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Simultaneous Colour Constancy Revisited: an Analysis of Viewing Strategies

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We examined whether matching instructions influenced the eye movements that subjects made during a colour constancy experiment. The instructions changed the average duration of exposure to the spectrally biased surround. We also measured the influence that small changes in exposure duration have on the perceived colour. Eye movement and adaptation data were combined to predict differences in colour matches. Two of the five subjects showed an instructional effect that was much larger than that predicted. Analysis of the eye movements, and an experiment with dynamic surrounding colours, reveal that several viewing strategies do not account for the influence of the instruction.

Colour vision Colour constancy Eye movements Adaptation Psychophysics

INTRODUCTION

Colour constancy is the phenomenon that perceived surface colours hardly change during considerable variations of the spectral composition of the illumination. Spatial comparisons play an important role in colour constancy. A grey surface in isolation takes on the colour of any light that illuminates it. When the same surface is embedded in a more complex scene it approximately retains its grey colour (e.g. Land, 1959; Tiplitz Blackwell & Buchsbaum, 1988a).

The main spatial interactions that underly this phenomenon are very local in nature (Walraven, 1973; Tiplitz Blackwell & Buchsbaum, 1988b; Brenner, Cornelissen & Nuboer, 1989; Valberg & Lange-Malecki, 1990; Brenner & Cornelissen, 1991; Cornelissen & Brenner, 1991). If these were the only mechanisms responsible for spatial interactions one would expect that surrounding colours have no influence when they are further away than about 1 deg. A conjunction of local retinal adaptation and eye movements can give more distant surfaces some influence without requiring the presence of a long-range neural mechanism (Lennie & D'Zmura, 1988; Shevell, 1980; Cornelissen & Brenner, 1990).

Several experimental (Walraven, 1973; Brenner & Cornelissen, 1991) and clinical (Land, Hubel, Livingstone, Hollis Perry & Burns, 1983; Wehrhahn, Heide & Petersen, 1990; Pöppel, 1986) reports seem to contradict the idea that a combination of eye movements and retinally localized adaptation is the only mechanism responsible for long-range interactions. However, the influence of the putative long-range neural mechanism appears to be quite weak, so that its contribution to colour constancy is probably quite limited.

Recently, Arend and Reeves (1986) found that the matching instructions they gave to their subjects strongly influenced the magnitude of colour constancy. In their "paper match" condition, they instructed subjects to regard the simulated surfaces on the video display as pieces of coloured paper illuminated by differently coloured light sources (stimulus as in Fig. 1). When subjects adjusted the test patch in such a way that it appeared to be cut from the same piece of paper as the reference, settings were approximately colour constant. In the "hue match" condition, subjects were instructed to make the reference and test colours look identical in hue and saturation. In that case weak constancy was obtained. This difference is evidence for a cognitive contribution to colour constancy. Later variations on their experiments confirmed these findings (Arend, Reeves, Schirillo & Goldstein, 1991; Troost & de Weert, 1991). What the cognitive factor is, is still unresolved. Colour constancy that is achieved by means of this cognitive factor can be avoided or ignored at will. Cognition could influence perception in two ways. The cognitive contribution could either be that subjects attend to different visual information, or they could change their interpretation of the same sensory information. The former option is examined in this study.

Our investigations focus on the possibility that subjects changed their viewing strategy as a result of the matching instructions. We examined this by determining whether,

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and if so how, the instructions influenced the eye movements subjects made. In the hue match, subjects only needed to inspect the surfaces they had to compare. In contrast, when carrying out a paper match, subjects had to take the surround into account. This could cause subjects to more frequently direct their eyes towards the surround and, consequently, their foveae to be exposed to the colours of the surround to a larger extent. This could lead to a different state of adaptation at the moment subjects switch their gaze towards the centre. Consequently, subjects might perceive colours differently, and make matches that are more colour constant. This hypothesis is quite plausible, because adaptation has been shown to play an important role in colour constancy and chromatic induction (Cornelissen & Brenner, 1991; Lucassen & Walraven, 1993; Brainard & Wandell, 1992). So far, no experiments have been carried out to test this hypothesis. It is necessary to do so, as it is relevant for the discussion on the relative contribution of peripheral, local mechanisms and more central, cognitive processing to colour constancy.

To test the hypothesis, we measured subjects' eye movements while they performed a colour constancy experiment. This allowed us to determine to what extent eye movements differ as a result of the matching instructions. Whether such differences will actually influence colour matching strongly depends on the speed of adaptation. The latter was determined by measuring the influence of short coloured flashes on colour perception. By combining the information from these two experiments, we could estimate to what extent adaptation, in conjunction with eye movements, should have altered the settings in the constancy experiment. We compared this estimate with the actual difference between the settings.

The eye movement recordings were further used to examine whether subjects used other specific viewing strategies. The results from previous studies (Arend & Reeves, 1986; Arend *et al.*, 1991; Troost & de Weert, 1991) imply the existence of a capacity to estimate illuminant colour and surface reflectance from the image on the retina. However, this point has not truly been proven. Subjects could have made the paper matches without having been aware of the illuminant's colour or of surface reflectance. Stimuli consisted of surfaces with identical reflectances at corresponding positions. Therefore, the subject had information on what all other surfaces looked like under both light sources. To adjust the colour of the test patch subjects did not need to recover surface reflectance *per se*. In principle, they had two other options. Firstly, they could have estimated the difference in colour between corresponding patches and used this estimate to adjust the test patch relative to the colour of the reference. Secondly, they could have estimated the difference between a specific surface in the surround and the target surface in the reference stimulus, and used this estimate to adjust the target surface relative to the colour of the corresponding surface in the surround of the test stimulus. If subjects used either of these strategies, a complex surround would not necessarily be required. Indeed, experiments have shown that observers are quite able to make paper matches in simple centre-surround stimuli (Arend *et al.*, 1991). In our view, this cannot be considered as an ability to recover surface reflectance (see also Arend & Spehar, 1993b). We examined whether subjects used either of these strategies by determining which features of the stimulus they attended to when performing the experiment. In addition, we tested this by comparing paper matches for stimuli in which identical reflectances had corresponding positions, with ones in which reflectance and position were uncorrelated and changed frequently.

MATERIALS AND METHODS

Simultaneous Colour Constancy Experiment (Experiment I)

Equipment and stimuli

The purpose of the first experiment was to determine to what extent eye movements differ when subjects receive different instructions for matching the colours. We presented stimuli on a RGB-monitor using an Apple Macintosh LC computer that has 8-bit resolution per gun. For programming the displays we used some of the C-routines provided by the "Videotoolbox" (Pelli & Zhang, 1991). Luminance was measured with a Minolta LS 110 meter and γ-corrected. The experiment essentially was a replica of the original experiment by Arend and Reeves (1986), except that we only used a grey reference colour (their data showed no systematic differences between colours). The stimulus (Fig. 1) consisted of two sets of coloured surfaces, each measuring 3.5×5 deg and separated by 1 deg. The stimuli are popularly referred to as "Mondrians", as they in some ways resemble the works of the Dutch painter Piet Mondriaan. The left "Mondrian" served as the reference stimulus while the right one served as the test stimulus. Subjects had to match a central 1×1 deg patch ("centre" in Fig. 1) on the test "Mondrian" to that of the reference "Mondrian". The "Mondrians" were generated by the computer and were different for the two test illuminations (but the same when we tested different matching instructions, see below). The colours of the surround lay along 8 lines radiating from the grey locus. Their distance from the grey locus was approximately 0.0275, 0.055 or 0.0825 CIE units (see Fig. 11). One-third of the colours were assigned a 10% luminance increase and one-third a 10% decrease to prevent blending of colours due to isoluminance. The colours were assigned at random to the patches of the "Mondrians". The centre of the reference "Mondrian" was always a simulation of a grey surface (CIE 1931 coordinates: X 0.313, Y 0.323). The experiment consisted of four conditions (Table 1). The simulated illuminant of the reference stimulus had a colour temperature of 6500K. The test stimulus was illuminated by a simulated 4000 or 10,000K light source. The coordinates of the light sources in CIE 1931 colour space were: 4000K, X 0.38, Y 0.376; 6500K, X 0.3135, Y 0.3236; and 10,000K, X 0.2787, Y 0.2919. Transformations between CIE units, monitor

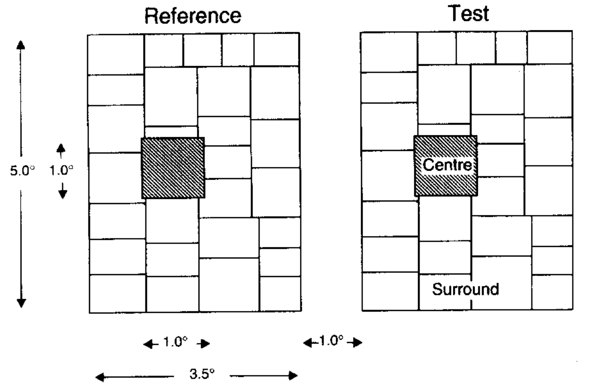

FIGURE 1. The stimulus used in Experiments I and III consisted of two sets of coloured surfaces (referred to as "Mondrians") next to one another. The left "Mondrian" served as a reference, the right one as the test stimulus. The "Mondrian" shown here is the one used in conditions 2 and 4 of Experiment I. In conditions 1 and 3 a similar Mondrian was used. In Experiment III, different "Mondrians" were generated by the computer for each condition and subject. The subjects had to compare the central 1 × 1 deg patches (centre) of the two "Mondrians". The centre of the reference "Mondrian" was always a simulation of a grey surface. The colour and saturation (and luminance in Experiment III) of the centre of the test "Mondrian" could be adjusted by changing the position of the computer's "mouse".

units and cone stimulation units were performed on the basis of Vos–Walraven cone primaries (Pokorny & Smith, 1986; see also Troost & de Weert, 1991; Lucassen & Walraven, 1993).

The colours under 4000 and 10,000K illumination were calculated on the basis of those under 6500K using a "Von Kries" transformation (Troost & de Weert, 1991). This is obviously an approximation, because the actual colour depends on a combination of the complete spectral reflectance of the surfaces and on the spectral composition of the illuminant (Young, 1987). As the surfaces' spectral reflectances are not specified, there is no "correct" transformation. The "Von Kries" transformation has been shown to be satisfactory in predicting blue–yellow shifts in a Munsell-paper environment (Worthey, 1985).

Matching instructions

The two instructions the subject received were either, to set the colour of the centre of the reference and test "Mondrian" so that these appeared to be equal in hue and saturation (hue match), or, to imagine that the coloured surfaces were pieces of paper under different sources of illumination, and to adjust the colour of the test centre in such a way that it appeared to be cut from the same piece of paper as the reference centre (paper match). As in the original experiment of Arend and Reeves (1986), it was pointed out that in the latter condition, subjects could use the colour relationships between the reference and test surround. Half of the subjects first received the hue match and then the paper match instruction (order of conditions 1–2–3–4, numbers refer to Table 1). The other subjects received the instructions in reversed order (order of conditions 3–4–1–2).

