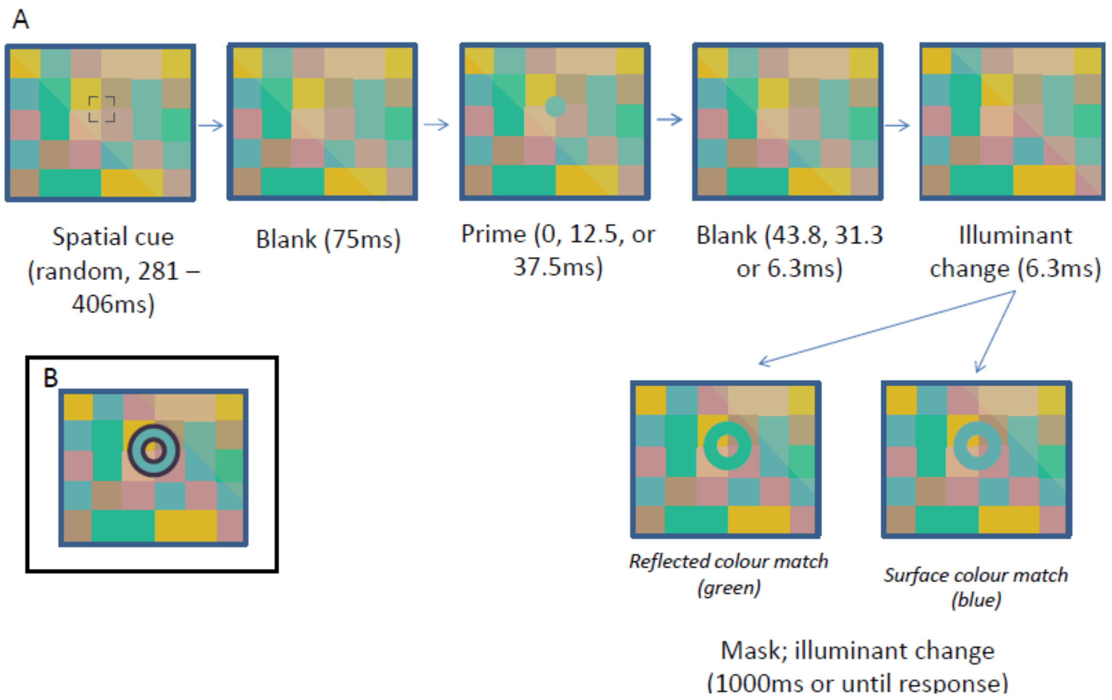

Figure 2 a. Experiment sequence. The sequence of an individual trial is shown, from left-to-right. An initial cue indicates the location of the prime and mask. After a delay the prime is then presented for a variable duration – either 0 (prime absent), 12.5 or 37.5 ms – and the duration of the following "Blank" display is dependent on the duration of the prime in order for the prime-mask SOA and the overall display duration to be kept constant across conditions. During the presentation of the prime, the scene is illuminated in one half by D50 and in the other half by D65, with the illuminant boundary bisecting the scene at an angle of 45°. The prime always appears in the D50 half. After the offset of the prime and before the onset of the mask, the illuminant boundary moves such that the target will appear under the D65 illuminant. The mask is shown in its two potential colours – the green is congruent with the prime in reflected-colour but the blue is congruent in surface-colour. Note that the figure is only an illustration of the stimuli – colour and scale of stimuli are not accurate**. b. Mask with inner and outer border annuli.** The dark chromatic annuli around the inner and outer regions of the mask annulus ensured that the mask and prime colours did not share a common chromatic contrast with the background in experiment 3.

