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The influence of depth segmentation on colour constancy

Annette Werner
Department of Experimental Ophthalmology, University Eye Hospital, D 72076 Tübingen, Germany;
e-mail: annette.werner@uni-tuebingen.de
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Abstract. In real scenes, surfaces in different depth planes often differ in the luminance and chromatic content of their illumination. Scene segmentation is therefore an important issue when considering the compensation of illumination changes in our visual perception (lightness and colour constancy). Chromatic adaptation is an important sensory component of colour constancy and has been shown to be linked to the two-dimensional spatial structure of a scene (Werner, 2003 *Vision Research* **43** 1611 – 1623). Here, the question is posed whether this cooperation also extends to the organisation of a scene in depth. The influence of depth on colour constancy was tested by introducing stereo disparity, whereby the test patch and background were perceived in either the same or one of five different depth planes (1.9 – 57 min of arc). There were no additional cues to depth such as shadows or specular highlights. For consistent illumination changes, colour constancy was reduced when the test patch and background were separated in depth, indicating a reduction of contextual influences. An interaction was found between the influences of stereo depth and spatial frequency on colour constancy. In the case of an inconsistent illumination change, colour constancy was reduced if the test patch and background were in the same depth plane (2-D condition), but not if they were separated in depth (3-D condition). Furthermore, colour constancy was slightly better in the 3-D inconsistent condition than in the 2-D inconsistent condition. It is concluded that depth segmentation supports colour constancy in scenes with inconsistent illumination changes. Processes of depth segmentation are implemented at an early sensory stage of colour constancy, and they define visual regions within which the effects of illuminant changes are discounted for separately. The results support recent models that posit such implementation of scene segmentation in colour constancy.

1 Introduction

An important feature of colour vision is the ability to perceive the colour of objects nearly independently of changes in their illumination (colour constancy). Whereas colour constancy in 2-D scenes has been extensively studied over the past 100 years, colour constancy in 3-D scenes has only recently become a focus in colour research (eg Brill 1990; Arend 1994; Bergström 1994; Maloney 2002; Kraft et al 2002; Yang and Shevell 2002, 2003; Delahunt and Brainard 2004). Such scenes pose a considerable challenge to the computation of colour constancy, since they contain multiple illuminations resulting from inter-reflexions, shadowing, and light filtering (for example, through the canopy of trees — Endler 1993). Furthermore, the effect of illumination depends on the orientation and, in particular, the depth plane of surfaces relative to each other and the light source. Therefore, different depth planes can have very different illuminations (Jacobsen and Gilchrist 1988). The effect of illumination changes may be highly inconsistent across the depth planes of the scene and it has been shown that such multiple illuminations can be detrimental to colour constancy (Yang and Shevell 2003). Recent theories of colour constancy propose, therefore, two computational stages. First, a process of scene segmentation which identifies regions that are likely to share the same illumination; second, the discounting of the effect of illuminant changes within each such region (Brill 1990; Adelson 1999; Gilchrist et al 1999; see also Katz 1935; Koffka 1935).

A number of studies have demonstrated significant high-level influences of the 3-D structure of a scene on lightness perception (eg Mershon and Gogel 1970; Gilchrist 1977;

Schirillo et al 1990; Knill and Kersten 1991; Schirillo and Shevell 1993; Perkins and Schirillo 2003) and—more rarely—on colour perception. For example, Bloj and colleagues (1999) demonstrated that the visual system uses cues from the 3-D shape of objects to interpret the effect of mutual reflection between adjacent surfaces. Also, Yang and Shevell (2002) reported that, in the presence of specular highlights, binocular disparity improves colour constancy. However, it remained unclear what aspect of the percept was affected by disparity. Overall, the processes underlying these presumably high-level influences on colour constancy in 3-D scenes are little understood (Delahunt and Brainard 2004).

The aim of the present study was to clarify the influence of stereo disparity on an early computational stage of colour constancy (sensory colour constancy). Two low-level mechanisms are of particular interest here: spatial colour contrast and temporal chromatic adaptation. Spatial contrast can contribute to colour constancy by encoding edge ratios (Hurlbert and Wolf 2004) and it has been shown that spatial cone contrasts between natural surfaces tend to be invariant under changes of daylight illumination (Foster and Nascimento 1994).

Chromatic adaptation is an important part of sensory colour constancy since it involves the automatic adjustment of the chromatic system in response to temporal changes of the stimulus, eg changes in ambient illumination. It includes multiple processes of multiplicative sensitivity control (gain adjustment) and subtractive mechanisms via lateral inhibition. It operates on local as well as on large spatial and temporal scales (Jameson and Hurvich 1972; Barlow and Lewick 1976; Walraven 1976; Hayhoe 1990; Shevell and Humanski 1990; Hayhoe and Wenderoth 1991; Rinner and Gegenfurtner 2000). The different processes exhibit different time courses, with time constants ranging from a few milliseconds for nearly instantaneous mechanisms to 20 – 30 s for slow processes (Fairchild and Lennie 1992; Fairchild and Reniff 1995; Rinner and Gegenfurtner 2000; Werner et al 2000).