TABLE 1. Conditions of Experiment I

Condition	Matching instruction	Test illuminant (K)	Reference illuminant (K)
1	Hue	4000	6500
2	Hue	10,000	6500
3	Paper	4000	6500
4	Paper	10,000	6500

The subject could adjust the colour and saturation of the centre of the test "Mondrian" by changing the position of the computer's "mouse". Horizontal mouse movements changed the red–green ratio and vertical movements the blue–yellow ratio of the stimulus. In this experiment, luminance was kept constant by the computer to facilitate matching. This was necessary because the eye movement recordings imposed a time constraint on the duration of the experiment (see below). Subjects pressed the mouse button when they had reached a satisfactory match. During a presentation, subjects made as many matches as possible. After each match the colour of the test centre was changed by a random offset in hue and saturation. The presentation ended at the first setting after the allotted time (210 sec) had expired. We used a fixed duration during which subjects made their matches, rather than a fixed number of matches. This has the disadvantage that the number of matches was not the same for all subjects and all conditions. This was done because of the limited time that we could measure eye movements (discussed below). Subjects viewed the screen from a distance of 0.6 m with their chin in a chin-rest. The average luminance of the stimuli was 35 cd/m^2. Before the actual experiments commenced, subjects were acquainted with the experiment and procedure.

Subjects

Subjects were one of the authors (FWC) and four volunteers (AB, AF, EvW and RG) who were naive as to the purpose of the experiment. All had normal or corrected-to-normal visual acuity, normal binocular vision and normal colour vision.

Eye movements

While making the colour matches, the horizontal and vertical movements of the subject's left eye were recorded with the scleral induction coil method (Robinson, 1963; as modified by Collewijn, Van der Mark & Jansen, 1975). Under the conditions of the present experiment, this recording method has a resolution that is in the order of the pixel size of the monitor. Eye positions were recorded with a frequency of 67 Hz (monitor frame rate) for the first 210 sec of each condition. Recording time was limited by the memory capacity of the eye position recording system. The eye position signals were calibrated prior to and after each experimental condition. For each condition, the subject fixated five calibration points on the face of the display for 10 sec each (the calibration points were at the centre of the display and the upper-left and lower-right corners of the reference and test stimulus surrounds). Calibrations before and after each condition confirmed the high stability of the eye position recordings. Eye positions were transformed into positions on the screen on the basis of the calibrations immediately before and after each condition.

We determined the time subjects spent looking at different positions on the screen. The data was either analysed over the full time of the recording, or only over the last 5 sec before a setting was made. In the latter case, an event (e.g. looking at the test centre or at the reference surround) that had commenced before this period of time was included for its full extent. If two matches were made within a 5-sec period, an event was only included once. Other parameters we looked at will be described in the Results section.

The duration of the experimental sessions was limited by the restricted data storage capacity of the eye movement equipment, and the time subjects can wear the plastic contact lens that contains the search coil. The colour constancy settings, therefore, may not be as accurate as in a "normal" psychophysical experiment. We could have tried to solve this drawback by adding data from separate experiments in which we did not record eye movements, or by measuring the same subjects more often. However, these solutions were rejected as undesirable. To avoid possible complications due to blurring of the image by the contact lens, subjects performed the experiment with both eyes open.

Measure of constancy

The data is analysed in terms of cone stimulation using the colour diagram described by Macleod and Boynton (1979). A drawback of the Macleod and Boynton colour diagram is that the values on the axis differ considerably in magnitude. Calculation of a two-dimensional measure would result in a strong bias towards the L/(L + M) axis. Changes in the phase of daylight mainly affect the short-wave-sensitive (SWS) cone (Lucassen, 1993). It has been shown that when one modulates the colour along one axis in this colour diagram, subjects' settings along the orthogonal axis are negligible and not systematic (Würger, Krauskopf & Landy, 1990). Considering these findings, and the illuminants used in our experiments, we do not expect to lose significant information by only measuring shifts along the S/(L + M)-axis. We explain our measure of colour constancy in Fig. 3(A). For comparison with published data we also calculated the colour constancy index proposed by Arend *et al.* (1991) from data plotted in 1976 CIE UV colour space [see Fig. 3(B)].

Adaptation (Experiment II)

The purpose of this experiment was to measure the influence of short exposures to colours (comparable to the 4000 and 10,000K illuminants) on subsequent judgement of a surface's colour. We used the same equipment as in Experiment I. The stimulus consisted of a single 10 × 7 deg "Mondrian" with a central 3 × 3 deg patch that served both as reference and test (Fig. 2). The form of the patches in the surround changed at random between conditions. A small dot in the centre of the central patch served as a fixation point. The colour of the centre changed sequentially (Fig. 2 depicts two sequences). In each sequence, it first was black (0.5 sec), then changed into the grey reference colour (CIE values: X 0.32, Y 0.32; 2.0 sec), then into a short coloured flash of variable duration (0.03, 0.06, 0.12, 0.25, 0.5 or 1 sec) and finally took on the test colour (0.25 sec). This sequence was repeated until the subject responded.

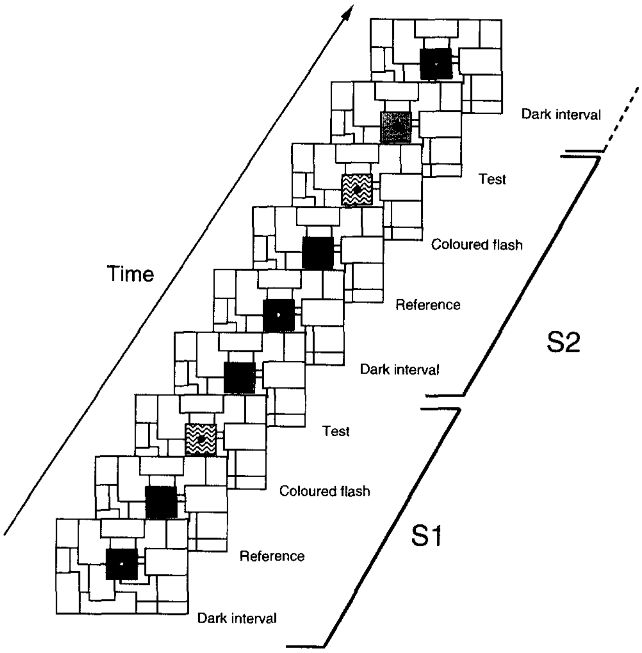

FIGURE 2. Two sequences of the presentations used in Experiment II. The stimulus consisted of a "Mondrian" measuring 10 × 7 deg with a central 3 × 3 deg patch that served both as reference and test. For each stimulus condition a new "Mondrian" was generated by the computer. A small dot in the centre of the central patch served as a fixation point. Every 0.5 sec, at the beginning of each sequence, new colours from a set of 24 were assigned at random to the patches in the surround. The colour of the central patch changed sequentially from black, to the reference colour, a short coloured flash of variable duration and then the test colour. Every sequence, the computer decreased or increased the cone stimulation provided by the test colour. The subject had to press the mouse button when the test colour had the same appearance as the reference colour.

Colours from the set of 24 possible ones described for Experiment I (see Fig. 11) were assigned at random to the patches in the surround. Every 0.5 sec, at the moment the centre became black, new colours from this set were assigned to the surround patches to avoid adaptation to specific colours. This was done within one fly-back interval in a screen refresh. Besides examining the influence of the duration of the coloured flash on the perceived colour, we also examined the influence of the duration that the test colour was presented (0.12, 0.25, 0.5 or 1 sec; flash duration was 0.25 sec).

The test colour started off being either much too blue or too yellow. Each sequence, the computer decreased or increased the SWS cone stimulation provided by the test colour. The subject had to press the mouse button as soon as the test and reference appeared to have the same colour. For each condition, each subject did three runs in which SWS cone stimulation increased and three in which it decreased with every presentation. The results were then averaged for each subject. The colour of the flash was chosen in such a way that it would stimulate the SWS cone 40% more or less than the reference colour (which is approximately the difference in SWS cone stimulation between a 6500K and a 4000 or 10,000K light source). The results are expressed relative to the difference in stimulation between the flash colours themselves, as measured along the S/(L + M)-axis in the Macleod and Boynton colour diagram (Macleod & Boynton, 1979). This measure is analogous to the first measure used in Experiment I [see Fig. 3(A)]. Subjects viewed the screen from a distance of 1 m. The average luminance of the stimuli was 30 cd/m^2.

Subjects

Subjects were three of those who participated in Experiment I (AF, EvW and FWC) and three other, naive subjects (AB, MV and JD).

Comparing Surfaces (Experiment III)

The purpose of this experiment was to investigate whether subjects need to directly compare surfaces to be able to make paper matches. The equipment, stimuli and method used were similar to those of Experiment I (Fig. 1). In this experiment, subjects could also adjust the luminance of the test centre. There were four different conditions in this experiment (Table 2). In all conditions, subjects received the paper match instruction, as explained for Experiment I. Two conditions (1 and 2) were identical to the paper matches in Experiment I. In the other two (conditions 3 and 4) the colours changed every 0.5 sec and did not correspond in reference and test stimulus (the form of the surfaces was the same and did not change). The frequently changing colours prevented subjects from trying to find patches with the same reflectance in the reference and test surround.

The surround consisted of about 40 patches. Colours were assigned to these patches at random from a set of 72 possible colours. These colours lay on two circles, 0.03 or 0.06 CIE units from the grey locus. One-third of the colours were assigned a 10% luminance increase and one-third a 10% decrease to prevent blending of colours due to isoluminance. We believe the number of patches was large enough to prevent substantial differential colour bias due to the random assignment of colours. In the condition in which the colours of the surround changed, a new set of colours was assigned to the patches every 0.5 sec. The test illuminant was a simulated 4000 or 10,000K light source. The reference was always a 6500K light source. Subjects viewed the screen from a distance of 1 m. The average stimulus luminance was 30 cd/m^2.

Subjects

Subjects were one of the authors (FWC) and three naive subjects, one of whom had also participated in the Experiment II (JB, SdV and MV). All had normal or corrected-to-normal vision, and normal colour vision.

RESULTS

Colour Constancy for Hue and PaperMatches (Experiment I)

The purpose of the first experiment was to determine to what extent eye movements differed when subjects received different instructions on how to match the colours of the reference and test stimuli. Figure 3 shows the average colour matches of two subjects. The data is presented in the colour diagram described by Macleod and Boynton (1979) as well as in 1976 CIE UV colour space. It can be seen that the settings better approached colour constancy when FWC made paper matches than when he made hue matches (the crosses show the settings that would be considered as perfect colour constancy). This difference is less evident for RG.

