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Colour Appearance of Surfaces as Affected by Different Time-Varying Colour-Adaptation Sequences

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We report on experiments in which observers judged colour appearance within the context of time-varying colour adaptation. We used pairs of contextual images consisting of a rapid succession of colour surfaces reproduced under different illuminants to analyse the effect of temporal colour adaptation rather than a spatial context on asymmetric matching and also to judge its influence upon the cone excitation components. We used adaptation colour distributions along the red–green and yellow–blue axes (selective conditions) and random colour distributions (non-selective condition). The results of observers' matches for both conditions showed approximate colour-constant appearance. Although light adaptation did not fully compensate the colour changes, we obtained average colour-constancy index values of 0.6. The results for the two opponent conditions showed similar contextual effects. No significant differences between each condition were found for the L- and S-cone mechanisms and the three test illuminants. On the contrary, some degree of interaction between the comparison-field cone excitations and the colour axis can be seen when the colour mechanisms are analysed separately. This seems to be more pronounced for the S-cone mechanism and suggests that the selective condition of the adaptation sequence may well affect the observer's chromatic matching response.

Key words: colour appearance, colour vision, colour mechanisms, colour constancy, adaptation, vision

1. Introduction

The colour appearance of surfaces depends upon previous adaptation to lights or surfaces as well as any lights or surfaces surrounding the stimulus in question. Chromatic adaptation processes adjust visual sensitivity according to the luminance and chromaticity of the light entering the eye. Many studies have analysed the influence of context on colour appearance but only a few have examined possible interactions between the chromatic mechanisms at post-receptor levels and their effect on colour appearance[1–4] and colour constancy.[5–9]

The perception of colour under different illuminant conditions may be influenced by contrast adaptation. Using surface reflectances derived from a Munsell set of colours, Webster and Mollon[7] found that temporal adaptation stimuli biased colour appearance towards the axes of their colour distributions. These authors also obtained similar results when they examined visual adaptation processes in response to natural images.[2] Their results showed partial chromatic selectivity when the bias of the adaptation stimuli varied along different chromatic axes. Adaptation to the high-contrast, yellow–blue variation of the colour distributions resulted in a relative loss in perceived colour contrast for the yellow–blue axis. According to these results, contrast adaptation, at least for stimuli with temporal rather than spatial contrast, does not seem to discount the illuminant completely (perfect colour constancy).

The effects of steady-state adaptation on colour appearance also suggest partial chromatic selectivity with red–green and yellow–blue adaptation, resulting in asymmetric matches that differ mainly in the L-2M or S-cone coordinates respectively.[1] Furthermore, changes in the illuminant alter chromatic mechanisms in a specific way and may be used to predict the constant colour appearance of surfaces. Illuminant changes induce additive changes along the red–green dimension and multiplicative changes along the yellow–blue dimension.[8] This has been experimentally confirmed by using chromatic-selective colours.[9] In these experiments observers' matches were adequately predicted by assuming affine transformations between test and standard illuminant conditions, although some discrepancies were found along the yellow–blue dimension. These correlations can be used in a simplified colour-constancy model, since all that is required to discount the illuminant is to know the average red–green and yellow–blue chromatic variation in a scene. These new approaches go beyond the Von Kries hypothesis[10] in characterising the effect of context for each colour mechanism.

But it has been shown that the colour appearance of surfaces depends upon their spatial colour context. Asymmetric colour matches between contextual pairs of images have demonstrated that the S-cone component of the matches depends upon the L and M cones.[3] Thus it is interesting to extend the experiments to time-varying contextual image pairs, which might allow us to predict the effect of temporal contexts on the cone-excitation components. Other experimental paradigms have demonstrated the existence of immediate mechanisms at the first stage of colour perception that involve little adaptation. The signal encoded by the L-, M- and S-cone receptors offers cone-excitation ratios that provide the cue for discriminating changes in the illuminant from those of surface reflectance changes.[11] These cone-excitation ratios are preserved even under fast illuminant changes in which the eye is not fully adapted to the differently illuminated surfaces,[12] which indicates the importance of the time involved for adaptation when any change in illuminants occurs.

In the experiment described here observers judged colour appearance in the context of varying colour sequences. A series of asymmetric matches were made in which the subjects were exposed to a rapid sequence of selected surface colours. We then analysed how these chromatic-

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selective adaptation sequences affected the shift in colour appearance under different illuminant conditions. Thus our study concentrates on the effects upon asymmetric matching arrangements of adaptation in a temporal context rather than the spatial context that has usually been given priority in previous works. More specifically we have studied whether temporal adaptation influences the chromatic component of the matches. We took particular care to test the bias in the additive and multiplicative effects that a change in illuminant has on colour appearance.

2. Methods

2.1 Apparatus

The experiment was run on a Pentium II computer with an 8-bit per gun Number Nine graphic card. Object colours were reproduced and presented on a high-resolution 17" Multisync E700 NEC colour monitor. A Photo Research Spectrascan PR-704 was used to calibrate the monitor. The apparatus provided a relative error in luminance measurements of 2% and ±0.003 for the chromatic co-ordinates (applied to the CIE A standard illuminant). The calibration procedure[13,14] basically involves measuring the spectral power distribution of each gun for the entire set of permitted DAC values. This allows the chromatic co-ordinates of any stimulus reproduced in the monitor to be calculated through the relationship between the DAC values and the tristimulus values in the CIE-1931 space.

2.2 Surfaces

There were two basic sets of surfaces: the *comparison surfaces*, which reproduced the surfaces to be matched under a given illuminant, and the *adaptation surfaces*, each of the surfaces being used in the time-varying sequence of adaptation colours.

All the surfaces used in this experiment were selected from the set of natural and man-made objects measured by Vrhel *et al.*[15] The spectra [surface spectral reflectance $S(\lambda)$] of this set of objects can be satisfactorily approximated by a suitable linear combination of three vectors in the following way

$$S(\lambda) = \sum_{j=1}^{3} \sigma_j S_j(\lambda) \quad (1)$$

where S_j represents the basis vector and σ_j its corresponding weight. The gamut of colour signals for each illuminant change was then calculated from the product of these surface spectral reflectance's, $S(\lambda)$, and the spectral power distributions, $E(\lambda)$, of each of the illuminants. From these colour signals it was straightforward to determine their L-, M-, and S-cone excitations according to the cone fundamentals of Smith and Pokorny.[16] The outputs of the cone are combined at post-receptor levels in two opponent-colour mechanisms—the red–green channel and the yellow–blue channel—and one non-opponent mechanism—the luminance channel. The two colour-opponent signals are represented by the axes of the MacLeod–Boynton chromatic diagram,[17] with the horizontal axis representing L/(L+M) and the vertical axis S/(L+M).