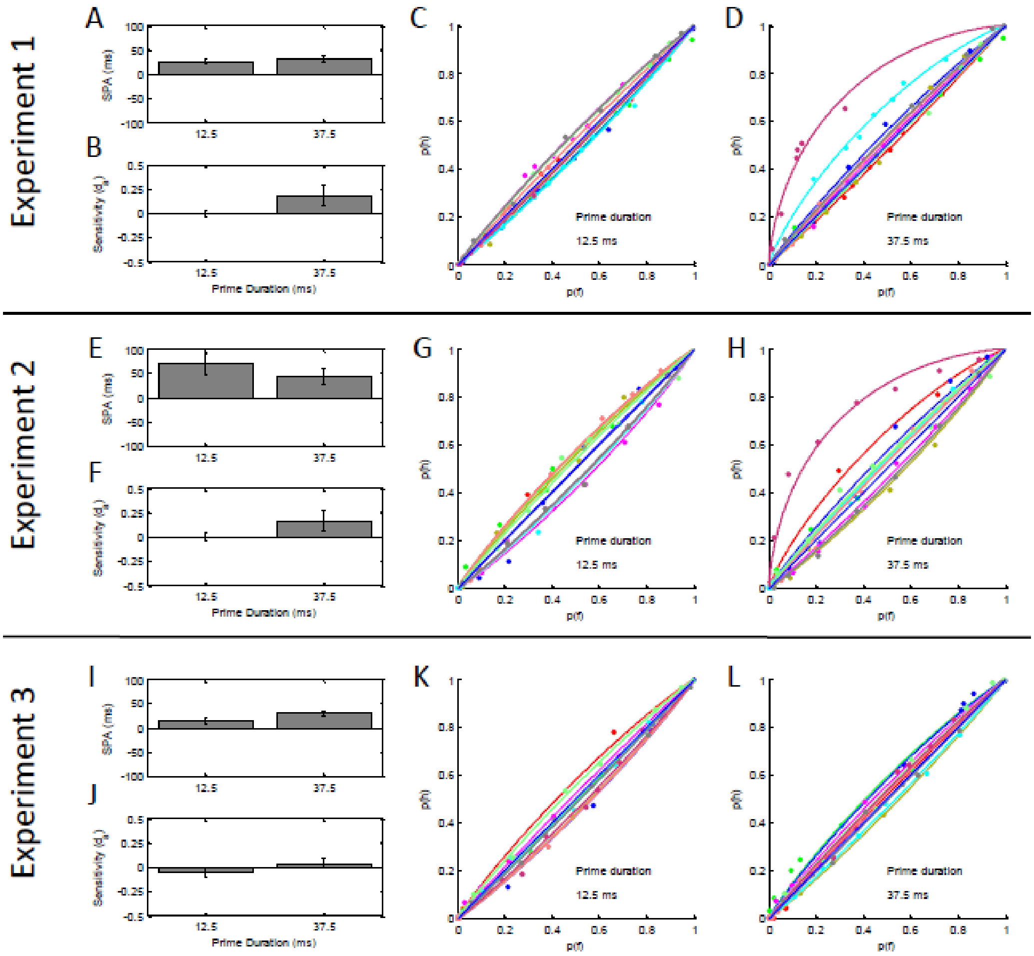

Figure 3 a-d. Experiment 1 results. e-h. Experiment 2 results. i-l. Experiment 3 results. The left panel shows the mean surface priming advantage (SPA; upper panel) and sensitivity calculations for detecting primes at short and long durations. The SPA is positive in all cases, indicating that the priming effect was driven by matches in surface-colour and not reflected-colour. In comparison, the sensitivity indices (d_a) do not differ significantly from zero, indicating very strongly that participants had no experience of the prime. Error bars show ± 1 SEM. The middle and right panels show ROC curves for each participant for detecting the prime at the short and long onset durations, respectively. ROC curves plot hit rate against false alarm rate across an individual's criteria range. The ROC curves showing sensitivity at the long onset durations (right panel) indicate that just two participants could detect the primes in experiments one and two. In contrast, no participants could detect the primes at the short onset duration in any experiment or at either duration in experiments three. See also Figure S2 for separate RTs to blue and green masks as a function of prime duration.

Experiment 2

This experiment tested whether the results can be explained by participants learning to anticipate how surfaces under D50 would appear under D65 given that observers attended to a location that invariably underwent this illuminant change on each trial. Such a strategy would be consistent with some inferential theories of colour constancy (see discussion in [7]).

Here we eliminated the predictability of the illuminant change – we randomly interwove trials with an illuminant change with those in which the illuminant did not change. Nevertheless, the SPA for illuminant-change trials remained significantly above zero (mean SPA = 69.5ms for short and 43.6ms for long prime duration; $t_{(9)}=3.359$, $p=0.008$ and $t_{(9)}=2.685$, $p=0.025$, respectively) and participants' d_a did not differ significantly from zero (mean d_a = 0.000 for short and 0.159 for long prime duration; $t_{(9)}$ = 0.007, p = 0.994 and $t_{(9)}$ = 1.479, p = 0.173, respectively, two participants could detect the presence of the prime at the long duration). The priming effects are unlikely to have arisen as a result of implicit learning.

Experiment 3

Here we sought to eliminate the possibility that the priming effect was due to constancy of colour *contrast*. The ratios of cone excitations in response to light reflected from adjacent surfaces remain approximately constant across an illuminant change [8]. In this study the prime and mask appear over the intersection of four background squares, so there was no single contrast to prime, lessening the probability that contrast constancy explains colour priming. But to eliminate this possibility we added a dark chromatic annulus to both the outer and inner edges of the mask in experiment 3, thereby removing the common set of local contrasts shared between prime and mask. The SPA was again significantly above zero (mean SPA = 14.2ms for short and 28.9ms for long prime duration; $t_{(9)}$=2.467, p=0.036 and $t_{(9)}$=5.186, p=0.001, respectively) and participants' d_a did not differ significantly from zero (mean d_a = -0.057 for short and 0.038 for long prime duration; $t_{(9)}$ = 1.193, p = 0.263 and $t_{(9)}$ = 0.737, p = 0.480, respectively). Thus the priming effect was not dependent on equivalence in local contrast between the prime and mask.