Figure 4 summarizes all subjects' hue and paper matches, using the measures of constancy explained in Fig. 3. The two measures of colour constancy provide very similar results. We will use the measure based on relative cone stimulation in the remainder of the paper.

The amount of constancy varies considerably between subjects. What we are interested in in this study, is the difference between the paper and hue matches: this is the influence of the matching instruction. It can be seen that this influence also differs notably between subjects. Two subjects (FWC and AF) show a fairly large difference between the hue and paper matches. The others show quite small influences (AB, EvW and RG) that are not statistically significant.

Eye movements in the simultaneous colour constancy experiment

Figure 5 shows the positions subject FWC was looking at on each frame of the presentation, when making hue [Fig. 5(A), condition 2] or paper [Fig. 5(B), condition 4] matches. The most obvious observation is that the subject did not scan the whole surround in either condition. Figure 5 does not show temporal relations between the positions the subject looked at. Figure 6 shows the horizontal eye movements of subject AF, while performing hue [Fig. 6(A), condition 1] and paper [Fig. 6(B), condition 3] matches (only the first 100 sec of each condition is shown). It can be seen that this subject

TABLE 2. Conditions of Experiment III

Condition	Matching instruction	Colour correspondence	Test illuminant (K)	Reference illuminant (K)
1	Paper	Yes	4000	6500
2	Paper	Yes	10,000	6500
3	Paper	No	4000	6500
4	Paper	No	10,000	6500

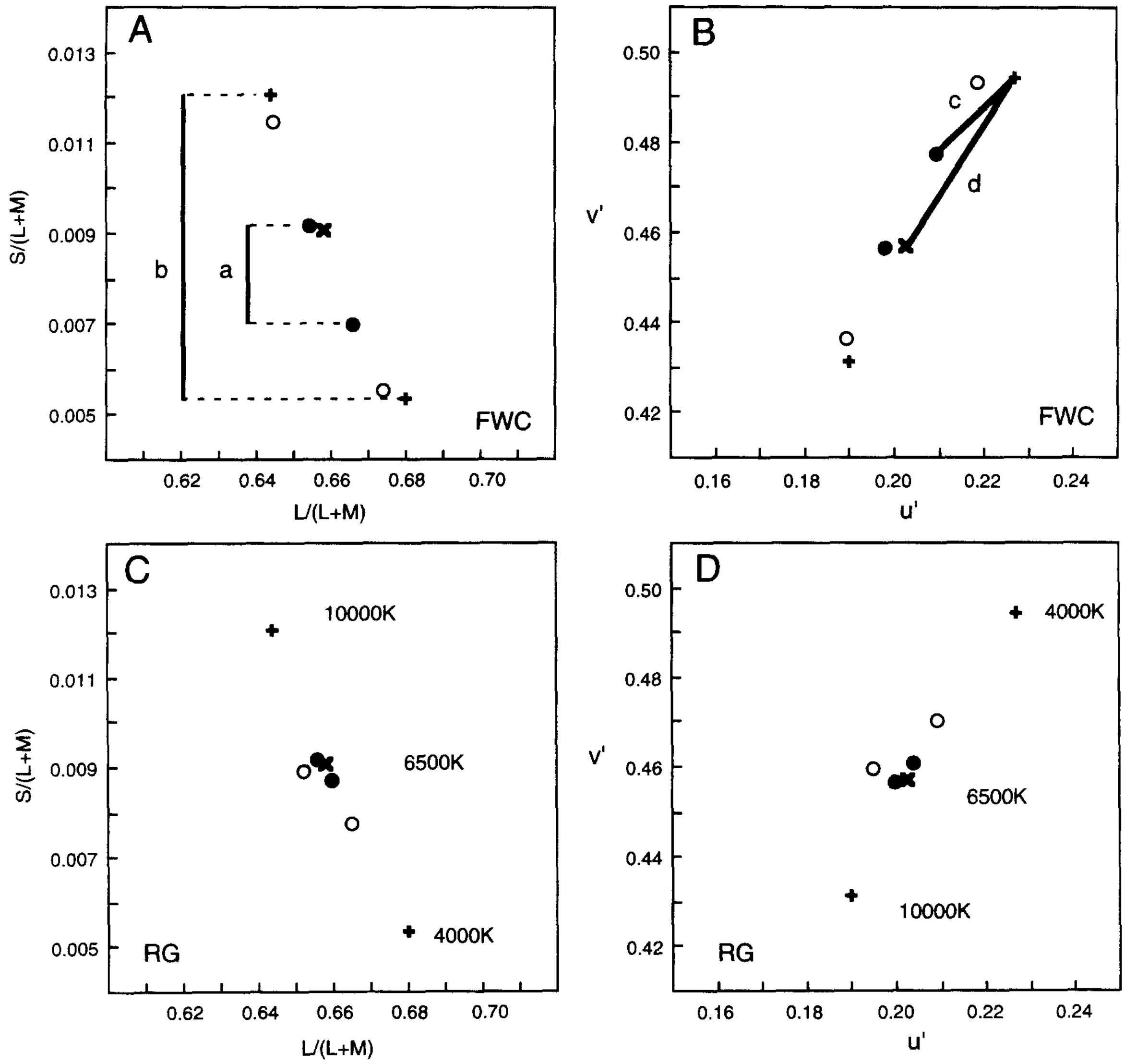

FIGURE 3. Examples of settings made by subjects FWC and RG in the simultaneous colour constancy experiment (Experiment I): (A, C) data in the colour diagram of Macleod and Boynton (1979); (B, D) the same data in the 1976 CIE UV colour diagram. ●, Average of the settings made during hue matches; ○, average of the settings made during paper matches. The paper match settings are closer to colour constancy (+, what we would consider perfectly colour constant; ×, chromaticity of the reference). Our measure of constancy, a/b, see (A), is the ratio of the distance between the settings made under the 4000 and 10,000K illuminants (a) and the distance between the "ideal" constancy settings (b), both measured along the S/(L + M)-axis. The constancy index of Arend *et al.* (1991) is 1 − c/d, see (B). The constancy indices for the two illuminants were averaged. Both examples show values for hue matches. Similar measures were obtained for the paper matches.

looked at the surround more often during paper matches (particularly the reference surround). The amount of time spent looking at the surround is small in comparison to the amount of time spent looking at the centres. In particular, a large part of the time is spent looking at the test centre. This is not surprising, as the subjects were manipulating this field's colour. The switches between the reference and test are quite manifest. Note the apparent increase in the number of switches just before a match is made (matches are indicated by ● in Fig. 6).

The first measure we investigated is the amount of time spent looking at various parts of the displays. We examined whether this differs for the two instructions. A difference could render differences in the foveal state of adaptation while following the two instructions. The relevant parameter is the state of adaptation of the foveae at the moment subjects switch their gaze towards the central patches. This is mainly determined by the colours one has been looking at during the immediately preceding period of time. To estimate the influence of adaptation, we need to know how much time was spent looking at the surround of the reference and test stimulus, immediately before looking at the centre of that stimulus. The average values for each subject are shown in Fig. 7(A). Figure 7(B) shows how much time was subsequently spent looking at the centre of the stimulus. The instructions had a significant influence on the amount of time that four of the subjects (all but EvW) spent inspecting the surround immediately before looking at the centre, and the time three of them (AF, AB and FWC) subsequently spent looking at the centre (Mann–Whitney U-test; $P < 0.05$).

The values in Fig. 7 were calculated for the full time span during which eye movements were measured. However, it is quite conceivable that the eye movements made shortly before a match were the most important. In Fig. 6 we saw that the number of switches tended to increase just before a match was made. In addition to analysing the data of the full 210 sec, we therefore also calculated the average values during the last 5 sec preceding each match. For the full time span of the experiment, subjects on average spent 2.1 times as much time looking at the surround when making a paper match than when making a hue match. This increased to 3.5 times during the last 5 sec before each setting. Limiting the analysis to the last 5 sec before each setting had no systematic influence on the time spent looking at the centre in any condition, or on the time spent looking at the surround of the reference.

Evidently, the instructions influenced the eye movements subjects made while performing the experiment. In this respect, the hypothesis that the different instructions resulted in a change in viewing strategy, as we put forward in the introduction, was correct. The most evident change in eye movements was that subjects spent more time looking at the surround immediately before looking at the centre in the paper match condition. This was most prominent just before a setting was made. As discussed in the Introduction, this may influence the state of adaptation of the foveae at the moment that subjects switch their gaze towards the centre, which may affect the perceived colour so that subjects make different matches. Of course, the credibility of this mechanism as the origin of the influence of the instruction depends strongly on the temporal characteristics of the process of adaptation. To determine the expected magnitude of such an influence, we need to know to what extent short exposures to a colour can actually influence subsequent colour perception. This was examined in Experiment II.

Adaptation (Experiment II)

The purpose of this experiment was to measure the influence of a short exposure to one colour on the subsequently perceived colour. If a colour "flash" influences the state of adaptation of the foveae, identical sensory stimulation will evoke a different colour percept before and after the flash. In the experiment, subjects had to compare the colour of the centre before and after a flash, and to indicate when it was the same. By varying the colour after the flash, we determined the difference in cone stimulation that was required to compensate for the change in the state of adaptation. Figure 8(A) shows the influence of the flash as a function of exposure duration. As the results for blue and yellow flashes were very similar, they were averaged.

It can be seen that even very short exposures (as short as 60 msec) influenced the subsequently perceived colour. Longer flash durations had a larger influence on the perceived colour. The time that the test stimulus was presented also influenced the perceived colour [Fig. 8(B)]. The influence of the coloured flash initially decreases with longer durations of the test colour. However, the influence is quite stable for durations longer than about 0.4 sec.