These processes are not restricted to the retina but are continued at cortical stages. Most importantly, adaptation, like induction, is modulated by the 2-D luminance structure of a scene, indicating interactions between spatial and chromatic processes at cortical stages (Barnes et al 1999; Smith et al 2001; Werner 2003; Hurlbert and Wolf 2004). As a consequence, adaptation is enhanced within the first seconds of its time course in the presence of an articulated (spatially complex) surround. In particular, it could be demonstrated that adaptation is tuned to the spatial frequency and orientation of an adapting region in a way similar to the effect of segmenting the scene according to its regional texture (Werner 2003).

Whereas local colour contrast is not interrupted by stereo depth (Hurlbert and Wolf 2004), Shevell and Miller (1996) reported a small but persistent reduction of chromatic adaptation when separating the test patch and contiguous background by stereo disparity. However, the design of the experiments leaves open the possibility that this effect may have been produced by the simultaneous variation of the chromatic complexity of the background and hence a change in the chromatic contrast (Shevell and Wei 2000).

The object of the present study has been to investigate how depth segmentation is implemented in chromatic adaptation and whether, in fact, two stages in the computation of colour constancy exist—one comprising scene segmentation and the other an adjustment of colour appearance within each segmented region. If so, how effective are these processes for the compensation of inconsistent illumination changes, eg in the case of different illumination changes across different depth planes of a scene?

2 Method

2.1 *Subjects*

Five subjects took part in the experiments. They had normal colour vision (Cambridge Colour Vision Test) and normal visual acuity. Four of them were paid volunteers, not familiar with the goal of this particular study, and one was the author. The subjects used prism goggles (±10 D) for the fusion of the stereo patterns and viewed the stimuli on a monitor screen binocularly from a distance of 80 cm. Subjects had their heads fixed in a head-rest and were instructed to fixate on the test patch. The Ethics Commission of the University of Tübingen Medical Faculty approved the experiments and informed consent was obtained from each observer.

2.2 *Stimuli*

The experimental setup was placed in a dark room. The stimuli were produced on a calibrated colour monitor (BARCO Reference Calibrator), with a VSG2/4 graphic card processor (Cambridge Research Systems). The test pattern was produced from two identical, segmented patterns (11 deg × 9.6 deg), which were binocularly fused (figure 1a). The remaining screen was masked with black cardboard. Each test pattern consisted of a central hexagonal test patch (1.8 deg × 2.1 deg) and a structured background, consisting of hexagonal patches of the same size as the test patch. In one experiment, a square-wave grating pattern was used instead (for details see experiment 3).

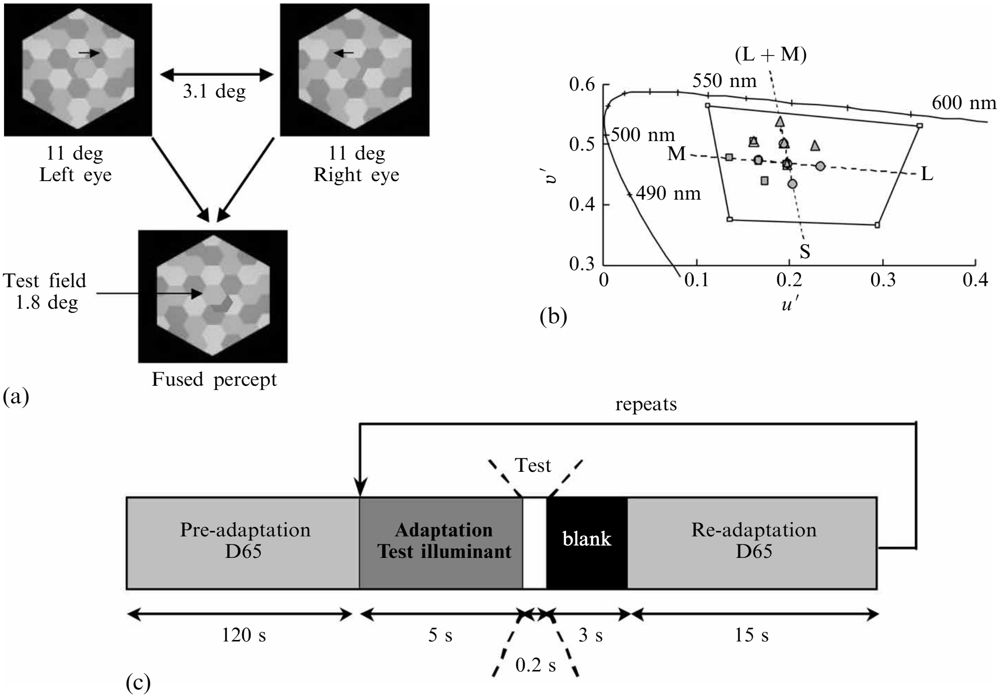

Figure 1. Experimental stimulus: (a) Two identical test patterns were binocularly fused with the help of prism glasses. The perceived depth relation between the central test patch and the background was produced by introducing crossed binocular disparity (relative displacement of the test patch, see arrows). The shadow in the lower pattern was not present in the actual experiments and is shown here only for illustrating depth perception. (b) Chromaticities of the stimuli in the CIE 1976 UCS diagram. The simulated illumination change shifted the chromaticities along an equiluminant (L/M) axis or S/(L + M) axis (dashed lines), by equal amounts ($\Delta E^*_{uv} = 22.18$). Different symbols refer to the colour loci under the different test illuminants (●: standard condition; ▲: 'yellow' condition; ■: green condition). (c) Experimental procedure (for details see text).