Experiment 4

We have discussed the surface priming advantages observed in experiments 1-3 in terms of constancy for surface-colour. Constancy can, however, also affect judgments made about reflected-colour [1, 9]. Adaptation in the retina that scales neural responses in proportion to the prevailing strength of signals from each cone-class (von Kries adaptation) can affect all cortically-mediated responses to colour. Can our results be explained in terms of such low-level mechanisms? In Arend and Reeves' [1] original experiments participants adjusted the colour of one patch under one illuminant to match that of another under a different illuminant in accordance with the instruction given: Either "Make the samples look as if cut from the same paper" or "Make the samples match in hue and saturation". The first yields a large degree of constancy, and we believe this instruction taps our ability to represent surface-colour, whereas the second yields a very small, but nonetheless present, degree of constancy, which we believe tap representations of reflected-colour. If low-level mechanisms of constancy produced the priming effects in this study then they should lead to a degree of constancy in representations of the prime's reflected-colour.

In experiment 4 we measured separate indices of constancy for surface- and reflected-colour between the prime and target using unmasked primes (made visible by extending their presentation duration) to show that only the surface-colour constancy can explain the priming effect. On a scale in which zero represents perfect inconstancy and 1.00 perfect constancy, the average degree of reflected-colour constancy did not differ significantly from zero (0.00; $t_{(9)}=0.034$, $p=0.973$), whereas that of surface-colour did (0.65; $t_{(9)}=7.355$, $p<0.001$). This value of surface-colour constancy is consistent with that found in other experiments (normal average of 0.66 [9]), but it is unusual to find a complete absence of reflected-colour constancy (normal average 0.23). A control condition shows that this anomaly is the result of presenting the prime and mask sequentially in the same spatial location. When the prime and mask were presented simultaneously, but spatially separated under different illuminants, the degree of reflected-colour constancy was 0.29 ($t_{(9)}$=5.499, $p<0.001$). Together, these measurements provide strong evidence that the unseen prime was represented in terms of its surface-colour and that the results of experiments 1-3 cannot be explained in terms of retinal adaptation.

Retinal adaptation nevertheless often does affect constancy for reflected-colour judgements. Why does it not do so in our experiments? Effects on reflected-colour judgments are typically found in experiments where there is a wholesale change of illumination across the visual scene. In our experiments we shift the boundary between two areas of illumination a small distance and so have much weaker changes in the overall colour of stimuli. We modelled how von Kries adaptation would affect the signals elicited by the stimuli in our experiments. These models suggest that retinal adaptation cannot account for the findings of experiments 1-3 (the modelling is described in the Supplemental Experimental Procedures; Figures S3 and Table S2 illustrate the modelling results). The similarity of colour signals between the prime and mask should determine priming. Even after adaptation the modelled signals from reflected-colour masks are still more similar to primes than those from surface-colour masks.

Discussion

These experiments used a metacontrast-masked priming task in which the prime and mask were presented under different illuminants; we showed that an unseen prime speeds the colour recognition of the mask if they share surface-colour, not reflected-colour. The priming effect did not result from implicit learning across trials, i.e. from the acquired ability to anticipate the effects of the illuminant change on the mask's appearance (experiment 2). Nor was the priming effect explained by the constant chromatic contrasts of the prime and mask with their checkerboard backgrounds (experiment 3).

Previous studies have provided good evidence that at least some aspect of colour constancy is automatic and possibly non-conscious. Barbur & Spang [10] showed that when we have no conscious access to an illuminant change, colour constancy is not diminished, and Foster et al [11] have demonstrated that we detect violations in colour constancy without attentional scrutiny. The present study provides the first strong evidence that the perception of surface-colour can occur in the absence of prior colour sensations, at least insofar as we understand 'colour sensations' as the conscious experience of (something akin to) reflected-colour.

This finding may appear to be at odds with a previous study [12] which found that although a white prime was more easily confused with a blue than a green mask, it acted as a congruent prime for the green mask on the basis that it was more similar in terms of the luminances of the RGB guns of the monitor. Unlike in the present study, however, the prime was not matched with the masks in either surface- or reflected-colour, so the priming effect might be driven by some other stimulus attribute such as colour contrast (whose impact is minimised in our experiments). To our knowledge the present study is the first to use a change in illuminant conditions in order to dissociate surface- and reflected-colour.

This study sheds light on the stage of processing at which surface-colour is estimated. The anatomy of colour vision shows a clear progression from midget ganglion cells in the retina where neural responses are determined primarily by the wavelength composition of light, through striate cortex, where cells responding to wavelength [13] and wavelength contrast [14] are found, and extrastriate areas that appear to compute colour constancy [15, 16]. One potential constancy mechanism relies exclusively on rapid adaptation of photoreceptors in the retina [17]. As indicated by the complete absence of constancy in participants' perception of reflected-colour under conditions of the priming task (experiment 4), however, such adaptation can be ruled out as an explanation of our results, as any mechanism operating prior to signals entering striate cortex is certain to modulate our experience of reflected-colour (or hue, saturation and brightness).

Another mechanism, not based on local adaptation processes and relying on spatial interactions, is extremely rapid and likely to have a cortical basis. This is likely to be associated with colour contrast cells in striate cortex [14, 19], which *could* signal the stable property of relative surface-colour under a changing illuminant given that cone excitation ratios between adjacent surfaces are invariant under such a change. It is important to note, however, that the priming effect we observed cannot simply be explained by priming at the level of colour contrast, and instead is likely to necessitate a representation of surface-colour beyond that in striate cortex. Cells in monkey extrastriate area V4 modify their chromatic sensitivity in accordance with changes in background colour [20] and areas in human cortex, including the fusiform gyrus, have been implicated in similar roles [10, 21]. It is entirely plausible that the unseen prime in the present task evoked such extrastriate processing, given that masked unseen primes are known to elicit activity in occipito-temporal areas [22]. Reduction in the visibility of masked colour primes by a metacontrast-mask probably occurs in early cortical areas V2 and V3 [23], but presumably the initial signal elicited by the primes can progress beyond these areas.