Combining the eye movement, adaptation and colour constancy data

Our hypothesis was that the differences in eye movements, due to the instructions, result in different states of adaptation, and hence in different matches. We can now combine the results of Experiments I and II to quantify the influence of the difference in eye movements. We calculated the influence that exposure to the surround would be expected to have had on the perceived colour, as a result of changes in the state of adaptation. In

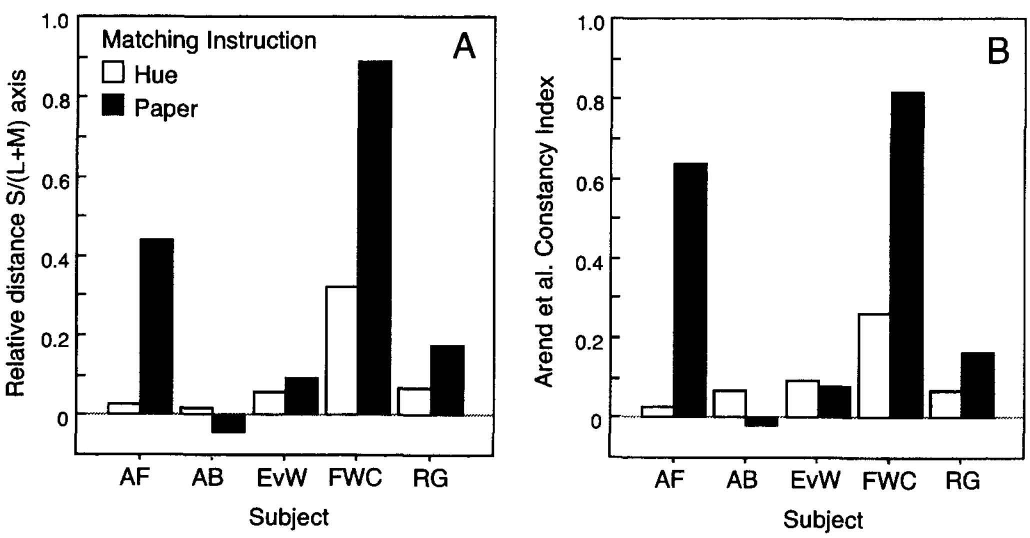

FIGURE 4. Average magnitudes of colour constancy for hue and paper matches. (A) relative distance along the S/(L + M)-axis between settings for 4000 and 10,000K test illuminants (the derivation of this measure is explained in Fig. 3(A). A value of 0 would indicate a perfect match of hue and saturation. A value of 1 is what would be considered as perfect colour constancy. Subjects on average made 10 matches in each condition. The SE was about 0.03 units for subjects FWC, AF, EvW and RG. Subject AB's SE was twice as large. The results of AF and FWC are significantly different for hue and paper matches (t-test, $P < 0.01$). Those of the others are not. (B) Constancy index of Arend *et al.* (1991), as explained in Fig. 3(B). Again, 0 would mean a perfect match of hue and saturation, whereas 1 would indicate perfect colour constancy. The two colour constancy measures yield very similar results.

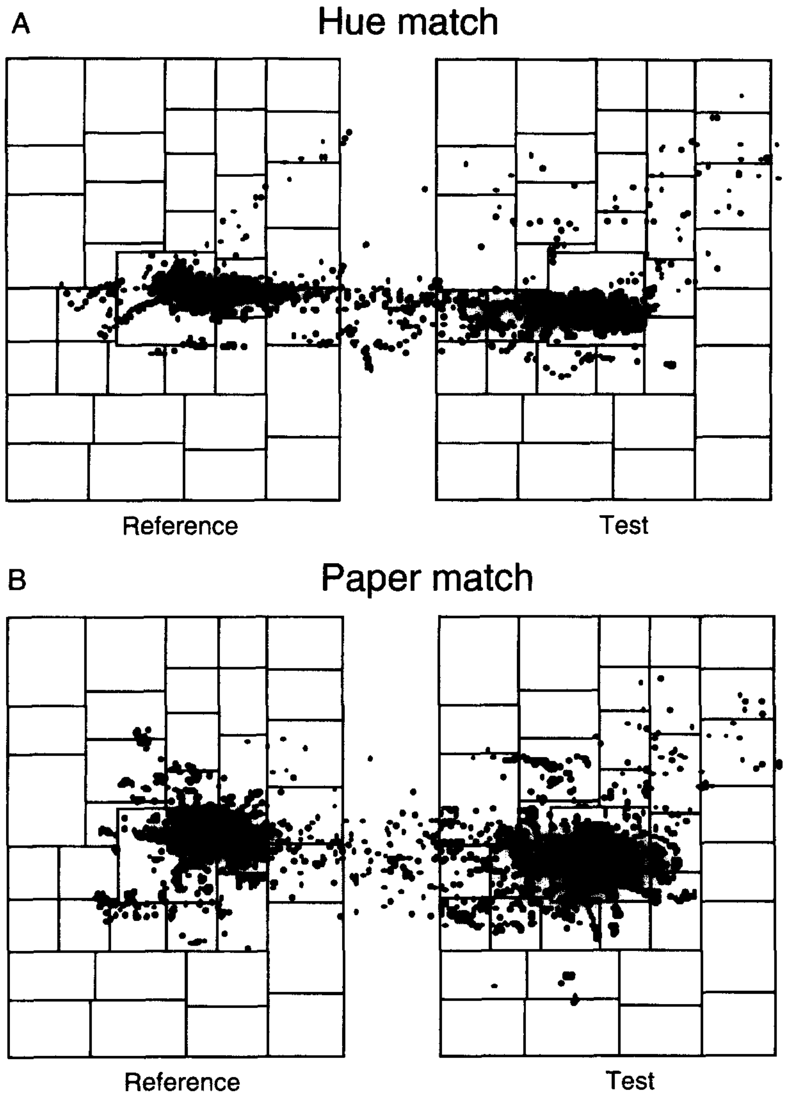

FIGURE 5. Direction of gaze on each frame presented on the computer monitor (67 Hz) after receiving hue (A, condition 1) or paper (B, condition 3) match instructions. The positions that subject FWC was looking at (dots) are superimposed on outlines of the patches of the two "Mondrians".

Experiment I, we measured how long subjects were exposed to the surround in each condition. These exposures were generally quite short. Experiment II provides us with an estimate of the influence of such short exposures on colour perception. To quantify the expected difference between instructions, we calculated an eye movement factor (EMF) for each subject.

The rationale behind the EMF is the following. The more time spent looking at the surround, the better a subject will be adapted to the colour of the illumination when subsequently looking at the centre. This will improve colour constancy. This reasoning holds for both test and reference stimuli, and in both the hue and paper match conditions. The time spent looking at the centre of the test and reference stimuli will also influence colour perception. The longer one looks at the centre, the less the previous exposure influences colour perception [Fig. 8(B)]. We saw that the average time subjects looked at the centre was slightly shorter for paper matches [Fig. 7(B)]. This could improve colour constancy. However, subjects usually looked at the centre for more than 0.35 sec, whereas the influence of the duration only makes a difference for shorter periods of fixation [Fig. 8(B)]. Moreover, for very short periods of fixation, we expect no influence to the settings as subjects would have had no time to judge and adjust the test centre's colour. We therefore did not use the time subjects spent looking at the centre when calculating the EMF.

The influence that each exposure to the surrounding should have on the perceived colour was determined from Fig. 8(A). Influences of exposure times lying between measured values were determined by means of linear interpolation. The effect we can ascribe to adaptation is the sum of the influences of exposure to the test and reference surrounds. The EMF is the difference between the effects of adaptation in the paper and hue match conditions (and is expressed in units of relative distance; as in Fig. 8).

We found that subjects' eye movements tended to change when they were about to make a match. It is unclear at what moment subjects make their actual decision, so that it is equally unclear which eye movements are most relevant. We calculated the EMF for the last 5 sec before each match was made, as well as for the full 210 sec. Figure 9 compares subjects' EMFs with the difference between their paper and hue matches [from Fig. 4(A)]. If eye movements and adaptation were fully responsible for the differences between subjects' settings for the different instructions, we would expect the data points to lie on the slanted line. Points above this line indicate that the influence of the instruction was larger then can be accounted for by eye movements and adaptation. Points below the line indicate that the influence of the instruction was smaller.

Clearly, there is no direct relationship between the EMF and the differences in colour settings. Two subjects (AF and FWC) have an instructional influence that is much larger than that expected on the basis of their eye movements. The instructional effect of subject EvW is approximately what would be expected on the basis of his EMF. Subjects RG and AB have instructional influences of a magnitude that could be due to differences in viewing strategy (as represented by the EMF), but do not correspond with their own EMF. Considering the uncertainty on when subjects actually make their decision, and these subjects inexperience with colour matches, their data cannot be considered as strong evidence against the EMF being the only factor responsible for the difference in settings. Note that their settings were not significantly different for the two instructions (Fig. 4). AB's instructional effect is opposite to that predicted by her EMF. Her paper matches showed less colour constancy than her hue matches, which is quite unusual (Arend & Reeves, 1986; Arend *et al.*, 1991).

Differential eye movements in conjunction with adaptation probably do contribute to some small extent to colour constancy. However, the data of subjects FWC and AF clearly shows that the instructions can also influence colour constancy in some further manner.

Attending to stimulus features

In this part of the Results section we will examine the eye movement data to investigate which stimulus features subjects were attending to. This might provide us with information about specific viewing strategies that subjects used (or did not use) while performing the experiment.

Surfaces. As a first step, we investigated what surfaces subjects had actually been looking at. There are several