Two types of test patterns were used: (a) a multicoloured pattern and (b) a monochrome pattern. In the multicoloured test pattern, the patches differed in chromaticity as well as in luminance. Their chromaticities were chosen from the L/M and S/(L + M) cardinal axes in colour space (see colour loci in figure 1b); their luminance was

$10.3\ \mathrm{cd\ m^{-2}}$, $19.3\ \mathrm{cd\ m^{-2}}$, or $28.3\ \mathrm{cd\ m^{-2}}$. The different chromaticities and luminances were distributed equally over the pattern. In the standard condition, the average chromaticity was neutral and equal to the chromaticity of the test patch ($u' = 0.197$, $v' = 0.468$; $L_{\mathrm{test}} = 19.3\ \mathrm{cd\ m^{-2}}$), which in turn was identical to the colour locus of standardised daylight D65.

In the monochrome version of the test pattern, all patches had the same chromaticity and appeared achromatic under standard condition ($u' = 0.197$, $v' = 0.468$), but differed in luminance ($L_{\mathrm{test}} = 19.3\ \mathrm{cd\ m^{-2}}$; $L_{\mathrm{background}} = 10.3\ \mathrm{cd\ m^{-2}}$, $19.3\ \mathrm{cd\ m^{-2}}$, or $28.3\ \mathrm{cd\ m^{-2}}$).

The multicoloured pattern was used in experiments 1 and 3 in order to measure the effect of depth in a typical colour-constancy experiment with multicoloured surfaces.

The monochrome pattern was used in order to investigate the influence of luminance contrast and 3-D luminance structure in particular, without additional chromatic contrast, on chromatic adaptation. Previous experiments had shown a modulation of chromatic adaptation by the 2-D spatial luminance structure (spatial frequency and orientation) of an image (Werner 2003). Human stereopsis mechanisms are predominantly sensitive to luminance contrast and, to a lesser degree, also to chromatic contrast (Kingdom and Simmons 1996; Krauskopf and Forte 2002). In order to make the new results comparable with those from the previous 2-D experiments, experiments 2 and 4 were carried out with the monochrome pattern.

The perceived depth relationship between the test patch and the background was produced by introducing crossed retinal disparity (figure 1a). The test patch was perceived either within the same depth plane as the background (2-D condition, zero disparity) or in a plane in front of the background; depending on the particular test situation, different disparities were presented (1.9, 9.5, 19, 47, or 57 min of arc).

In addition to crossed disparity, uncrossed disparity was also initially tested (the test patch appeared further away than the surround). However, because the depth percept was more difficult to maintain during these tests, and the results were identical to those obtained with crossed disparity, the study was continued with crossed disparity only.

Colour constancy was measured for the transition from a simulated neutral daylight ('D65') to a simulated green illumination ($u' = 0.166$, $v' = 0.473$) or yellow illumination ($u' = 0.198$, $v' = 0.468$). This was achieved by applying weighting factors to the underlying receptor values (Vos and Walraven 1971). The weighting factors were determined by the amount of change in the receptor values that was necessary to obtain a shift of the colour locus of the test patch by a distance of $\Delta E^*_{uv} = 22.18$ [colour difference in the CIE 1976 ($L^*u^*v^*$) colour space; after Wyszecki and Stiles 1982]. Identical scaling factors were then applied to calculate the new colour loci of the other patches of the test pattern. The effect was, therefore, to shift the colour loci of all patches by an identical amount along the same axis [$\mathrm{L/M}$ or $\mathrm{S/(L+M)}$] in an equiluminant plane in colour space.

2.3 *Experimental procedure*

The experimental procedure is depicted in figure 1c. Each test session commenced with a 10 min dark-adaptation period, which was followed by a 2 min adaptation period to the test pattern under standard conditions. The test patch was present throughout the entire presentation time of the test pattern.

At the beginning of a test series, the individual achromatic colour locus (colour locus for the individual perception of grey under the given experimental conditions) was determined for each subject, and was in all cases within one just noticeable difference from the colour locus of D65. 'Grey' was defined as neither reddish nor greenish and neither bluish nor yellowish.

During the actual test, the subject was adapted for 5 s to the test pattern under the test illuminant (green or yellow). This was followed by a 200 ms test interval (indicated by a beep tone) during which the subject had to indicate whether the test patch did or did not appear grey. After the test interval, there was a blank screen (black) presented for 3 s in order to prevent the influence of afterimages on the observer's judgments. Afterwards, the subject was re-adapted to the standard condition for 15 s and the procedure was repeated automatically with 5 s adaptation to the test illuminant (see figure 1c).