Figure 1 shows the chromaticity co-ordinates of the nine surfaces used as comparison surfaces in the experiment. The surfaces were located along two axes: a tritanopic confusion line, where only the excitation level of the S cones varied, and an equal-excitation line of the S cones, where the excitation of the L and M cones was opposing. Their luminance was fixed at 20 cd/m^2.

Table 1 shows the average chromaticity co-ordinates of the surfaces used for adaptation as they were offered under each illuminant. These surfaces, as we shall explain below, were projected onto both the comparison and test areas in the monitor, and reproduced under the comparison or the test

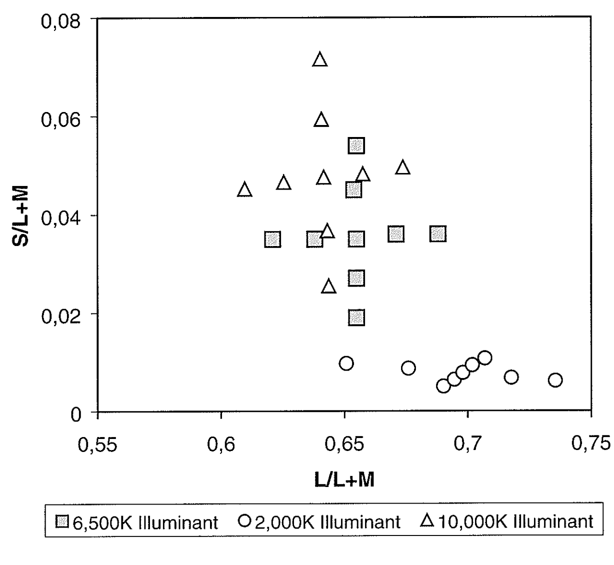

Fig. 1. Chromaticity co-ordinates of the surfaces used in the experiments. The squares represent the 9 comparison surfaces when they were shown under the 6,500 K illuminant. The co-ordinates of surfaces under the test illuminants are also shown.

Table 1. Average chromaticity co-ordinates of the surfaces used for adaptation as they were offered under each illuminant. These surfaces define each of the lines used in the three adaptation sequences: Rg–Yb, Yb–Rg and non-selective condition.

Line	6,500 K illuminant		2,000 K illuminant		10,000 K illuminant	
	L/(L+M)	S/(L+M)	L/(L+M)	S/(L+M)	L/(L+M)	S/(L+M)
RG	0.683	0.023	0.707	0.006	0.659	0.032
YB	0.681	0.020	0.729	0.005	0.682	0.028
Non-selective	0.682	0.021	0.717	0.006	0.676	0.029

illuminant respectively. The colours comprising the sequences were selected from the 170 natural objects measured by Vrhel *et al.*, and were chosen either along lines of equal excitation of the S cones or lines of constant excitation of the L cones. These critical axes were selected according to an arbitrary tolerance criterion because the natural-object colour set was of finite extension (total quantity of 170 objects). The tolerance was selected according to previous chromatic discrimination results[18] and to ensure a minimum number of objects in the adaptation colour distributions.

2.3 *Illuminants*

Three illuminants were used: a 2,000 K illuminant, representing the radiation of a black body at 2,000 K, a 10,000 K illuminant, representing the radiation of a black body at 10,000 K, and a 6,500 K illuminant, representing a daylight phase with a correlated colour temperature of 6,500 K. The 6,500 K illuminant was also used as the reference illuminant. The illuminants were reproduced using a three-dimensional linear model.[19,20] The chromaticity co-ordinates of the illuminants are shown in Table 2, where the weights M_1 and M_2, which characterise each of the spectral power distributions as a linear combination of the mean vector and two characteristic vectors, are also given.

2.4 *Spatial configuration*

The surfaces were presented on a colour monitor screen at a distance of 100 cm (maximum visual field of 7.5 horizontal × 10.6 vertical deg) from the observer. The matches were always made binocularly and a forehead rest was used to keep the observer's head in place. All the experimental sessions were run with the monitor in a black chamber to avoid visual interference from any other objects.

The comparison surfaces were presented upon a uniform background (upper field in the monitor) with a visual angle of 7.5 × 5.3 deg (Fig. 2); this area was kept at the chromaticity of the comparison 6,500 K illuminant with a luminance of 19.5 cd/m^2. The comparison stimuli occupied a 2-deg field centred 0.6 deg above a red cross as fixation point. The test surfaces were also presented upon a uniform background (lower field in the monitor) with a visual angle of 7.5 × 5.3 deg; in this case the area was kept at the chromaticity of the test illuminant with an average luminance of 19.5 cd/m^2. The test stimuli occupied a 2-deg field centred 0.6 deg below the fixation point. The time-varying sequence of adaptation colours was presented on both the upper and lower fields, as explained below.

2.5 *Experimental procedure*

Each of the observers set matches to nine different

Table 2. Chromaticity co-ordinates and weights M_1 and M_2 of the comparison and test illuminants.

Illuminant	*x* co-ordinate	*y* co-ordinate	M_1	M_2
2,000 K	0.4538	0.4280	−0.7560	−0.5025
6,500 K	0.3129	0.3272	−0.0036	0.0160
10,000 K	0.2773	0.2948	0.1617	−0.0134

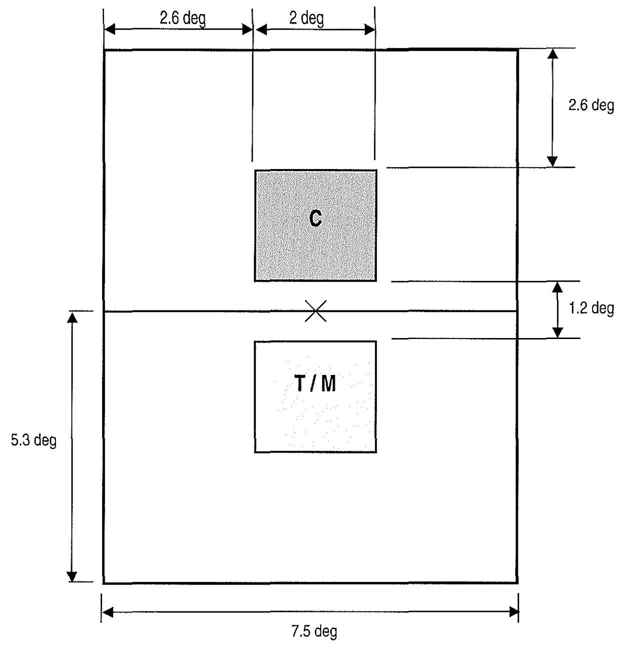

Fig. 2. Spatial arrangement for the comparison (C) and the test/match (T/M) areas.