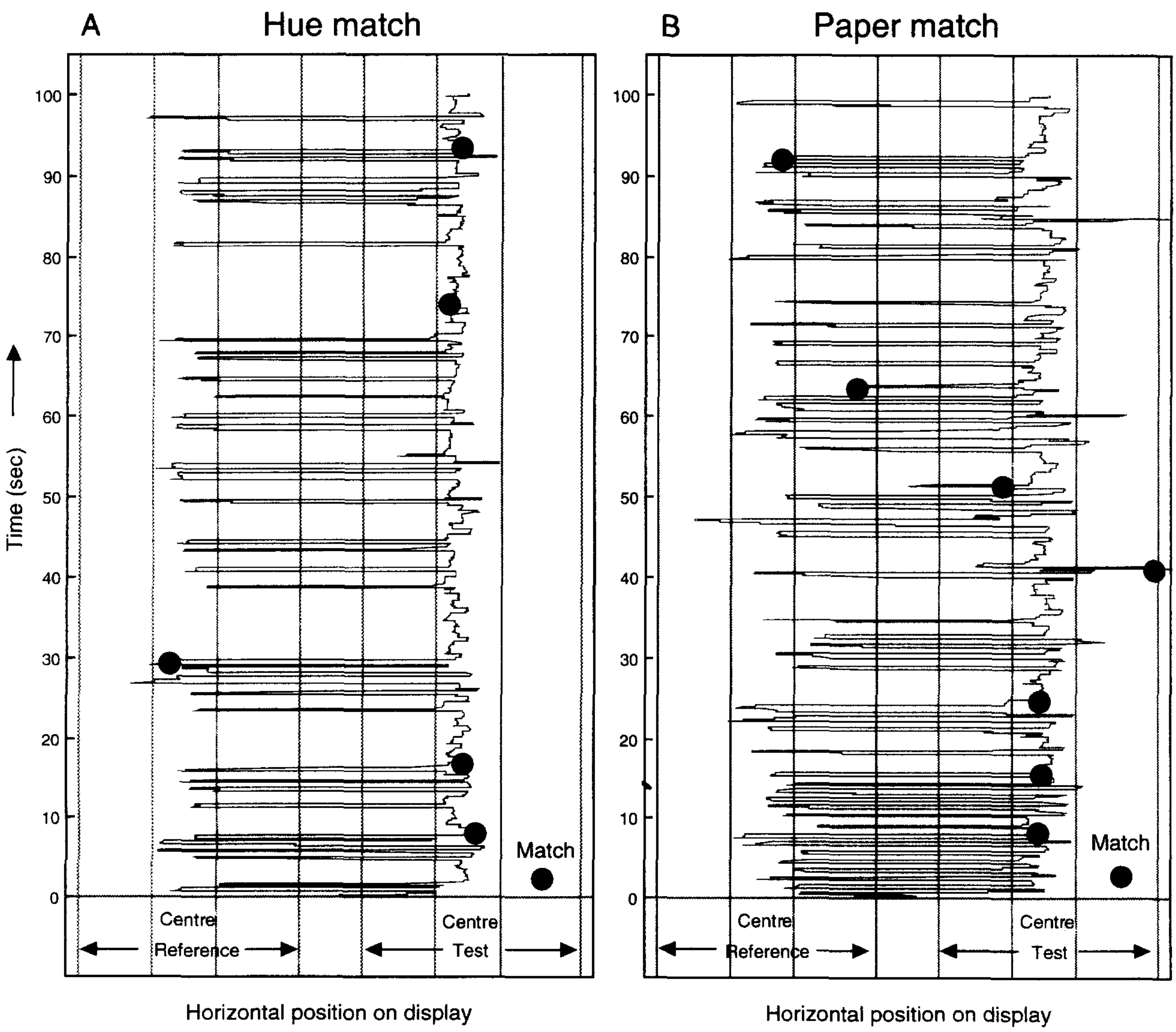

FIGURE 6. Horizontal eye movements of subject AF after receiving hue (A, condition 2) or paper (B, condition 4) match instructions. Data for the first 100 sec of each experiment: ● show when a setting was made; ...... indicate the horizontal position of the border between the surround and centre of the two "Mondrians" and the "Mondrian" boundaries.

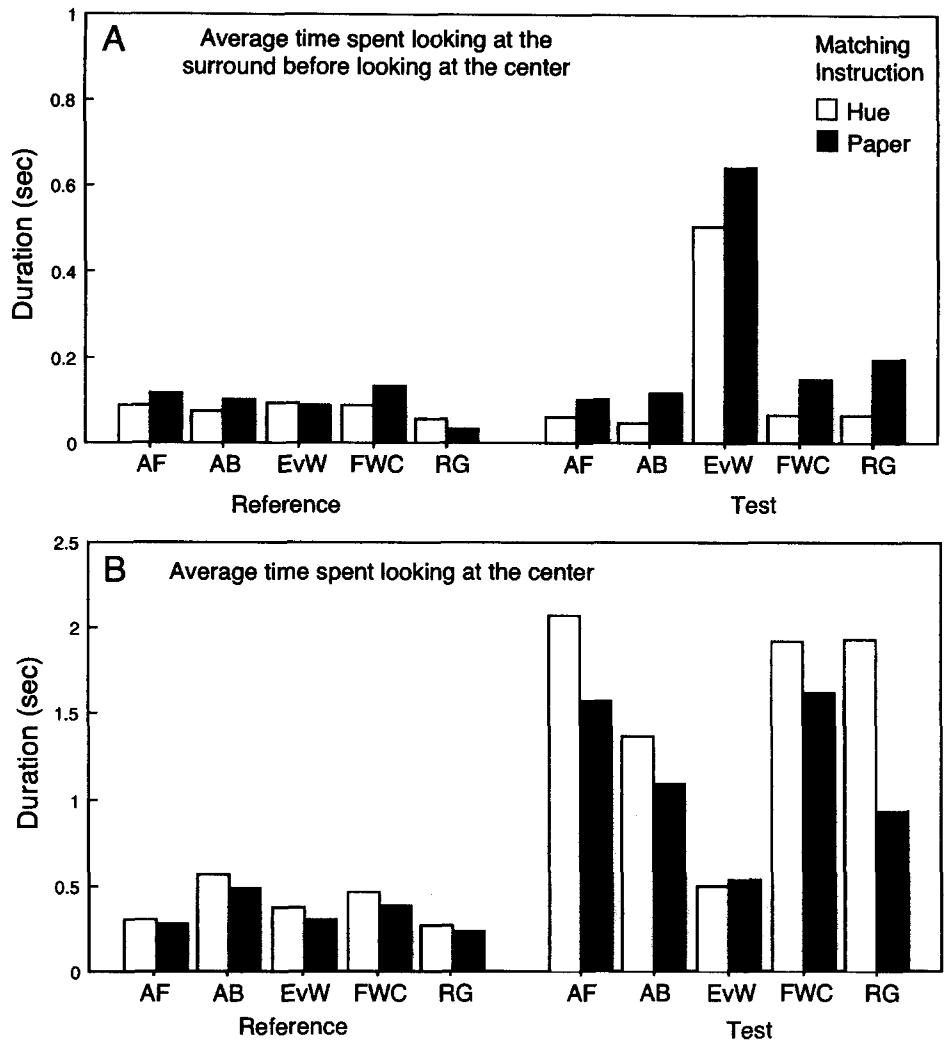

FIGURE 7. Average amount of time spent looking at the surround immediately before looking at the centre (A) and the average amount of time subsequently spent looking at the centre (B), for both the reference and test "Mondrians". Results of five subjects. Subjects carried out a simultaneous colour constancy experiment, after either receiving a hue or a paper match instruction. While making paper matches, subjects spent more time looking at the test surround. Thus, their foveae could adapt to the colour of the test illuminant for a longer period of time.

reasons to look more closely into this aspect. Adaptation only aids colour constancy if it is primarily determined by the colour of the illuminant. In the previous analysis, we assumed that subjects scanned the patches in the surround at random (i.e. that looking at the surround was equivalent to looking at a grey surface under the relevant illumination). If this is the case, subjects should have looked at many different patches while performing the experiments. If not, they adapt to the colour reflected by specific patches, rather than to that of the illuminant. Figure 10 shows the "Mondrians" used in the two paper match conditions. The fraction of the total time spent looking at the surround that was spent looking at each particular patch is indicated by the density of the texture. Subjects looked at a fairly large number of surfaces, but spent a large part of the time looking at certain surfaces. Most time was spent looking at surfaces in the direct vicinity of the centres, and the ones lying between the two centres. The specific surfaces that were looked at differed between subjects. Most subjects did not scan even nearly the whole surround. Moreover, some subjects clearly tended to look at the same patches in the two stimuli (e.g. EvW in condition 4), whereas others clearly did not (e.g. RG, condition 3).

Colours. Examining the colours of the patches that were attended to most does not provide a clue as to how subjects obtained better colour constancy when making paper matches. We took care not to include neutral greys in the surround, as this could have provided subjects with direct information about the illuminant. In order to estimate the colour of the illuminant, subjects could only attend to the most desaturated colours. The relative influence of the illuminant is largest for these colours. Figure 11 shows the colours of the patches that subjects AF and FWC looked at most frequently in both test and reference stimulus (combined data for paper matches by AF and FWC, conditions 3 and 4). There was no tendency to mainly look at desaturated colours.

Edges. We next examined whether subjects paid more attention to the edges between the centre and surround in the paper match conditions. The work of Craven and

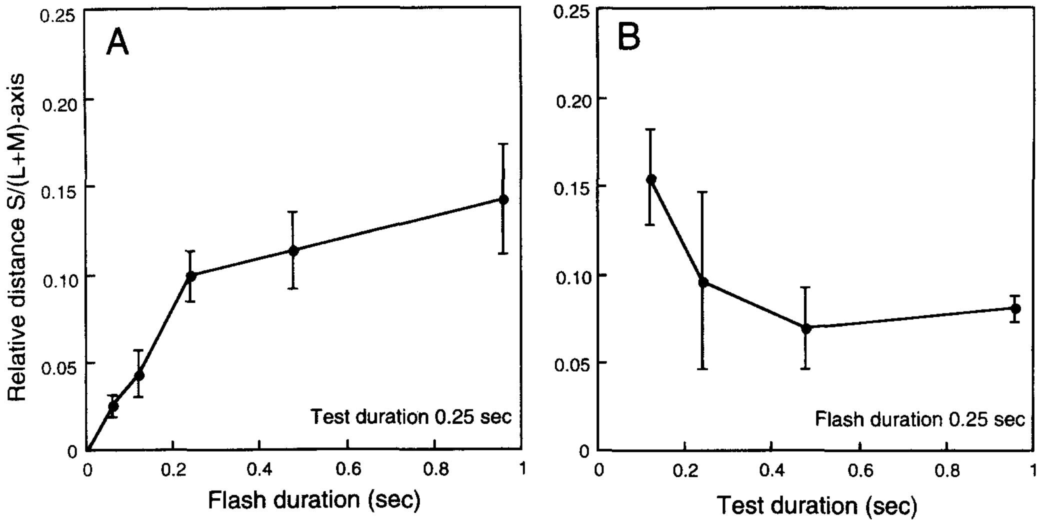

FIGURE 8. Influence of short exposure to a coloured flash upon subsequent colour perception. The flash was a 40% increase or decrease in SWS cone stimulation. Results for incremental and decremental flashes were similar, and their average is shown. (A) Change in perceived colour as a function of flash duration (test stimulus duration 0.25 sec); average of six subjects. There is a clear increase in the influence of the flash with flash duration. (B) Change in perceived colour as a function of the time that the test stimulus was present (0.25 sec flash); average of two subjects. Bars show ± 1SE between subjects.

Foster (1992) suggests that edge information might be relevant for obtaining colour constancy. We concentrated on the results of subjects AF and FWC, because they showed the largest instructional influence. If any information on viewing strategy can be found in the eye movement data, it should be present in theirs. We calculated the distance to the nearest edge of the centre, for each frame of the display. In Fig. 12, these values are shown in a normalized frequency histogram (for both sides of the centre-surround edge). If subjects spent more time looking at edges in the paper match condition, one would expect a peak at the position of the edge (0). Such a peak cannot be found.

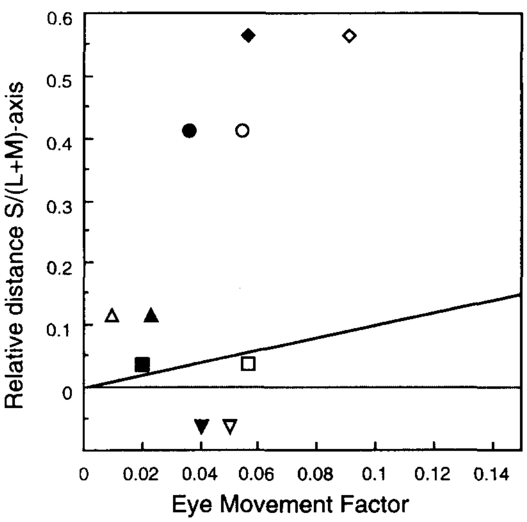

FIGURE 9. Predicted vs measured change in colour constancy. Horizontal axis: predicted change (EMF; see text for explanation). Vertical axis: measured change [difference between paper and hue match settings from Fig. 4(A)]. Different symbol types refer to different subjects: AF (●), EvW (■), RG (▲), AB (▼) and FWC (◆). Closed symbols: EMF calculated for the full 210 sec. Open symbols: EMF calculated for the last 5 sec before each match was made.