The initially perceived greenish or yellowish tint of the test pattern gradually diminished during adaptation to the test illuminant (yellow or green illuminant). This corresponded to a shift of the perceived achromatic colour locus from its position in the standard condition (near the colour locus of D65) towards the locus of the new illumination. Colour constancy was quantified by measuring the shift of the achromatic colour locus by a hue cancellation method. If the test patch did not appear grey after the given adaptation period, the remaining tint was nulled with a keyboard device and the new setting was presented in the following test interval. This was repeated until the subject was satisfied with the setting of the achromatic colour locus, which was then recorded. Each subject repeated each setting five to ten times.

The results are presented as degree of colour constancy (DC) and refer to the shift of the subjective achromatic colour locus relative to the shift of the colour locus of the illumination. DC is calculated in the CIE 1976 ($L^*u^*v^*$) colour space from

$$\mathrm{DC} = |\mathrm{Ach}_{\mathrm{D65}} - \mathrm{Ach}_{\mathrm{test}}| / |\mathrm{Cl}_{\mathrm{D65}} - \mathrm{Cl}_{\mathrm{test}}|\,,$$

where $\mathrm{Cl}_{\mathrm{D65}}$ is the colour locus of standard illuminant D65 and $\mathrm{Cl}_{\mathrm{test}}$ the colour locus of the test illuminant (green or yellow, respectively); $\mathrm{Ach}_{\mathrm{D65}}$ is the subjective achromatic colour locus of the test patch under standard condition, and $\mathrm{Ach}_{\mathrm{test}}$ the subjective achromatic colour locus after adaptation to the respective test illuminant. Colour differences are calculated according to the CIE 1976 ($L^*u^*v^*$) colour difference formula (Wyszecki and Stiles 1982). A DC value of 1 refers to a complete compensation of the illumination change (optimal colour constancy). Data are presented as means and standard error of the mean (SEM). The t-test was used for the statistical analysis of the data.

3 Results

3.1 *Experiment 1: The effect of stereo disparity on colour constancy*

The object of the first set of experiments was to test how the depth relation between test patch and background influenced colour constancy. Green or yellow adaptations were measured, respectively, with the use of the multicoloured test pattern. In the first experiment, colour constancy was compared for two conditions: (a) 'no depth' condition (2-D): the test patch was presented in the same depth plane as the background ie without stereo disparity, and (b) 'test patch in depth' condition (3-D): the test patch was separated from the background in depth (crossed disparity 19 min of arc). Figure 2 shows the results of two subjects. One subject (AW) was tested for green adaptation, the other (AG) for yellow adaptation. The first bar in each result block represents the 'no depth' condition, the second bar the 'test patch in depth' condition. In both subjects, the degree of colour constancy was significantly reduced by stereo disparity as compared to the 2-D condition (t-test: $P < 0.01$).

A control experiment was carried out in order to test whether the reduction of colour constancy was due to a specific tuning of adaptation to the relative depth plane of the test patch or to an effect of stereo disparity itself. Again, the multicoloured test pattern was used but, in contrast to the previous 'test patch in depth' condition, the patches adjacent to the test patch were presented with the same disparity as the test patch. Thus, they were perceived together with the test patch within the same frontal plane ('pattern in depth'

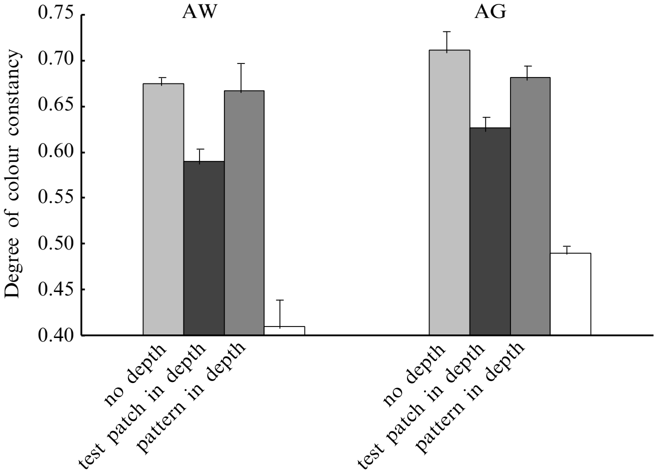

Figure 2. Results of experiments 1 and 2, showing the effect of stereo disparity and relative depth on colour constancy. Results are shown for two subjects (AW, AG). First bar of each result group represents the degree of colour constancy in the 2-D pattern ('no depth'), the second bar represents colour constancy with separation of test patch and background by stereo disparity ('test patch in depth', disparity 19 min of arc), third bar shows colour constancy with test patch and contiguous surround within the same depth plane ('pattern in depth'). The degree of colour constancy with a uniform adaptation field (baseline) is shown by the fourth bar (no pattern).

condition: crossed disparity, 19 min of arc). If the presence of stereo disparity alone would produce the observed reduction in colour constancy, we would expect the same reduction as in the previous experiment. On the other hand, if adaptation is tuned to the relative depth plane of the test patch, then the addition of patches within the same depth plane should increase the degree of colour constancy as compared to the previous experiment. Green or yellow adaptation was measured with the use of the multicoloured test pattern. As can be seen in figure 2, in both observers colour constancy in the 'pattern in depth' condition (third bar in each result block) increased to nearly the same amount as measured in the 'no depth' condition (first bar in each result block, no significant difference in the t-test: $P > 0.05$). From this result it is concluded that the presence of stereo disparity itself cannot account for the observed reduction of colour constancy. Rather, the results indicate a tuning of adaptation to the relative depth plane of the adapting stimulus.