comparison surfaces. To address the problem of the effects of adaptation upon the colour appearance of surfaces, a series of asymmetric matches were made with a similar experimental arrangement to that followed by Webster and Mollon.[7] The main innovation was the time-varying adaptation sequence presented on the test field. This allowed us to use in a temporal context pairs of images—the comparison and the test/match field—which could be reproduced under two different illuminations.

The sessions began with 3 minutes' dark adaptation followed by 10 seconds' adaptation to both the comparison (upper field) and the test (lower field) achromatic backgrounds. A beep indicated the end of this period and the beginning of a further 5 minutes' adaptation to a random sequence of surfaces every 1 s. These adaptation colour distributions appeared simultaneously in the upper comparison field and in the lower test field under a 6,500 K or a test illuminant respectively. The presentation frequency of 1 Hz was a compromise between the shorter and the larger times that contribute to colour appearance and sufficed to total adaptation.[21] Although recent studies have found an additional fast component of colour appearance of no more than a few milliseconds,[22] we tried to avoid undesirable chromatic after-effects and take into account only strict adaptational effects rather that colour contrast phenomena. The observers were encouraged to keep their gaze steady on the fixation point and to avoid alternating their attention rapidly between the two fields. This was done to maintain a separate but constant adaptation in the upper and lower visual areas. Each surface of the adaptation colour sequences was drawn from the adaptation colour distributions defined by the average chromaticities shown in Table 1. Once the adaptation period was over the comparison and test fields were held at the chromaticity of the 6,500 K and test illuminants for 1 s. The observer was then presented in turn

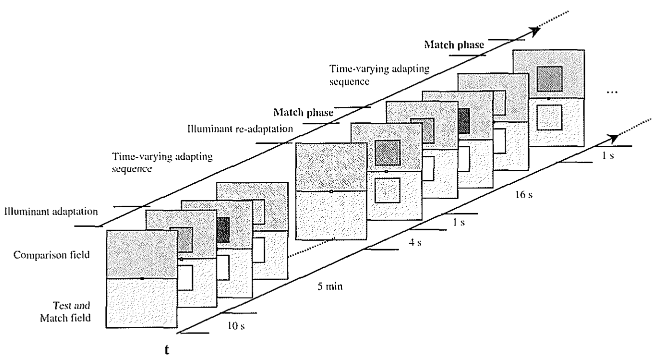

Fig. 3. Time sequence of the experimental sessions.

with a comparison surface in the upper field for 4 s followed by the achromatic background and a 16 s interval of re-adaptation to the colour sequence (Fig. 3). While the comparison surface was present in the upper field the observer set a colour match between this surface and the test field placed below the fixation point. The matching surface was then followed by a 16-second interval of re-adaptation to the test colour sequence. The observer had six keys available on the keyboard to separately increase or diminish the DAC values of the red, green, and blue guns of the monitor by one unit. Two additional keys controlled brightness.

According to the colour distributions (adaptation sequences) selected, there were three kinds of experimental sessions: the '*Rg–Yb condition*', in which the comparison field was presented with a red–green adaptation-colour sequence and the test field with a yellow–blue adaptation-colour sequence; the '*Yb–Rg condition*', in which the comparison field was presented with a yellow–blue adaptation-colour sequence and the test field with a red–green adaptation-colour sequence; and the '*non-selective condition*', in which the comparison and test fields were presented without any pre-ordained selection in the adaptation-colour sequence. The observers were not informed about the kind of experimental session they were involved in. In each session the observers set matches to five different comparison surfaces and only one test illuminant condition was presented. The matches reported were based on the average of four colour matches made for each comparison surface and adaptation-sequence combination.

2.6 *Observers*

One of the authors and two naïve observers participated in the experiment. All were corrected to normal acuity and had normal colour vision according to standard colour tests (Ishihara and Farnsworth D-15).

3. Results

Previous to all our experiments we made a series of control matches to test the influence of the adaptation sequences with no changes in the illuminant. We then measured the extent of chromatic adaptation for the two opponent conditions: the Rg–Yb condition and the Yb–Rg condition, and also the non-selective condition, this latter condition being used as a standard to investigate the effect of the opponent adaptation sequences in the colour matches.

3.1 *Control experiment*

The matches were made without illuminant changes between the upper (comparison) and the lower (test) areas. These matches were symmetric and controlled any possible biased results which might have been due to the time-varying sequence configuration. The results for observer JN are shown in Fig. 4. The means of the matches never deviate far from the position of the 6,500 K test co-ordinates. Figure 5 shows the same data for observer E, but separately for each cone component. All the matches cluster around the line of unity slope, indicating an almost perfect match between the comparison and test areas.