Scanning strategy

The last aspect we examined is the way in which subjects scanned the stimuli while performing the experiment. Again, we concentrate on the results of subjects AF and FWC. One strategy, as mentioned in the introduction, could be to pick out corresponding surfaces in reference and test surround, and use these to determine the difference in colour caused by the illuminants. Subjects could use this estimated difference to adjust the colour of the centre of the test stimulus. If subjects used this strategy, we would expect them to frequently view corresponding patches in reference and test stimulus in succession. In order to judge which patches subjects looked at after having looked at a particular patch, we had to find a way to exclude patches that subjects did not actually fixate. To do so, we only considered a patch as having been looked at, if subjects spent at least 60 msec looking at it. Figure 13 shows the number of times that a subject made scans between certain patches (we only show events that occurred at least three times). The width of the arrow indicates how often such an eye movement occurred. The path of the arrow is not relevant.

Only a restricted set of scans is made. As we already knew (Fig. 10), certain patches were viewed quite often, while others were not looked at at all (or only very infrequently). The most frequent scans were ones directly between the two centres (about 20% of all scans). There are also many scans between the centres and the surfaces in their direct vicinity, especially those that are situated between the reference and test centres. There were few scans between corresponding patches in both surrounds. In fact, in the two paper match conditions, FWC in total only made 7 scans between corresponding patches in the surrounds, from a total of 472 scans. AF made 23 such scans, of a total of 537. This finding almost excludes the possibility that subjects estimated the illuminants' colour difference by directly comparing corresponding surfaces.

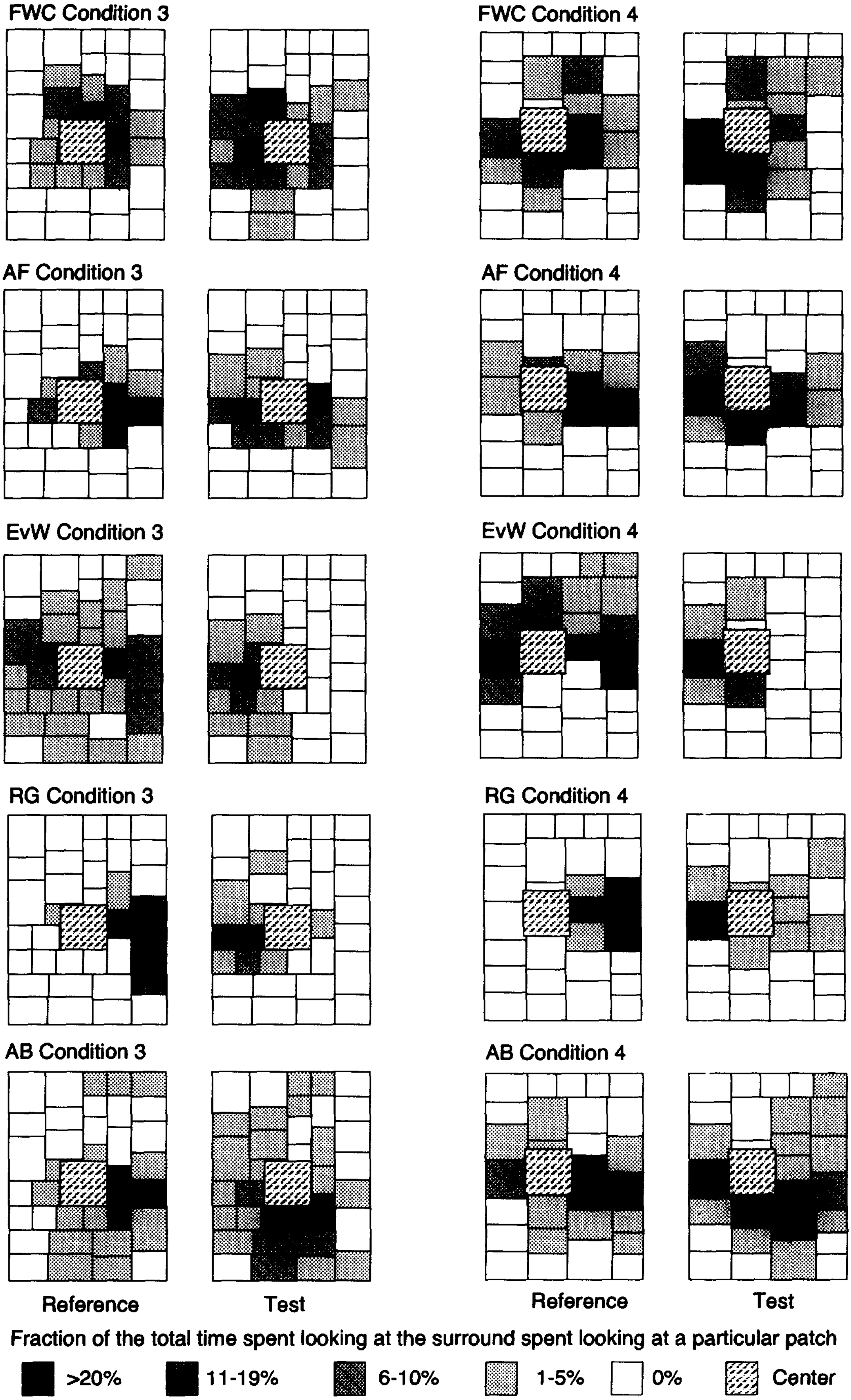

FIGURE 10. Fraction of the total time spent looking at the surround that subjects looked at particular surfaces. Results are shown for both paper match conditions. Fractions were calculated separately for reference and test stimuli. Note that subjects tended to spend a large part of the time looking at a relatively limited number of surfaces (darkest ones). These were not necessarily the same in reference and test stimuli.

Similarly, we do not consistently see a large number of scans between the centre and certain patches in the two surroundings.

Subjects might have used the colour of corresponding patches to improve colour constancy in the paper matches, without directly looking at these patches in succession. In our analysis so far, we assumed that subjects must look at a surface in order to judge its colour. It might be possible to judge a colour without directly looking at it. To examine these options, we performed a psychophysical experiment that tested whether correspondence between patches in the reference and test surround was necessary to obtain good colour constancy.

Comparing Surfaces (Experiment III)

The purpose of this experiment was to see whether subjects need to be able to directly compare surfaces in the surround to obtain good colour constancy in the paper matches. We compared conditions in which the simulated reflectance of corresponding patches was identical in the reference and test patterns (as in Experiment I), with ones in which surface reflectance did not correspond and frequently changed. In the first condition, subjects did not necessarily have to actually estimate surface reflectance to perform the task. They could try to estimate the differences between certain patches and use this estimate to adjust the colour of the test centre. In the second condition, they could not. Moreover, the colours changed every 0.5 sec, so that it was virtually impossible to find patches with corresponding reflectances (if they were present at all). Subjects, therefore, have to actually estimate surface reflectance, taking account of the illuminant, if they are to obtain similar colour constancy

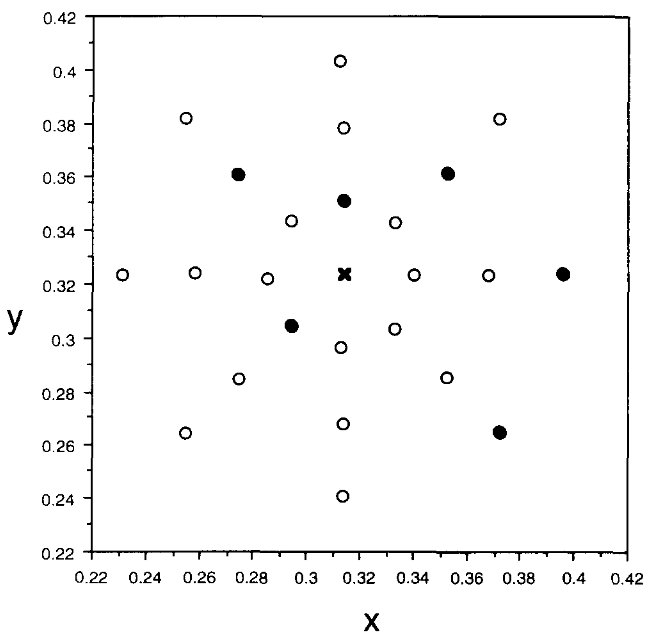

FIGURE 11. Colours of the surround patches under the simulated 6500K test illuminant (in the CIE 1931 diagram; × shows the locus of the 6500K light source). ● Indicate the six patches that were looked at most frequently in both test and reference stimuli during paper matches (data for AF and FWC, conditions 3 and 4, are combined). The subjects attended to both saturated and desaturated colours with different hues and did not mainly look at patches with desaturated colours.

in these two conditions. Otherwise, we expect colour constancy to deteriorate dramatically in the second condition. The results for this experiment are shown in Fig. 14.

It can be seen that none of the subjects performed truly worse in the conditions without corresponding colours in the surround. The small differences are not statistically significant. Subject SdV showed some overcompensation for the illuminant, but she did so in both conditions. The settings did not deviate systematically from equiluminance (in this experiment the subjects set the luminance). We conclude that subjects do not need to compare corresponding surfaces.

DISCUSSION

That there is a cognitive contribution to colour constancy is evident from the fact that matching instructions influence the magnitude of colour constancy (Arend & Reeves, 1986; Arend *et al.*, 1991; Troost & de Weert, 1991). Our analysis of the eye movements that subjects made during a colour constancy experiment provides us with insight into the nature of this cognitive influence. Our main question in this analysis was whether the instructions caused subjects to change their viewing strategy, and thereby the magnitude of colour constancy.

A first manner in which a different viewing strategy could have enhanced colour constancy, is by increasing the time that the eyes are directed at the (spectrally biased) surround. A change in this duration would lead to a different state of adaptation of the foveae at the moment subjects direct their gaze towards the centre. Improved adaptation to the illuminant could change colour perception in the direction of better colour constancy.