3.2 *Experiment 2: Colour constancy as a function of stereo depth*

In another set of experiments, colour constancy was measured with the monochrome test pattern as a function of increasing stereo disparity between the test patch and background. Figure 3 shows the results of three observers. Colour constancy was found to decrease as a function of increasing separation in depth between the test patch and background, whereby the function levels off at a disparity of 19 min of arc onwards. A further drop in the degree of colour constancy was observed at the largest measured disparity (57 min of arc), which correlated with the reported onset of strong diplopia.

3.3 *Experiment 3: Combined effect of stereo depth and spatial frequency on colour constancy*

Previous work has demonstrated that contextual influences in adaptation are tuned to the spatial frequency and orientation of the adaptation pattern (Werner 2003). The following experiments were intended to test whether the spatial tuning of adaptation to depth and spatial frequency are independent processes or whether they interact. If the same contextual processes were involved in both, we would expect to find the tuning to depth also to be specific for spatial frequency. This was tested in the following experiments for green adaptation with the monochrome test pattern.

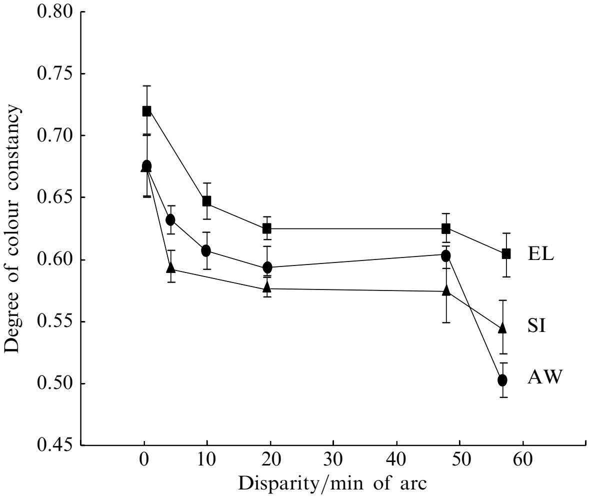

Figure 3. Colour constancy as a function of binocular disparity (1.9 – 57 min of arc) between test patch and background. Results of three observers are shown; test illuminant was 'green'.

Colour constancy was measured as a function of the spatial frequency relationship between the background and test patch, with or without additional separation by stereo depth (figure 4, grey and black symbols, respectively). In this set of experiments, the background consisted of a monochrome square-wave grating (0.1 or 0.21 or 3 cycles $\deg^{-1}$); the size of the test patch corresponded to 0.21 cycle $\deg^{-1}$ (see inserts in figure 4).

As can be seen in figure 4, a significant reduction of colour constancy by depth segmentation was observed for matching spatial frequencies of test patch and background (middle data points in each curve; t-test: $P < 0.01$). In the case of different spatial frequencies of test patch and background (background 0.1 cycle $\deg^{-1}$ or 3.0 cycles $\deg^{-1}$, test patch 0.21 cycle $\deg^{-1}$), binocular disparity did not reduce colour constancy further than the spatial-frequency differences alone. This was independent of whether the two features were consistent with respect to depth perception (spatial scale of the test patch is larger than that of the background) or inconsistent (spatial scale of the test patch is smaller than that of the background). In other words, an effect by depth segmentation was observed only for matching spatial frequency of the test patch and the background. Note that the lowest degree of colour constancy in these experiments was still higher than baseline (colour constancy when using a uniform background). It is, therefore, concluded that depth segmentation is effective only within those spatial frequency channels to which adaptation is tuned. In other words, stereo depth and spatial frequency are not independent, but interact.

3.4 *Experiment 4: The effect of stereo depth on the compensation of inconsistent illumination changes*

The previous experiments demonstrated a segmentation of the adaptation pattern by depth. This could potentially support colour constancy in the case of an inconsistent illumination change across different depth planes. The following experiment was designed to test this possibility. The multicoloured test pattern was used to simulate a yellow illumination change which exclusively affected the test patch, whereby the illumination of the background was kept constant at standard condition (inconsistent illumination change). Therefore, the background could not contribute to the yellow adaptation (neither via sensitivity control nor by contributing constant contrast signals/ratios). In fact, contrast signals encoded across the border of the test patch and the background would rather signal a material change towards yellow owing to the changed simultaneous contrast between the test patch and the background. For a 2-D presentation of test patch and background it is, therefore, expected that colour constancy in the inconsistent condition would decrease as compared to a consistent condition (the illumination