In neuropsychology, it is clear that the neural bases of colour constancy and colour experience are difficult to distinguish [13] – in cases of cerebral achromatopsia [24, 25], wherein colour experience is lost, there is also no measurable implicit perception of surface-colour [26] and therefore no colour constancy. Indeed, in Zeki's model of colour perception, it is V4 that is the site of both constancy and experience [16, 27], but the two are nonetheless functionally separate, at least to the extent in which experience remains intact whilst constancy is impaired [16, 28]. The results from the present study suggest that the reverse dissociation can hold – colour constancy can occur in the absence of colour experience. One candidate area for the neural correlate of colour experience [29] lies anterior to the constancy areas implicated in these studies, and there is some controversy over whether any of the earlier stages gives rise to colour experience [30], and so one might speculate that estimates of surface-colour might feed into colour experience.

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Author contribution statement

L.J.N., C.A.H. and R.W.K. designed the experiments. L.J.N. ran the experiments and analysed the data. All authors contributed to writing the manuscript. This work was supported by the James S. McDonnell Foundation.

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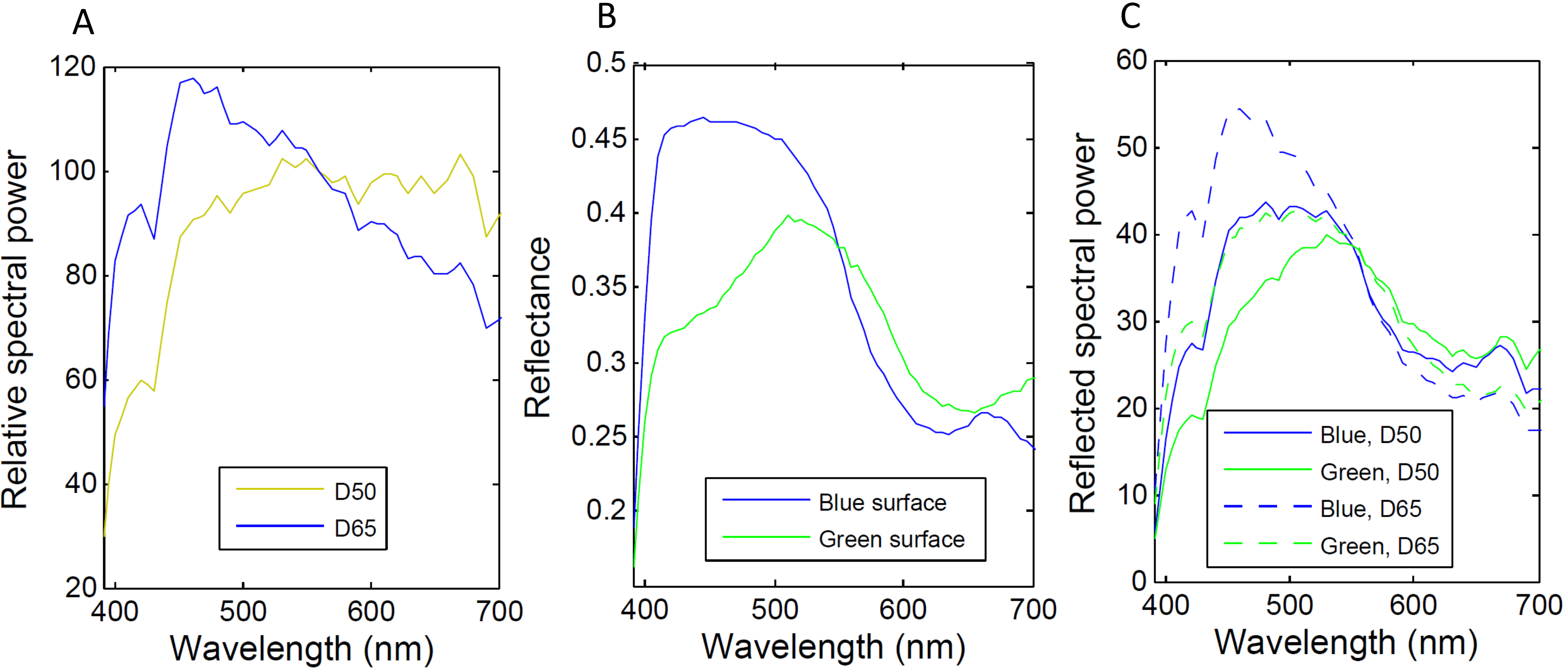
A
Relative spectral power
Wavelength (nm)
D50
D65
20
40
60
80
100
120
400
500
600
700
B
Reflectance
Wavelength (nm)
Blue surface
Green surface
0.2
0.25
0.3
0.35
0.4
0.45
0.5
400
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600
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C
Reflected spectral power
Wavelength (nm)
Blue, D50
Green, D50
Blue, D65
Green, D65
0
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400
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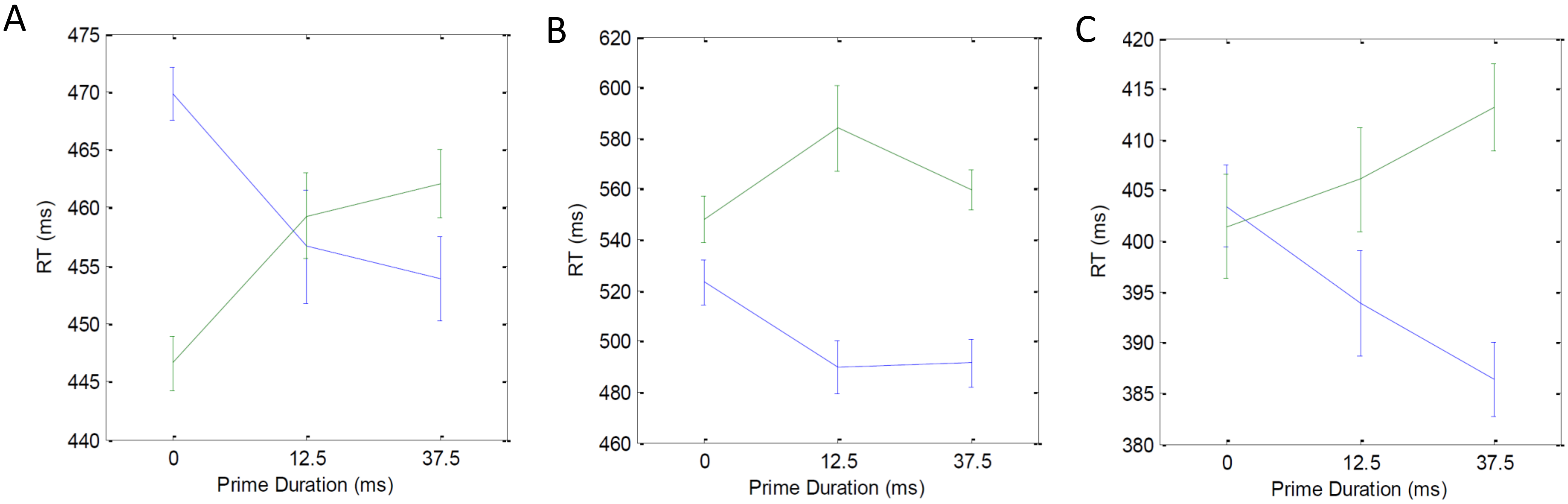
600
700