Indeed, eye movements changed notably as a result of the instructions. When making paper matches, subjects spent more time looking at the test surround (immediately before looking at the patch they had to adjust), so that they were exposed to the test illuminant for a longer period of time. In Experiment II, we found that adaptation was sufficiently fast for small changes in exposure duration to result in differences in colour perception. We combined the eye movement and adaptation data to predict the change in setting we expected for each subject, and compared this EMF with the actual difference in settings. For three subjects, the instructional influence on colour matches was small enough to be consistent with the hypothesis that the instructional influence is mainly caused by differences in eye movements (although the actual values were only similar for one subject). Two other subjects had an instructional effect that was much larger than that predicted by their EMF. For them, the change in eye movements must have contributed to the improved colour constancy, but was certainly not the only cause of the instructional influence.

Although the eye movements and influence of adaptation were determined quite accurately, there are uncertainties with regards to the magnitude of the EMF. To calculate it, we used all measured eye movements.

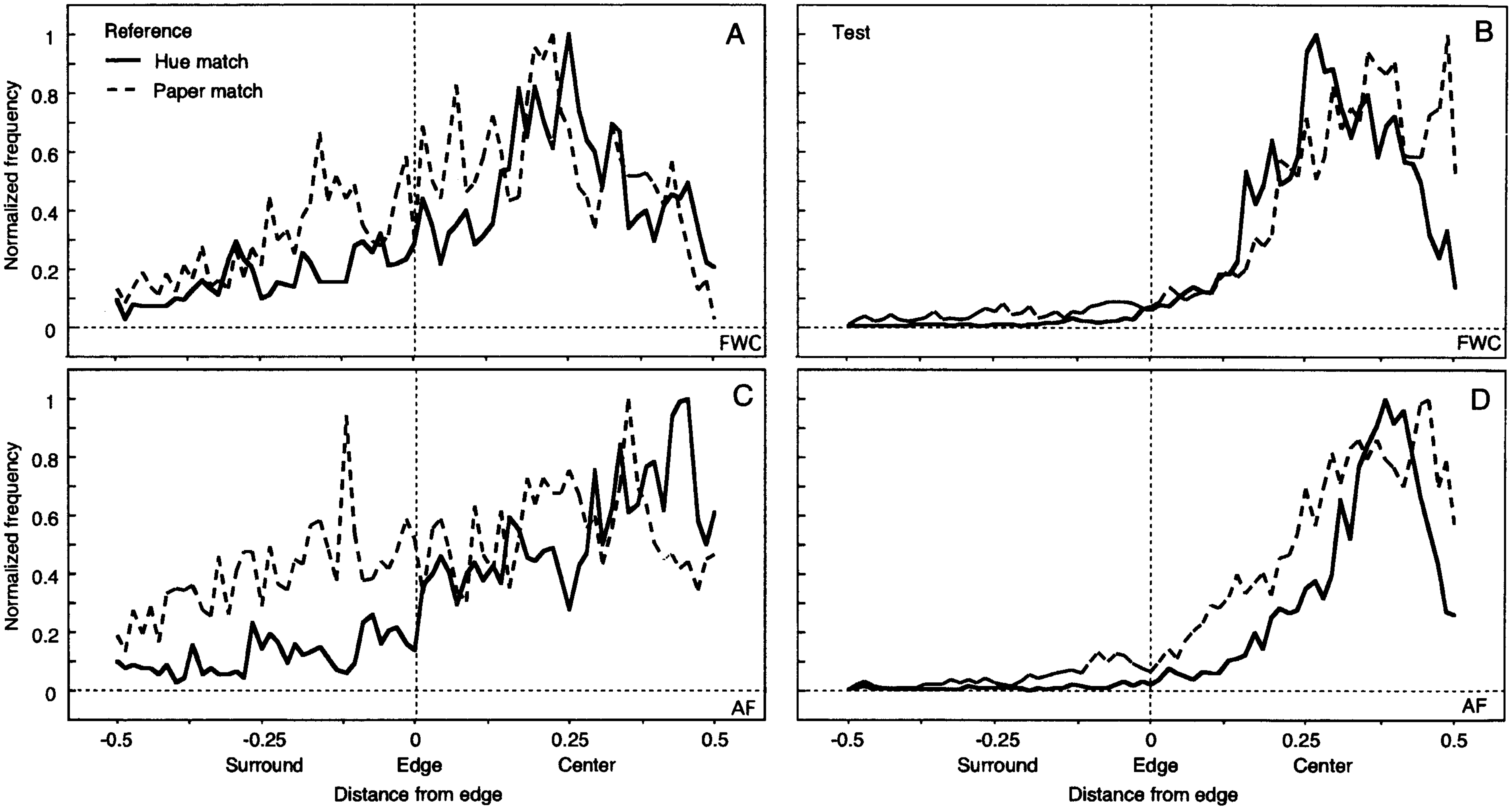

FIGURE 12. Normalized frequency of frames during which two subjects (FWC and AF) looked at certain distances from the boundary between the centre and surround of the "Mondrian". For each frame, we determined the distance to the nearest boundary between the centre and surround (:). This was determined separately for reference (A, C) and test (B, D) stimuli. Results are averages of two conditions. Subjects clearly spent more time looking at the surround, particularly that of the reference stimulus, when making paper matches. There is no peak at the position of the edge. Subjects do not attend specifically to edges in the paper match condition.

However, a considerable number of exposures were so short that subjects had no time to judge and adjust the test centre's colour during this period of time (Fig. 15). Such short exposures may have had no influence at all. If such exposures were accompanied by particularly long or short exposures to the surround, this will affect the magnitude of the EMF. A further complication is that subjects' eye movements tended to change when they were about to make a match. We do not know when subjects make their decision about the correctness of a match, so that it is unclear which eye movements are the most relevant. It seems likely that subjects spent the first few seconds finding the approximate colour, and then proceeded to make more precise adjustments. If so, the eye movements made immediately before a match are the most important. However, even if we base the EMF on the last 5 sec before a match, and only include exposures to the surround that were followed by fixations of the centre that lasted at least 60 msec, the EMF could still only account for about 10 and 15% of the change in colour constancy of AF and FWC, respectively.

There is another reason to believe that adaptation played a limited role in achieving better colour constancy in the paper matches. Unless the colours of patches in the surround are very desaturated, the colour of the light they reflect is largely determined by their reflectance characteristics. For the average adaptation to be to the colour of the illuminant (which we assumed to be the case when calculating the EMF), subjects should either have scanned the surround more or less at random (otherwise they would adapt to the colours of specific patches), or only have looked at very desaturated patches. We found that subjects attended to a relatively limited number of patches, and spent a large part of the time inspecting just a few patches. These were not specifically the least saturated ones. We conclude that the instructional influence cannot be solely explained on the basis of differences in eye movements in conjunction with adaptation.

In the current study, we limited our analysis to fields containing a grey target surrounded by patches of various other colours, all lying on a single surface and illuminated evenly by a single light source. Moreover, we assumed that the patches' reflectance properties were such that we could use a Von Kries transformation to simulate the change in illuminant. We believe that these limitations are not crucial to our conclusions concerning the cognitive contribution to colour constancy, and the role of differences in viewing strategy therein, although they may have influenced the level of colour constancy that subjects could attain.

There was a clear difference in the magnitude of colour constancy between experienced and naive subjects. The

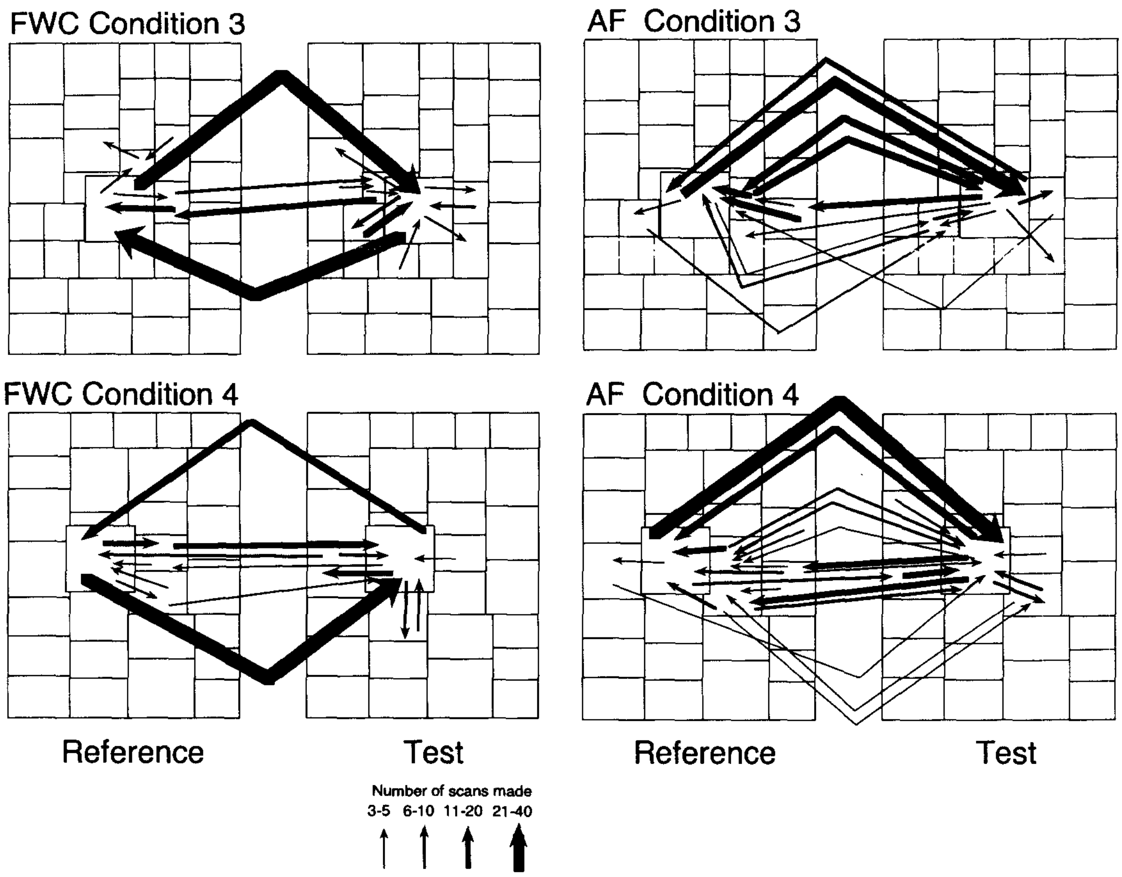

FIGURE 13. Scans made during paper matches. We determined which surfaces were frequently looked at in succession. Subject had to look at a patch for at least 60 msec for it to be included in this analysis. We only show scans that occurred at least three times. The width of the bar indicates the number of scans that were made between the surfaces connected by the line. The direction of the arrow corresponds with the direction of the scan. Most scans were between the two centers and between the centre and surfaces in its direct vicinity. Scans connecting corresponding patches in both surrounds or between the centre and certain patches in the two surroundings were very rare.