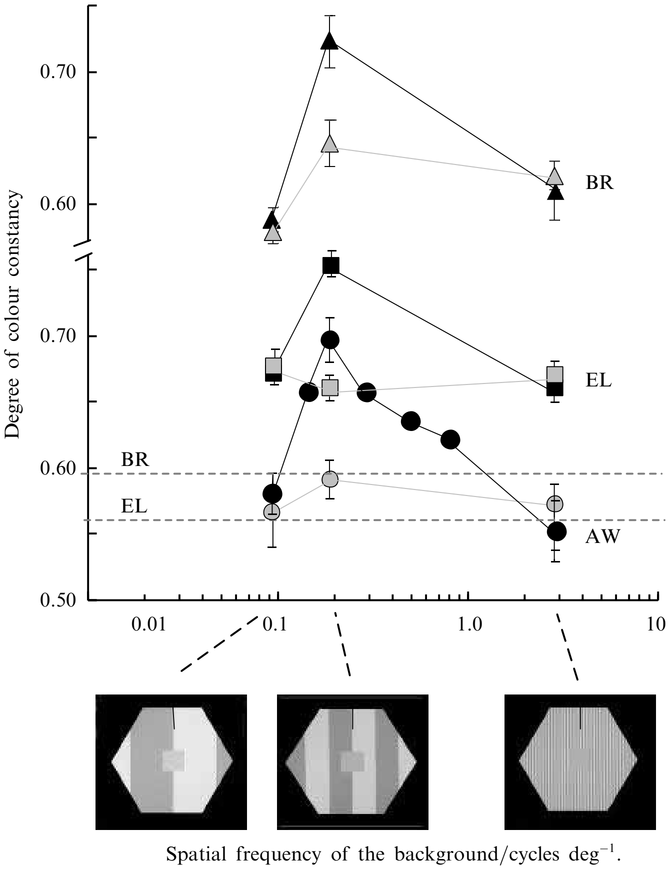

Figure 4. Combined effect of binocular disparity and spatial frequency difference on colour constancy. The degree of colour constancy is shown as a function of the spatial frequency of the background (0.1, 0.21, 3 cycles deg^{-1}; square-wave gratings, see inserted figures); the size of the test patch corresponded to 0.21 cycle deg^{-1}, throughout the experiments. Results are shown for three observers. Black symbols indicate colour constancy without additional disparity (2-D condition), grey symbols indicate colour constancy with additional disparity (3-D condition: crossed disparity, 19 min of arc). Dashed lines indicate the baseline, ie colour constancy with a uniform background (baseline of AW is at 0.41).

change affects test patch and background equally). Furthermore, in the 3-D presentation, if depth segmentation were not effective for separating the regions with different illuminations, the degree of colour constancy would also be expected to drop in the inconsistent as compared to the consistent condition.

Colour constancy for the inconsistent illumination change was determined in the 'no depth' (2-D) condition and the 'test patch in depth' (3-D) condition (disparity of the test patch: 19 min of arc). As before, the degree of colour constancy was measured for the achromatic appearance of the test patch. The results are compared with those measured in experiment 1 for a consistent illumination change in the 'no depth' and the 'test patch in depth' conditions, respectively. As can be seen in figure 5, colour constancy with the 2-D pattern was significantly reduced (t-test: $P < 0.001$) in the inconsistent condition as compared to the consistent condition. This was, however, different with the 3-D pattern: here, no difference in the degree of colour constancy was found between the inconsistent condition and the consistent condition. Moreover, colour constancy with the 3-D pattern (consistent and inconsistent changes) was significantly higher than colour constancy for the inconsistent illumination change with the 2-D pattern (t-test: $P > 0.05$).

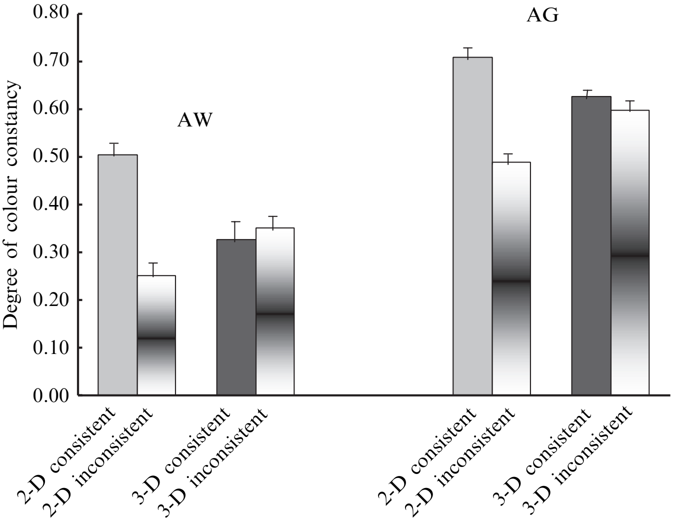

Figure 5. The effect of consistent and inconsistent illumination changes on colour constancy. Results are shown for two observers (AW, AG). First double block for each subject shows colour constancy with test and background in the same depth plane, for a consistent (first bar: 2-D consistent) and an inconsistent (second bar: 2-D inconsistent) illumination change (same results as in figure 2). Second double block for each observer shows the degree of colour constancy with test patch and background separated in depth, for consistent (first bar: 3-D consistent) and inconsistent (second bar: 3-D inconsistent) illumination changes.