Below we define a simple colorimetric evaluation and

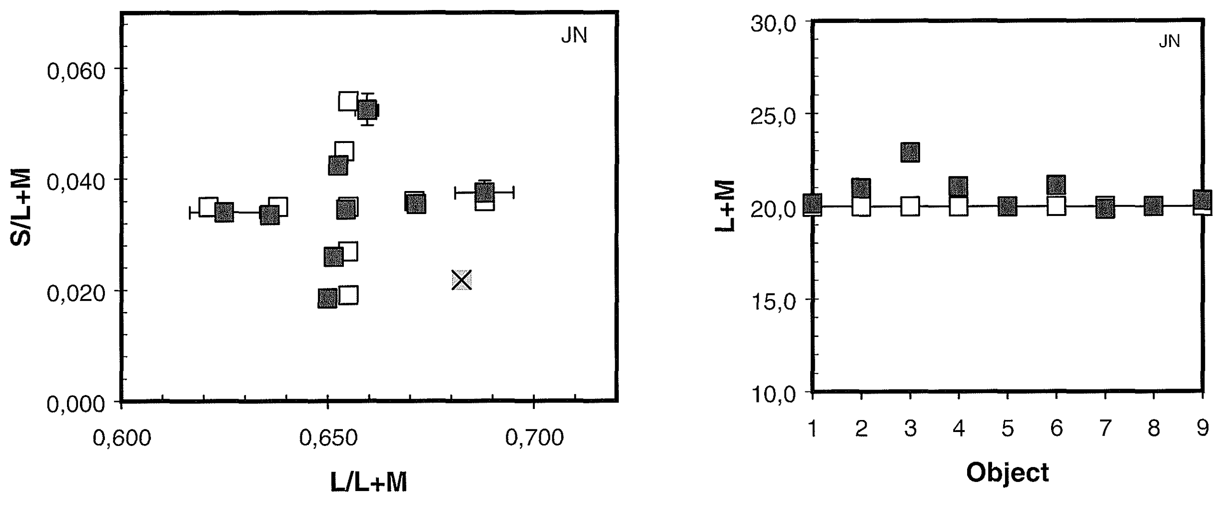

Fig. 4. The left-hand panel shows the cone co-ordinates of the comparison (open symbols) and match (solid symbols) stimuli for observer JN in the control experiment. The right-hand panel shows the same data with luminance plotted against the surface in view. Similar results were obtained for the other observers. The crossed symbol specifies the average colour of the adaptation sequence. The error bars indicate ±1SEM.

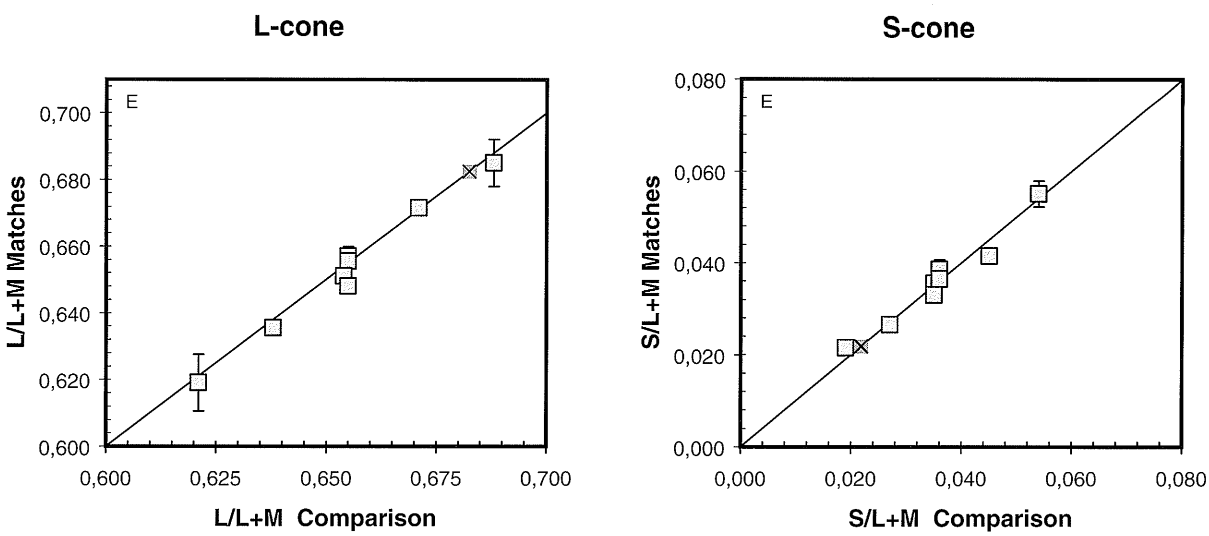

Fig. 5. The same data as that in Fig. 4, here for observer E, and set out separately for each cone class. The panels plot the L-cone and the S-cone components of the matches (solid symbols) *versus* the comparison components.

convert our data to the CIELUV uniform colour space[23] for evaluating the extent of the colour differences. The white point for the transformation to L*u*v* space represents the tristimulus values of a perfect reflecting diffuser under the 6,500 K comparison illuminant and a luminance of 20 cd/m^2. The mean values obtained for all the observers and objects were 4.1 ΔE^*_{uv} units, which concurs with the degree of error found in similar experiments.[5,24] What is more, although the colour of the adaptation sequence (solid crossed square) does not coincide with the central point of the comparison set of objects, this does not influence the control matches. This result forestalls the possibility that the results of our subsequent experiments might be biased by chromatic-induction effects caused by the spatial configuration of the comparison and test areas.

An additional test was made to check the dependence of the control matches upon the illuminant. In these symmetric matches we chose both the 2,000 K and 10,000 K illuminants as comparison illuminants and repeated the above experiment. The results were qualitatively the same as those shown in Fig. 4. Thus we were satisfied that the key experimental factor would be the variable colour appearance induced by the adaptation-colour sequences between the comparison and the test areas.

3.2 Adaptation colour sequences and changes in illuminant

3.2.1 Non-selective adaptation condition

In this experiment the matches were made under two different illuminants: the comparison area was viewed under the reference 6,500 K illuminant and the test area under one of the test illuminants (either the 2,000 K or 10,000 K illuminant). The results for observer JN are shown in Fig. 6. The top panels plot the results for the L-cone component and the bottom panels those for the S-cone component. The effects of temporal context are revealed in the figures when the match and test co-ordinates differ for one cone class. Our results suggest that context effects are not clearly evident for both test illuminants since the observer's matches lie along the positive (solid line) diagonal. Only for the S-cone and the 2,000 K illuminant do a few matches fall any distance away from the positive diagonal. These matches correspond to the test objects characterised by the highest values of the S-cone component. What is clear is that the matches do not lie along the lines which connect the origin and the cone co-ordinates (crossed symbol) of the averaged adaptation sequence.