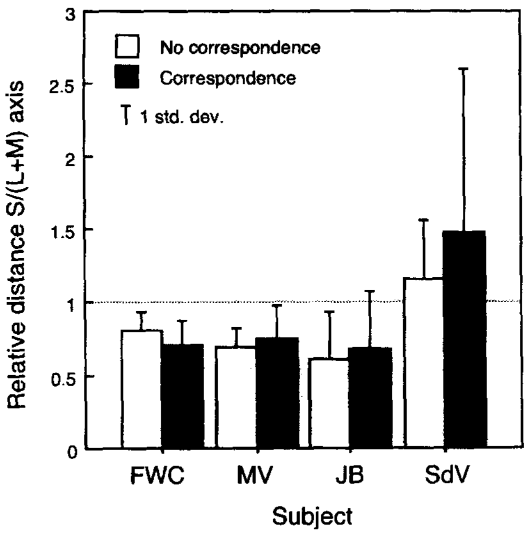

FIGURE 14. Influence of correspondence between colours in the surround on paper match settings. The measure used is similar to the one used in the other experiments [see Fig. 3(A)]. A score of 1 indicates perfect colour constancy. Results for 4000 and 10,000K test illuminants were similar, and their average is shown. None of the subjects performed significantly worse when surround colours did not correspond between the reference and test "Mondrian". Subjects do not need correspondence in colours to perform the paper matches.

largest instructional influence was found for subjects AF and FWC. They differed from the other three subjects of Experiment I in that they had experience in working with colours and lighting. AB, EvW and RG knew very little about illuminants and surface reflectance. Subject FWC is certainly not naive (in this respect at least) as he programmed the displays. Although subject AF was naive with respect to these experiments, he is a photographer who could even fairly accurately name the colour temperatures of the simulated illuminants. Inspection of individual data of previous studies (Arend & Reeves, 1986; Arend *et al.*, 1991) confirms that there is a difference between the results of naive and experienced subjects. Using a different experimental paradigm (Craven & Foster, 1992; Foster, Craven & Sale, 1992), it was found that naive subjects could only reliably attribute colour changes to simulated illuminant or reflectance changes after they had received feedback. The three naive subjects that participated in Experiment III performed nearly as well as the experienced subject. None of them knew anything particular about colours and illuminants. One difference between the experiments was that subjects could not adjust luminance in Experiment I (the computer kept luminance constant), which may have prevented them from making certain adjustments to the colour. However, the settings made in Experiment III did not systematically deviate from equiluminance.

Experiments by Foster *et al.* (1992; Craven & Foster, 1992) suggest that information at borders between patches are relevant to the ability to discriminate between changes of the illuminant and of surface reflectance. We found no evidence that subjects directed their gaze more frequently towards the edges when making paper matches. However, subjects may attend to the edges without looking at them. The idea that the contrast at borders between patches is used to obtain colour constancy is further refuted by the results of Experiment

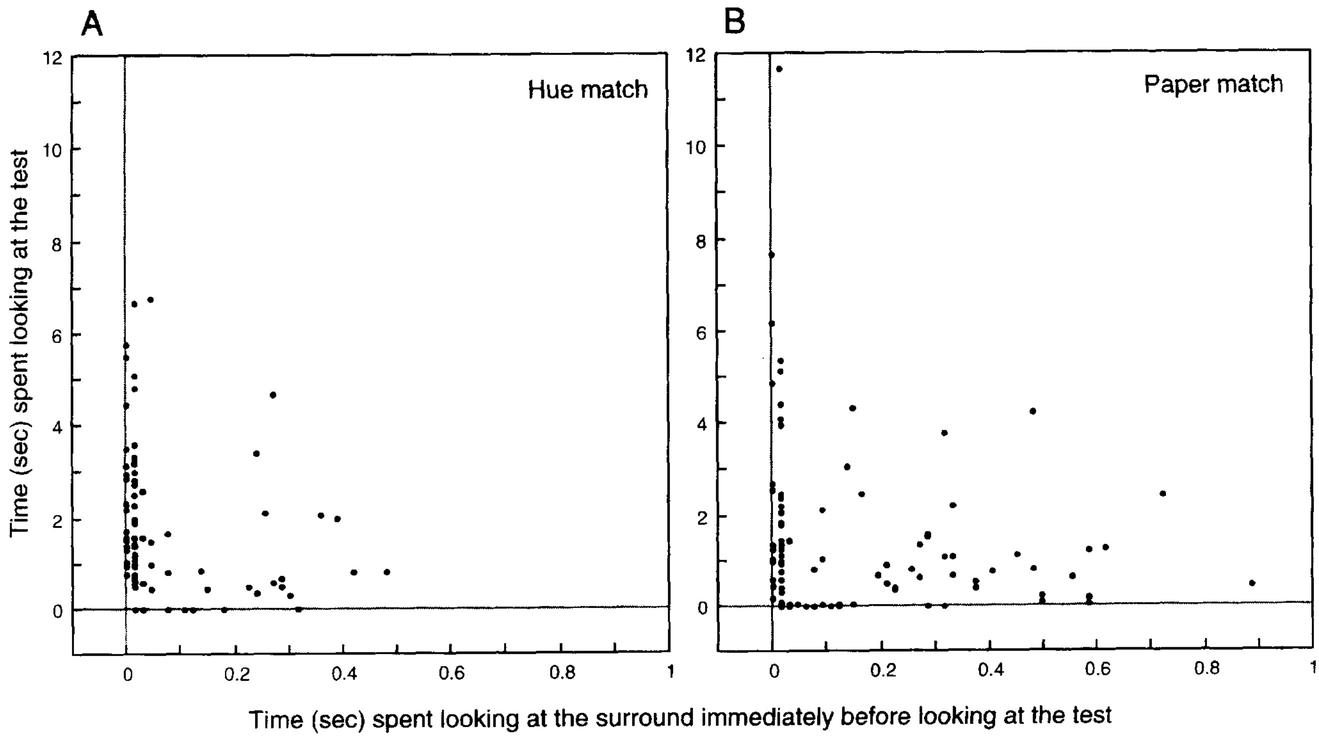

FIGURE 15. Individual durations of exposures to the test surround and subsequently to the test centre, for subject FWC: (A) while making hue matches (condition 1) and (B) while making paper matches (condition 3). The subject more frequently looked at the surround for periods of time that could influence his settings in the paper match condition. In both hue and paper match conditions, a large number of exposures to the centre were so short that judging and adjusting its colour would have been impossible during this period of time.

III. Subjects performed equally well when local contrasts were not stable.

A further possibility that could be rejected by our analysis was that subjects used an estimate of the colour difference between two corresponding patches in reference and test stimulus to adjust the test patch relative to the colour of the reference. Subjects hardly looked at corresponding surround patches in direct succession. Moreover, this strategy would not have worked in Experiment III. Frequently changing surround colours prohibited subjects from choosing one surface, and comparing its colour in reference and test stimulus. For the same reasons, we could reject the possibility that subjects estimated the difference between a specific surround patch and the centre in the reference, and use this to adjust the test patch relative to the corresponding patch in the test surround. The results of Experiment III (changing surround colours) are supported by the findings of Troost and de Weert (1991), using a different procedure. They found an influence of instruction in a successive constancy experiment with changing surround colours.

In the above analyses, we made the assumption that the time spent looking at a certain patch, or the number of scans to it, is correlated with its relevance to the subject's strategy. This need not necessarily be so. Viewing strategy could have changed without an accompanying change in eye movements. The eye movements were only essential for our initial adaptation hypothesis. On the basis of the results of Experiment III, we can also reject the option that subjects used one of the strategies (as mentioned in the preceding paragraph), but without directly looking at the particular patches or edges.

To return to our main question, it appears that subjects' viewing strategy did change significantly as a result of the instructions. Differences in adaptation due to this change may have enhanced colour constancy to some extent. For some subjects, this was certainly not the only factor that played a role. With regards to the remaining influence, we can rule out a number of strategies. The surfaces and colours that subjects looked at do not appear to be very critical. The surfaces that were actually chosen were those most readily available; the ones nearest to the centre, and those encountered anyway when moving one's eyes from centre to centre. Whether the change in viewing strategy is actually necessary for the better colour constancy after receiving paper match instructions, or is simply another response to the instruction, remains unknown.

The question remains how some subjects were able to recover surface reflectance when asked to make paper matches. Possibly, they first estimated the illuminant's colour, and used this to estimate surface reflectance from the light emitted at the position of the surface of interest. In order to estimate the illumination one must make assumptions about the visual environment. For instance, one can assume that the average surface reflectance within scenes, or parts of scenes, does not change. In that case, the average chromaticity of light reaching the eye provides an estimate of the illuminant. This assumption will introduce considerable perceptual errors if there is, for instance, a large green surface within the scene. An alternative is to assume that the *range* of reflectances is identical for different scenes (Arend & Spehar, 1993a). Again, large errors can arise, for instance if there are various green surfaces, but no bright red ones within the scene.

Beside assumptions on the environment, the above-mentioned mechanisms assume that the surfaces in question all receive the same illumination. Even without systematic biases in surface reflectance, the illumination can therefore be misjudged if it is not homogeneous (i.e. if there is more than one light source, if the light reaches surfaces at different angles or if there are shadows or reflections). To help overcome this problem, only light from surfaces in the same plane and with the same orientation appear to be used to judge the illuminant of a target surface (Gilchrist, 1979; Schirillo & Shevell, 1993; Szura & Gilchrist, 1994). Alternative strategies for judging the illuminant, such as the use of highlights (Hurlbert, Lee & Bülthoff, 1990) or of the colour of familiar objects (Bramwell & Hurlbert, 1993), depend on similar assumptions (e.g. single illuminant, correct assumption of the familiar object's colour).

Despite these considerations, we believe that the improved constancy in paper matches is the result of judging the illuminant on the basis of such assumptions. Some of the effects that have been attributed to long-range neural mechanisms (e.g. Walraven, 1973; Land *et al.*, 1983; Pöppel, 1986; Wehrhahn *et al.*, 1990; Brenner & Cornelissen, 1991) could also be the result of such judgements of the illuminant. The differences in colour constancy between naive and experienced subjects can be considered as evidence that subjects must learn which assumptions to make.

Considering the results of the current study, adaptation may appear to be a relatively unimportant factor in maintaining colour constancy. However, frequent switching between different illuminants, as occurred in the current experiment, prevents adaptation from playing a more significant role. In more realistic situations, one will be exposed to a single illuminant for a longer period of time. We have previously shown that modifying conditions in a way that enhances adaptation can change colour matches considerably (Cornelissen & Brenner, 1991). Under conditions that favour adaptation hue matches can largely be explained by changes in receptor sensitivity [assuming adaptation to the illuminant (Brainard & Wandell, 1992; Lucassen & Walraven, 1993)].

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