It is therefore concluded that separating test patch and background in depth successfully supported selective adaptation to the illuminant of the test patch.

4 Discussion

4.1 *Colour constancy and scene segmentation*

The results showed that presenting test patch and background in different depth planes reduced the degree of colour constancy compared to a 'no depth' presentation of the same stimulus (figure 2). The effect of stereo depth on colour constancy increased as a function of increasing disparity (up to a disparity of 19 min of arc; figure 3). Colour constancy was not reduced when the test patch was presented together with a contiguous, complex surround within the same frontal depth plane ('pattern in depth' condition; figure 2). These findings are interpreted as an influence of stereo mechanisms on contextual processes, which contribute to chromatic adaptation in complex visual scenes. These contextual interactions are stronger within the same depth plane than across different depth planes and thus appear to follow a coplanar rule similar to that already described for lightness perception (Koffka 1935; Gilchrist 1977) or the judgment of surface colour appearance (Yamauchi and Uchikawa 2005).

The results indicate that the processes of chromatic adaptation are at the cortical stage not strictly local but include influences from the spatial context, since they can be modulated by changes in the surround of the stimulus. This has recently been shown for contextual changes concerning spatial frequency and orientation of the background pattern (Werner 2003), and here for changes in perceived depth. Thus, although such local gain adjustments are implemented at an early, retinal stage (MacLeod et al 1992; Smithson and Zaidi 2004), later stages seem to increase the spatial window over which adaptation processes operate.

An integration of signals over large parts of a visual scene is important for achieving a stable colour code and this is therefore included in many lightness algorithms (eg the retinex theory; Land 1977). However, it has also been shown that colour constancy does not exclusively rely on the global average of the signals (Kraft and Brainard 1999). In fact, this would be counterproductive and pose a serious problem for colour constancy in real scenes, where illumination may often be inconsistent. Thus, it follows that there should be a stage in the computation of colour constancy which discriminates between regions under different illuminations. At mid-level, this could be implemented by processes of scene segmentation, based on the assumption that regions in different depth planes are likely to be under different illumination.

The results of experiments 1 and 2 are consistent with this idea: contextual influences from other depth planes are less effective than those within the same depth plane, indicating that steps of depth segmentation precede adaptation.

Consequently, we should find colour constancy to be less affected by inconsistent illumination changes if the differently illuminated regions are separated in depth. This is, in fact, what experiment 4 showed. Here the inconsistent illumination change (only the chromaticity of the test patch shifted towards yellow) reduced the degree of colour constancy in the 2-D pattern considerably, but it did not affect colour constancy in the 3-D pattern. This cannot be explained by a floor effect because inconsistent adaptation in the 2-D condition produced an even lower adaptation rate (see figure 5). It is concluded that depth segmentation supports colour constancy in scenes with inconsistent illumination changes.

It is interesting to consider the consequences of the changed local contrast between test patch and background, which follows from the inconsistent illumination condition. Because of the resulting changes in cone contrasts one can expect a reduction of colour constancy and this was indeed observed in the 2-D condition. However, it has been shown that local colour contrast is not interrupted by stereo disparity (Hurlbert and Wolf 2004). The effect of changed local contrast should therefore be the same in the 2-D and the 3-D conditions and cannot account for the observed differences of the experimental results. Most importantly, it follows that the reduction of colour constancy is due to an effect of depth segmentation on contextual processes of chromatic adaptation and not on local contrast.

It can be argued that the depth segmentation may per se be counterproductive for the compensation of consistent illumination changes since it reduces the contextual influences and thus the overall amount of colour constancy (figure 2). However, in real scenes, inconsistent illumination changes are rather the rule than the exception and under this condition the degree of colour constancy with depth segmentation is higher than that obtained without segmentation (see figure 5). Furthermore, the degree of colour constancy in the 3-D condition was independent of whether there was a consistent or inconsistent illumination change. Also, it should be noted that in the reported experiments, the test patch was actually isolated from its surround. In real scenes, on the other hand, surfaces are usually not seen in total isolation from each other, but together with other surfaces within the same depth plane. In this case, spatiochromatic interactions within the same depth plane will contribute to adaptation, as shown in experiment 2.

It is concluded that the segmentation of the adaptation pattern into different depth planes effectively creates regions in a visual scene ('adaptation frames'), within which the processes of chromatic adaptation cooperate more strongly than across other regions. The findings support the notion of multiple stages in the computation of colour constancy, whereby processes of scene segmentation precede the adjustment of colour appearance within differently illuminated regions of an image (Brill 1990; Adelson 1999; Gilchrist et al 1999).