Figure S1 related to Figure 1. A. Spectral power functions for illuminants D50 and D65. Note that the difference between the illuminants refers not to differences in overall intensity of light but to the differences in wavelength composition **B. Spectral reflectance functions of blue and green surfaces (masks). C. Spectral power functions of light reflected from the blue and green surfaces when illuminated by D50 or D65 light.**


A
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385
380
RT (ms)
0
12.5
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Prime Duration (ms)

Figure S2 related to Figure 3. M**ean RTs for blue and green masks (blue and green lines, respectively) as a function of the prime's onset duration in experiments 1 (A), 2 (B) and 3 (C).** By comparing the change in RTs at either 12.5 or 37.5 ms relative to 0 ms (0 ms onset duration indicates that the prime was absent), the effect of the prime can be shown to speed responses to the blue mask and slow those to the green. Error bars show ± 1 SEM, with between-participant variance removed. In each experiment, the prime can be shown to speed responses to the blue mask and slow those to the green. Participant debrief suggests that differences between experiments in baseline mean RTs to blue and green masks are likely to be explained by variation resulting from individual differences in colour categorisation (the extent to which blue and green masks were unambiguously blue or green or were closer to the subjective blue/green category boundary varied between participants).

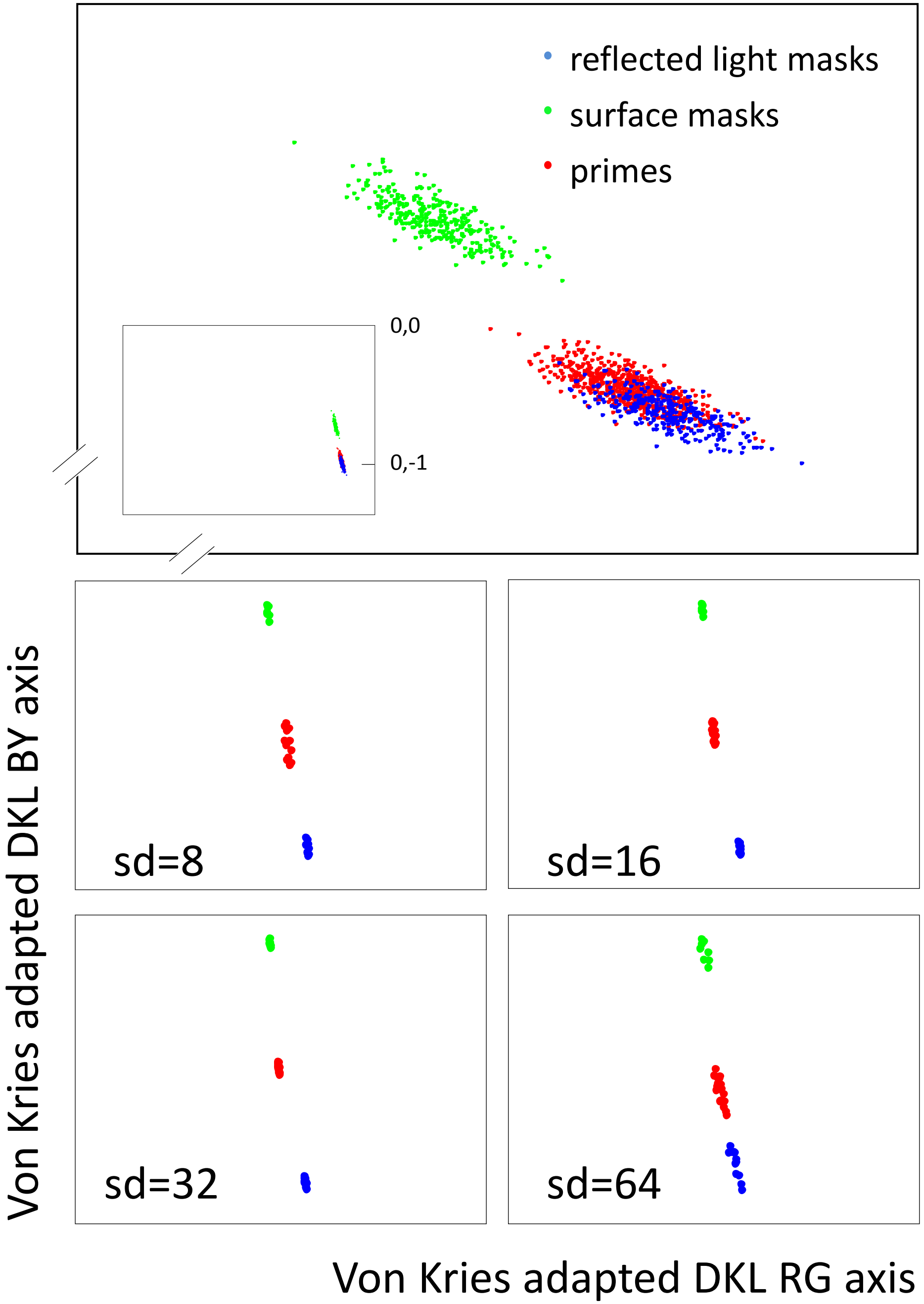
reflected light masks
surface masks
primes
0,0
0,-1
sd=8
sd=16
sd=32
sd=64
Von Kries adapted DKL BY axis
Von Kries adapted DKL RG axis

Figure S3 related to Figure 1. Colour co-ordinates in DKL space of the primes and masks after the transformations of von Kries adaptation to their individual backgrounds. If von Kries adaptation explained our results we would expect the co-ordinates of the adapted primes and the adapted surface masks to be similar. As can be seen in the uppermost panel, however, these are less similar to one another than the adapted primes and adapted reflected light masks. The lower four smaller panels show the resultant DKL colour co-ordinates with different scales of Gaussian adapting kernels. When pooling of the adapting signal varies from less than the radius of the prime (16 pixels) to greater than the outside radius of the mask (32 pixels) there is still no evidence for greater similarity between primes and surface match masks than between primes and reflected light masks. Note that the main plot in the upper panel has been rotated and offset to permit the spread of data to be visualised clearly. The small upper inset shows that same data plotted unrotated with the origin to the upper right. Plots in the lower panels are unrotated but their axes do not include the origin.

Colour	**D50**	**D65**
Blue (7.5B, 4)	0.180, 0.471, 3.4	0.172, 0.447, 3.5
Green (10G, 2)	0.190, 0.491, 3.5	0.180, 0.472, 3.5
Yellow (10Y, 2)	0.210, 0.505, 3.6	0.199, 0.489, 3.7
Yellow-Red (10YR, 2)	0.220, 0.502, 3.6	0.208, 0.485, 3.6
Red-Purple (5RP, 2)	0.219, 0.485, 3.6	0.207, 0.464, 3.6
Purple-Blue (5PB, 2)	0.203, 0.478, 3.7	0.192, 0.456, 3.7
Purple (10P, 1)	0.212, 0.483, 2.6	0.201, 0.462, 2.6

Table S1. Chromaticities of stimuli used as background checks or target colours, specified as a triplet value corresponding to CIE 1976 u’, v’, L coordinates. The left column in the table specifies the Munsell hue and saturation references associated with each colour. The first two colours were used for the blue and green masks. All colours were used to define the checks comprising the display scene, except for the last (deep purple) which was used to define the fixation cross and spatial cue.