The context effect is more clearly shown in Fig. 7, where the S-cone component is plotted against the L-cone component. The figures also show the luminance component *versus* test objects. Constant colour appearance, or colour constancy, should be indicated by a coincidence of the solid squares and the open triangles. The upper left-hand panel, which corresponds to the 2,000 K illuminant, suggests a temporal contextual effect although no systematic trend appears. As expected from the previous figures, the S-cone values deriving from the observer's matches are greater than the predicted (open symbols) test values. We have evaluated this trend via a standard colour-constancy index, as defined by Arend *et al.*,:[25]

$$CI = 1 - \frac{a}{b} \qquad (2)$$

where a is the distance between the observers' matches and the comparison objects (reproduced under the 6,500 K illuminant) and b is the distance between the test objects (reproduced either under the 2,000 K or 10,000 K illuminants) and the comparison objects. The indices were calculated for the CIELUV colour space; the comparison 6,500 K illuminant and the luminance of 20 cd/m^2 were taken as nominally white for the calculations. Although light adaptation does not fully compensate the colour changes, we obtained average colour-constancy values of 0.6. This value is close to previous findings employing artificial environments, but is a long way from the highest values reported in other studies using natural environments.[26]

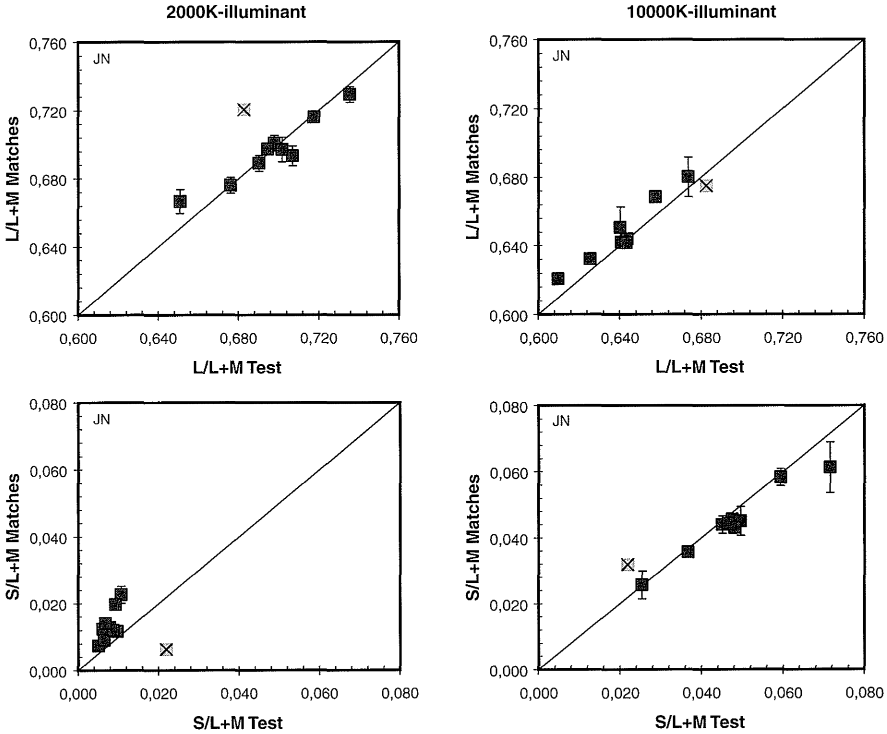

Fig. 6. The figure shows the L-cone and S-cone components of the matches (solid symbols) derived from the non-selective condition for observer JN. The match co-ordinates are plotted against the corresponding test co-ordinates deriving from the observer's matches under the 2,000 K illuminant (left-hand column) and the 10,000 K illuminant (right-hand column). Similar results were found for the other observers. The crossed symbol specifies the average colour of the adaptation sequence. The error bars indicate ±1SEM.

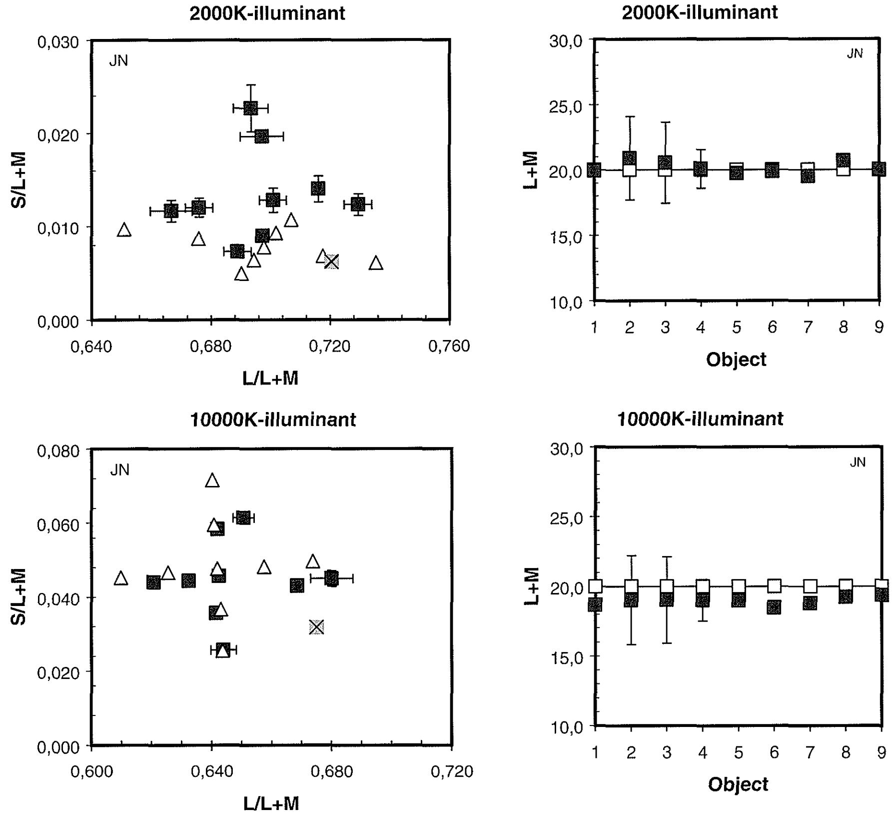

Fig. 7. The same data as that in Fig. 6 but here in the MacLeod–Boynton chromaticity space. The right-hand panels plot luminance against the surface in view. The error bars indicate ±1SEM.