	L	**M**	**S**
Prime	0.0540	0.0240	0.0684
Prime Background	0.0572	0.0238	0.0648
Surface Mask	0.0536	0.0249	0.0918
Surface Mask Background	0.0571	0.0239	0.0678
Reflected Mask	0.0540	0.0240	0.0684
Reflected Mask Background	0.0571	0.0239	0.0676
	$\boldsymbol{L/\bar{L}}$	$\boldsymbol{M/\bar{M}}$	$\boldsymbol{S/\bar{S}}$
Von Kries Scaled Prime	0.944	1.011	1.055
Von Kries Scaled Surface Mask	0.938	1.040	1.354
Von Kries Scaled Reflected Mask	0.946	1.006	1.012

Table S2. Results of modelling the effects of von Kries transformation on sample prime and target stimuli. The upper six rows show the average L, M and S activations elicited either across the whole scene for each type of stimulus or just within the prime or mask. Note that there is very little difference in the global average signal elicited as the illuminant boundary shifts between prime and mask conditions. The lower three rows show the effect of global von Kries-like scaling on the prime and each type of mask by dividing their respective L, M and S co-ordinates by the average activations across the whole stimulus in each case.

Supplemental Experimental Procedures

Apparatus

Stimuli were presented on a gamma-corrected ViewSonic 17’’ display monitor (resolution: 680 x 480 Hz; refresh rate: 160 Hz; viewing distance: 47cm) using a Cambridge Research Systems ViSaGe Graphics System calibrated with a Cambridge Research Systems ColorCal chromameter and a Cambridge Research Systems SpectroCal spectroradiometer.

Chromaticities

The stimuli were constructed by computing the activations of cones in the retina that would be elicited by matte Munsell surfaces under two types of illumination and presenting colours in the computer display that would elicit the cone signals corresponding to the simulated materials and lighting in the stimulus. Spectral reflectance functions of matte Munsell samples were acquired from the online Database of the University of Joensuu Color Group (http://spectral.joensuu.fi). In addition, samples of the radiance functions of the CIE illuminants D50 and D65, normalised to unity at 560nm, were acquired from Hunt and Pointer [S1]. Both the radiance functions and reflectance spectra were sampled in 5nm steps within the interval 390-780nm. The RGB values for a particular colour under a particular illuminant were calculated using the following procedure. The spectral reflectance function of the Munsell surface was first multiplied by the spectral power distribution of the illuminant, wavelength by wavelength, giving the spectral power distribution of the reflected light. This resultant distribution was then multiplied individually by the short-, medium- and long-wavelength cone sensitivity fundamentals, wavelength by wavelength. The three resultant distributions were then summed over wavelength to give the relative cone excitations (LMS triplet) for the reflected light for a standard observer. Each LMS triplet was then multiplied by a common factor to attain colours that were reduced in intensity as this improves the masking of the prime (see

Table S1 for chromaticity and luminance information). The LMS triplet for each colour could then be converted to an RGB triplet through use of a matrix that is the inverse of the product of the cone sensitivity fundamentals and the RGB primaries of the monitor.

Participants

A separate group of ten participants took part in each of the four experiments. These participants were either undergraduate or postgraduate students or members of staff at Durham University.

Procedure

A single session in the priming and detection phases consisted of 200 trials, which included the 0 (prime absent), 12.5 ms and 37.5 ms prime durations in the ratio of 2:1:1, and the blue and green mask colours in the ratio of 1:1. The presentation of a trial was contingent on the participant fixating the central cross within a radius of 1°, as measured by an infrared video eye-tracker (Cambridge Research Systems).

The display was divided into 6 x 6 evenly spaced checks (each subtending 8.30° x 5.86°) with each one assigned a random surface reflectance from a set of six on each trial (see Table S1 and Figure 1 for chromaticity information). The checks at the location of the prime and target, however, were not assigned the colour of either blue or green. Half the display, bisected at an angle of 45° or 135°, was illuminated by the standard CIE illuminant D50 and the other half by D65. In half the trials the prime was not present (prime duration 0 ms). When present, the prime (a disc with 1.76° diameter) always appeared in the D50 section of the display, 5.86° either above or below fixation, and remained onscreen for 12.5 or 37.5 ms before its offset. The stimulus onset asynchrony (SOA) between the prime and mask was always 50 ms. Between the offset of the prime and the onset of the mask (an annulus with 4.39° outer diameter and 1.76° inner diameter), the illuminant boundary of the scene changed such that the prime and mask appeared under different illuminants - D50 and D65, respectively. The mask was either blue or green. The prime's chromaticity was always equal to that of the green mask, but because the prime was seen in the context of the D50 illuminant this chromaticity matched almost identically that of the blue mask if it were illuminated by the prime's illuminant (D50).

In experiment three, the prime and mask sizes were increased to 1.98° and 6.59°, respectively, to accommodate the inclusion of the chromatic borders. The chromatic borders occupied the inner and outer .70° of the mask.