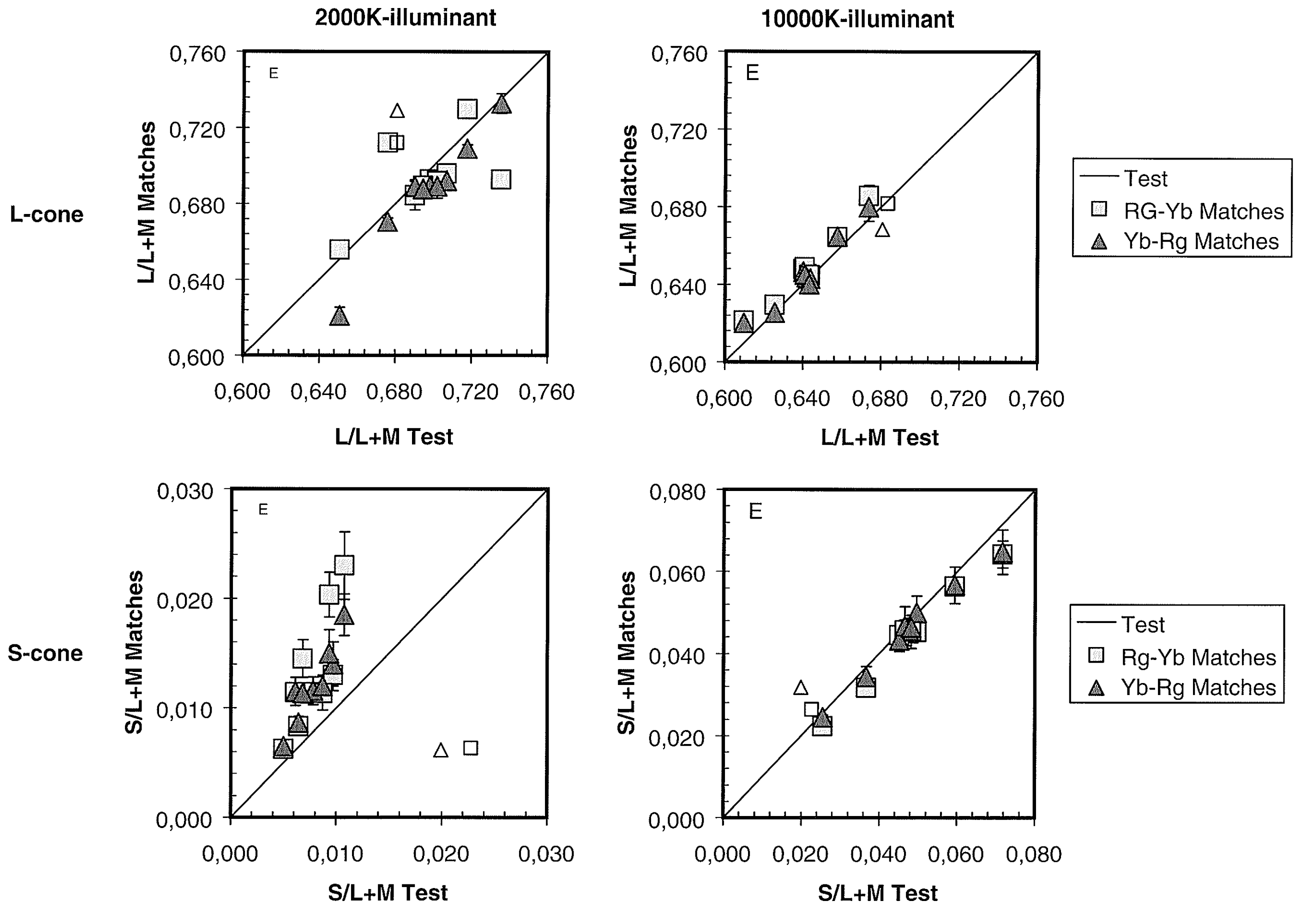

Fig. 8. The L-cone and S-cone components of the matches (solid symbols) derived from the two opponent, Rg–Yb and Yb–Rg, conditions for observer E. The match co-ordinates are plotted against the corresponding test co-ordinates deriving from the observer's matches under the 2,000 K illuminant (left-hand column) and the 10,000 K illuminant (right-hand column). Similar results were found for the other observers. The open symbols specify the average colour of the adaptation sequence used in the Rg–Yb condition (open square) and the Yb–Rg condition (open triangle). The error bars indicate ±1SEM.

3.2.2 *Selective adaptation condition*

In the subsequent experiment we tested whether the time-varying colour selectivity of the adaptation sequences influenced the matches. The matches were made under different illuminant conditions (2,000 K and 10,000 K illuminants) and the two opponent adaptation conditions (Rg–Yb and Yb–Rg) were used. In both cases the comparison area was viewed under the reference 6,500 K illuminant and the test area under one of the test illuminants.

Figure 8 shows observer *E*'s results with regard to the effect of context for the two opponent adaptation sequences. The left-hand column in the figures corresponds to the observer's matches for the 2,000 K illuminant whilst the right-hand column corresponds to the settings for the 10,000 K illuminant. The temporal context effects can be seen when the match and test co-ordinates differ for one cone class. The effect seems to be apparent for the 2,000 K illuminant, where the S-cone values deriving from the observer's matches fall outside the positive diagonal. To measure these deviations we calculated the errors in distance between the test co-ordinates (positive diagonal in the figure) and the matches. We obtained an average error of 0.018 for the L-cone component and 0.603 for the S-cone component, with the means being statistically different for a 95% confidence interval. This confirms the context effect for the 2,000 K illuminant.

In addition, the results for the S-cone component deriving from the two opponent conditions seem to be different. The S-cone values obtained from the Rg–Yb condition are generally greater than the corresponding values from the Yb–Rg condition, and are associated to the 2,000 K illuminant. These differences seem to point to high excitation of the S-cone mechanism. One concern in interpreting this behaviour is whether the differences are significant with regard to the excitation level of the colour mechanisms. To check this dependence a 3×3 MANOVA analysis was made separately for each surface and cone component. This allows us to test any possible interaction between the illuminant (10,000 K, 2,000 K, and 6,500 K) and condition (two selective and one non-selective) factors. As expected from the preceding section, we found significant differences for the illuminant factor for all surfaces and cone components. An analysis of illuminant-condition interaction leads to the following results: for the S-cone the interaction is significant only for surfaces 2 ($F = 6.287$; $p = 0.076$) and 8 ($F = 5.409$; $p = 0.084$), and close to significant for surface 5 ($F = 3.569$; $p = 0.140$), whilst for the L-cone and L+M mechanism the interaction did not produce any significant differences. Neither were significant differences found between either condition (selective and non-selective) for the L-cone, S-cone or L+M components and each of the test illuminants. The results suggest therefore that the temporal-context effects are associated to the selective colour sequences and depend upon the illuminant rather than the colour mechanism considered.

We then went on to make an analysis of variance to test the condition factor separately for each cone component, illuminant and surface. This factor appears to be significant only for the illuminant that caused the greatest colour differences in each cone component. This results in there being significant differences (or close to significant, $p < 0.1$) for the 2,000 K illuminant and the L-cone component for surfaces 1 ($F = 67.98$; $p = 0.022$), 2 ($F = 37.0$; $p = 0.101$), 3 ($F = 864.063$; $p = 0.02$), 7 ($F = 36.37$; $p = 0.11$), 8 ($F = 30.093$; $p = 0.12$) and 9 ($F = 163.0$; $p = 0.05$). Significant differences appear for the 10,000 K illuminant and the S-cone component for surfaces 1 ($F = 31.0$; $p = 0.12$), 2 ($F = 76.0$; $p = 0.08$), 4 ($F = 79.0$; $p = 0.079$), and 5 ($F = 172.0$; $p = 0.054$). With regard to the luminance component, no significant differences appear to be connected to the condition factor (at least for the isoluminant constraint established in the selection of the comparison surfaces).

3.2.3 Interaction between the adaptation conditions and colour axis

Since the comparison surfaces were selected along two critical axes, we tested a possible source of interaction between the condition (two selective and one non-selective) and the colour axis (five levels which correspond to the surfaces selected either along a tritanopic confusion line or along an equal-excitation line of the S cones). Thus, two different 3×5 MANOVA analyses were made separately for each cone component. For the L-cone component we tested the interactions between the condition and the *y–b* axis factor; and for the S-cone component we tested the interactions between the condition and *r–g* axis factor. The results revealed that as far as the L-cone component was concerned the condition caused no significant differences ($F = 0.510$; $p = 0.635$) but that there were almost significant differences for the *y–b* axis ($F = 7.906$; $p = 0.090$). A similar pattern emerged for the S-cone component, there being no significant differences for the condition ($F = 0.735$; $p = 0.535$) but close to significant differences, in this case for the *r–g* axis ($F = 12.089$; $p = 0.07$).

To complete the above results, Fig. 9 shows the L- and S-cone components derived from the condition of each adaptation-colour sequence and each of the critical axes (*r–g* and *y–b*) along which the surfaces were selected. The results suggest that the possible source of interaction between condition and axis is at the highest or lowest values of the test cone components. We can see once more from these figures that only for the 2,000 K illuminant does any context effect appear (the matches and test co-ordinates differ for at least one cone component). This is clearly shown in the upper right-hand panel of the figure, where the S-cone components are situated some way from the positive diagonal. This deviation is accentuated for high excitation values of the test co-ordinates and the non-selective condition.

4. Discussion and Conclusions

The results suggest a time-varying context effect associated to selective adaptation-colour sequences. We found that the temporal context effect depends upon the illuminant but is independent of the cone component in question (no interactions appeared between the adaptation conditions and the colour mechanisms). Furthermore, some differences resulted between each of the selective conditions, particularly with surfaces far removed from the white under the test illuminant. In each case colour constancy was similar for each colour sequence tested.

4.1 Identification of temporal context effects

Although the differences in the results between the selective and non-selective adaptation sequences may seem to be fairly insignificant it is nevertheless surprising that such differences should appear at all. The classic approach to multiplicative adaptation at the receptor level adopted by von Kries[10)] and Ives[27)] would assume that both types of experiment are characterised by the average chromaticity of the time-varying adaptation sequences. This average chromaticity would act as an effective adaptation stimulus (neutral light), giving rise to an illuminant discount process by normalizing the receptor responses to the same level under this neutral light. The choice of the adaptation sequences used here was determined by the selection and size of the set of natural objects measured by Vhrel *et al.* Although this means that the average value of the stimuli is not the same for all three types of adaptation sequence, even for the somewhat modest range of sequences and surfaces used in our experiments, the results are still noteworthy.

4.2 Observer's task and illuminant changes

One additional problem involved in colour-appearance experiments lies in the observer's task. It has been shown that colour constancy is critical about this point: matches which are made according to a surface-colour-match criterion yield better colour constancy than apparent-colour-match criteria do.[25,28,29)] Recently, Kuriki and Uchikawa[30)] have solved this complication by introducing two classes of colour appearance: surface-colour perception, i.e. the perceived colour is associated with a surface, and apparent-colour perception, i.e. the perceived colour is associated with a light rather than a surface. Nevertheless, inconsistencies between the two kinds of colour perception under chromatic illuminants (non-white illuminants) still remain. The adaptive state of the visual system has a non-linear correlation with the change in chromaticity of the illuminant, with the differences between surface- and apparent-colour perception being very considerable as the