In experiment four (the matching tasks), surface-colour constancy indices were acquired by asking a separate set of 10 participants to vary the chromaticity of the mask until the prime and mask appeared to be cut from the same material. Reflected-colour constancy indices were acquired by asking participants to vary the mask's chromaticity until it matched the prime's appearance in terms of hue and saturation. A third control condition was also run. Here, the reflected-colour constancy index was measured through the simultaneous presentation of the prime and mask in separate halves of the display under separate illuminants (whilst maintaining local contrast cues across conditions). This third condition more closely resembles the standard methodology of asymmetric colour matching and thus it served to validate our methodology for determining the indices of colour constancy for both surface and reflectance colour. For each condition observers completed a block of six matches after a practice block. Participants adjusted the chromaticity of the mask along an axis in CIE u' v' space that intersected the points corresponding to the chromaticities of the green wavelength-matched mask and the blue surface-matched mask (separated by 20 steps). The starting chromaticity of the mask within each block was random and counterbalanced. To avoid effects associated with retinal adaptation, participants were allowed to move their eyes freely during the task. The prime was made visible by increasing its exposure duration to 1875 ms. The mask was also displayed for 1875 ms.

Modelling the effects of adaptation through von Kries scaling.

It is important to show that our findings are not simply explained by low-level mechanisms of constancy (i.e. von Kries transformation of photoreceptor sensitivity). This does not seem plausible given the results of our final experiment in which the judgments subjects made when attending to the hue, saturation and lightness of targets were unaffected by changes in illumination even when we found substantial effects on judgements about surface-colour. Any subcortical adaptation should surely affect judgments both of surface and reflected light. Subcortical adaptation can affect hue, saturation and lightness judgments but typically does so in experiments where there is a wholesale change of illumination across the visual scene. In contrast, in our experiment we shift the boundary between two areas of illumination and so have much weaker changes in the overall colour of stimuli.

Nonetheless, we modelled the effects of von Kries-like scaling on LGN responses to our stimuli as follows. First, we computed the unadapted L, M and S cone activations elicited at each point in the entire prime stimulus, the entire surface-colour mask stimulus and the entire reflected-colour mask stimulus. For each stimulus we computed the average L, M and S activations elicited across the whole scene (the L, M and S activations for each region of colour weighted by area; see Table S2). We computed the effect of global von Kries-like scaling on the prime by dividing the L, M and S co-ordinates of the prime itself by the average activations across the entire prime stimulus. We similarly computed scaled surface and reflected mask activations by dividing the untransformed co-ordinates of each mask by the average activations of the entire stimulus in which it appeared. These adapted responses were then converted into DKL space (luminance = L+M, red-green = L-M, blue-yellow = S – (L+M)) and the hue angle in the isoluminant plane was calculated for the adapted prime, adapted surface-colour mask and adapted reflected-colour mask. If von-Kries scaling is to account for our observed surface priming advantage then the difference between the hue angles of the adapted prime and adapted surface-colour mask should be smaller than the difference in hue angle between the adapted prime and the adapted reflected-colour mask. This is not the case, for example, when we use the same set of background rectangles for both types of mask stimuli the hue angle between the adapted prime and adapted reflected-colour mask is very small, 0.6 degrees of colour angle in our model, whereas the angle between the adapted prime and adapted surface mask is much larger, 5.1 degrees. Von Kries-like adaptation cannot account for our findings.

In addition, we have also run the same analysis on an entire set of stimuli that would be presented in a full sequence of trials (n=600) in experiment 1. The results of this modelling are shown in Figure S3. The graph plots the colour co-ordinates in DKL space of the primes and masks after the transformations of von Kries adaptation to their individual backgrounds. If von Kries adaptation explained our results we would expect the distances between the points representing the adapted primes (red dots) and those representing the adapted surface masks (green dots) to be more similar than the distances between the points representing the prime and those representing the adapted reflected light masks (blue dots). As can be seen, however, this is evidently not the case, and the cluster of adapted reflected light masks almost overlies that of the adapted prime colours.

Finally, we extended the model to explore the effects of variation in the spatial scale over which the adapting signals were sampled. In our previous analyses we pooled adapting signals over the entire visual field. At the other extreme, if the adapting stimulus for any cone is simply the activation of that cone itself then rapid complete von Kries adaptation will simply result in all cone signals being scaled to unity. The receptive field over which adapting signals are integrated must be larger to be useful. It is not, however, clear exactly how large they must be (see e.g. discussion in Rieke & Rudd, 2009). Here, instead of using averages across the entire stimulus as the von Kries scaling factors, we modelled the effect of using different sizes of Gaussian receptive fields for each point in the stimulus for generating adapting signals. We convolved the stimulus with a Gaussian filter to compute an adapting signal for each cone class at each point in the stimulus. We then compute the scaled response for each point within a prime or a mask and take the average across the prime or across the mask. We applied this model with Gaussians whose standard deviations ranged from 4 to 64 pixels to a set of 20 random prime and mask stimuli (the radius of the prime is 16 pixels, the radius of the outer edge of the mask is 32 pixels). None of these Gaussians results in a closer match between adapted primes and adapted reflected light masks than between adapted primes and adapted surface match masks. Figure S4 illustrates a representative subset of these results.

Supplemental References:

[S1] Hunt, R. W. G., & Pointer, M. R. (2011). *Measuring Colour.* West Sussex: John Wiley & Sons, Ltd

[S2] Rieke, F. & Rudd, M.E. (2009). The Challenges Natural Images Pose for Visual Adaptation. *Neuron, 64*, 605-616.