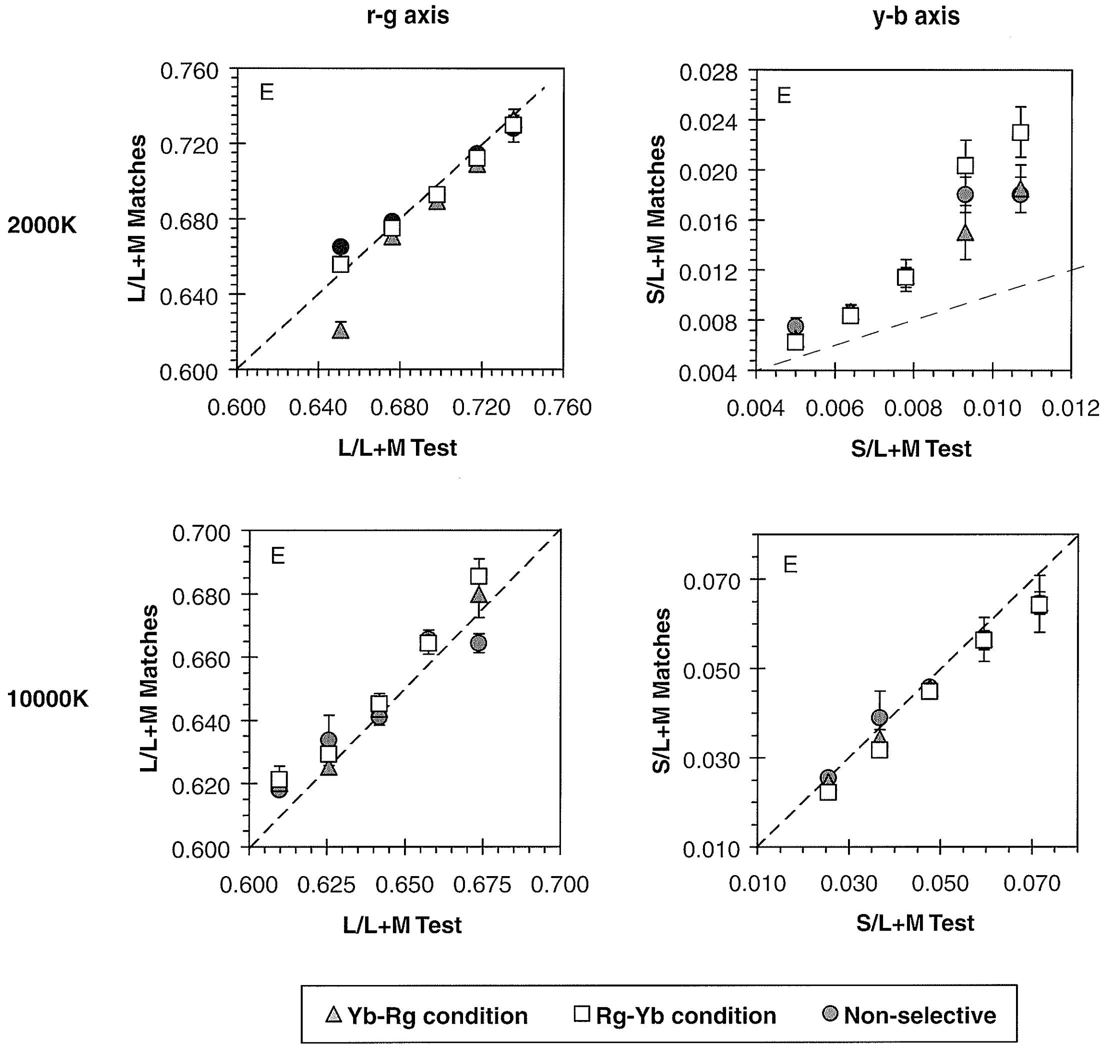

Fig. 9. The L-cone component (left-hand column) and S-cone component (right-hand column) of the matches as a function of the critical axis (*r–g* or *y–b*) along which the surfaces were selected.

illuminant becomes more chromatic.[30] Our results would seem to confirm this point, given that the lowest colour-constancy indices were obtained with the 2,000 K illuminant, which is precisely the most chromatic and that which induces most chromatic disparities. Under this illuminant the adaptation displacements deriving from the observers' matches did not completely compensate for the colorimetric ones caused by the change in the illuminant.

In this kind of study it is essential to distinguish between the bias caused by the experimental conditions and that due to the variance in the observers' matches.[12] Since particular care was taken to define the task before the experiments began, we are fairly confident that the results were not biased by differences in the observers' performance. Furthermore, the fixation point in the centre of the screen served to dissuade the observers from switching their gaze between comparison and matching areas. The poor colour constancy obtained in our experiments may possible be put down to the fact that the observers could not take advantage of viewing other surfaces simultaneously. In colour constancy experiments the surfaces due to be matched are usually included in a Mondrian surround, which might allow the observers an accidental glimpse of similar surfaces under the same illuminant.[25]

The human visual system, on the other hand, has mechanisms that do not require adaptation and allow good colour constancy with the presentation of sequential stimuli.[12] In accordance with this mechanism our results should have been better and the fact that they were not goes to support the hypothesis that the temporal effect was what restricted the response of the underlying adaptation mechanisms rather than the observer's task or the kind of asymmetric matching carried out. The observers should not decide if a particular illuminant change was detected or perceived. As we have mentioned we encouraged observers to avoid alternating their attention between the comparison and the test/match fields (a situation which is very common in simultaneous colour constancy experiments). If the observers adequately followed the given instructions a stable luminous adaptation was obtained in the upper and lower field, and they made their colour matches according only to colour appearance criteria and not based on detection or perception of illuminant change criteria.

4.3 Context effects

On the one hand, the effects of spatial context have been demonstrated by Delahunt and Brainard.[3] Despite the fact that in the experiment presented here the key factor is temporal rather than spatial, we also observed context effects. Whatever the kind of adaptation sequence used (either selective or non-selective), these effects modify the contextual image pairs mainly for the 2,000 K illuminant. Our results also concur with those obtained by Webster and Mollon,[2,7] who used highly restricted colour distributions characterising natural images. Whatever the case, we found changes in colour appearance, which indicates that the colour selectivity of the adaptation sequences could well affect match chromatically.

On the other hand, Barnes and Shevell[31] have demonstrated the influence of S-cone stimulation in colour appearance. They used haploscopic, asymmetric matching and stimuli, which selectively isolate changes in L/M- or S-cone stimulation. Their results show that the match settings depended upon the level of S stimulation in the test field, with the matching S values being little affected by the surround when the test weakly stimulated the S cones. This dependence upon S-cone stimulation has also been shown in colour constancy experiments by Nieves *et al.*[32] The results in Fig. 9 suggest a similar influence of the S-cone component for time-varying contexts: as the excitation of the S-cone mechanism increases there is a concomitant increase in the differences in its gain, differences which would appear to depend upon the conditions of selective and non-selective adaptation used in these experiments.

4.4 Perceptual organisation and grouping

We have found that the neutral light (average chromaticity) of each colour-adaptation sequence would not appear to be responsible for the changes in colour appearance that we found in our experiments. We used three temporal arrangements that alter the perceptual organisation of the surfaces comprising the adaptation sequences. Previous authors have pointed out the importance of perceptual grouping within a large visual stimulus,[33] describing experiments in which they altered the perceptual organisation of the stimuli and showed how the spatial average failed to predict chromatic induction under different spatial, rather than temporal, arrangements. In our case the background was the only adaptation point from which the observers might have extracted any accidental information while setting their matches. Given that the chromaticity of the background did not coincide with the mean of each adaptation sequence it might be valid to ask whether this would induce an additional bias to that of the neutral point. This possible bias might be responsible for the colour appearance not remaining constant under temporal varying conditions on the one hand, and on the other, for the fact that the neutral light of any sequence is unable to predict these adaptation shifts. At the empirical level, our results with temporal adaptation sequences would seem to confirm this idea and suggest that specific temporal relationships between the stimuli may play some part, which would directly influence the colour appearance of objects. This is important if we bear in mind that in our daily lives changes in illumination occur either brusquely or gradually, caused by clouds crossing the sun or moving from shady to sunny areas, which precisely correspond to those defining the temporal adaptation conditions experienced by our observers. Thus it is a matter of further studies to extend this experimental paradigm to practical colour adaptation which would involve a more realistic description of our three-dimensional visual environment.

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