4.2 *Interactions between spatial processes*

The tuning of chromatic adaptation to relative depth planes supports and extends the findings of a previous study which demonstrated a tuning of chromatic adaptation to the 2-D features of a scene (spatial frequency and orientation; Werner 2003). In testing the relationship between the tuning to spatial frequency and tuning to depth, a specific interaction between the two spatial features was found. It was observed that spatial frequency influences the effect of stereo depth on chromatic adaptation exclusively within the tuned spatial-frequency range (matching spatial frequency of test patch and background; figure 4). This observation is in agreement with a spatial channel model of stereo vision, where stereo mechanisms are considered to work within spatial-frequency bands (Glennerster and Parker 1997). Therefore, stereo depth cannot reduce adaptation in general. Rather, the effect of stereo depth specifically affects those contextual influences which are at the same time tuned to other spatial features of the image, ie spatial frequency and orientation. This is in agreement with the observation that no reduction of adaptation by depth segmentation was found for uniform backgrounds (unpublished results). Furthermore it can be concluded that the contextual processes involved in chromatic adaptation are jointly sensitive to chromatic and spatial aspects (spatial frequency and depth) of the adapting stimulus and are influenced by mechanisms of scene segmentation.

Another interesting argument follows from the specific interaction between spatial frequency and stereo depth: when disparity between the test patch and the background was introduced, the test patch was perceived as having a slightly smaller size than the patches of the background because they have the same size on the retina but are perceived in different depth planes. In the present experiments, this was only a small effect, which was initially not observed by the subjects, but confirmed when it was pointed out to them. Because of the spatial tuning of chromatic adaptation, this may have added to the reduction of colour constancy in the 'test patch in depth' experiments. However, since the effect of depth is specific for the tuned spatial frequency (experiment 3, figure 4), it is concluded that the perceived decrease of size of the test patch could only marginally influence the results.

The new results and other psychophysical findings (eg Mullen 1987; Flanagan et al 1990; McIlhagga and Mullen 1997; Clifford et al 2003; Kingdom 2003; Hurlbert and Wolf 2004) underline the significance of the coprocessing of spatial and chromatic features of an image, from early cortical stages onwards. This notion is supported by a number of recent electrophysiological studies (eg Lennie 1999; Johnson et al 2001; Vidyasagar et al 2002; Wachtler et al 2003; Gegenfurtner and Kiper 2003) which demonstrated multiplexing properties of neurons in visual areas V1, V2, and V3 of the primate cortex. Of particular interest in connection with the present study are electrophysiological recordings in V1 of macaque monkeys, which showed a possible physiological substrate for early scene segmentation by texture, disparity, and colour (Zipser et al 1996).

4.3 *Relation between adaptation and induction*

At the same time this points to a principal difference between chromatic adaptation and induction. It is well established that local chromatic contrast is encoded at a low level (in the retina or early in V1) before processes of depth segmentation become effective (Shevell and Wei 2000; Hurlbert and Wolf 2004). However, chromatic contrast is influenced at a later stage by central, non-local mechanisms of contrast gain control from remote regions of a background (Shevell and Wei 2000). On the other hand, contextual influences in adaptation appear to be more centrally localised since they can be influenced by depth segmentation (present study) and their effects can be fully interocularly transferred (Werner et al 2000). Furthermore, it could be demonstrated that the central spatial mechanisms controlling adaptation cannot be identical to the central mechanisms of contrast gain control (Werner 2003). This is because adaptation is increased by the presence of matching spatial features in test patch and surround (background, spatial frequency, and orientation), rather than reduced as in the case of induction (Barnes et al 1999). This suggests that there are principal differences in the contextual processes involved in induction and adaptation, either in the characteristics of their underlying mechanisms or in the functional stage at which these processes are implemented in the visual pathways.

4.4 *Relation to other work*

The present results are consistent with the outcome of a study by Shevell and Miller (1996), who reported a small but persistent reduction of chromatic adaptation when introducing stereo disparity between test field and background. Although the authors originally interpreted their results in terms of the effect of a separation of test patch and background in depth, it was later suggested that the effect of depth on adaptation may instead be explained by an influence of depth on a central mechanism of contrast gain control (Shevell and Wei 2000). Unfortunately, the design of their adaptation experiments did not distinguish between the two alternatives, because it confounded the effect of depth segmentation and chromatic variation in the background, which activates a contrast gain control.

The new findings support an interpretation of the results in terms of scene segmentation in depth, because in the present experiments the chromatic variation of the background was kept constant while only depth cues were varied.

Yang and Shevell (2002) reported an improvement of colour constancy by stereo disparity. This seems at first to contradict the present results, but the studies were different in several important aspects. Yang and Shevell's simulation of a visual scene was very complex, containing shadows, illuminant gradients on the background, specular highlights, and 3-D surfaces of objects. Most importantly, Yang and Shevell tested the effect of stereo disparity in combination with the presence of specular highlights, whereas in the present work the effect of stereo disparity alone on colour constancy was tested. Since colour constancy in the Yang and Shevell study did not depend on the perceived 3-D geometry of the specular highlights, the open question remains what aspect of their complex scene was affected by disparity. The different outcome of the two studies may therefore reflect different influences of stereo disparity on different aspects of the scene and/or at different computational stages (low-level versus high-level influences).

5 Summary and conclusion

Colour constancy is influenced by the spatial structure of a scene in that chromatic adaptation is tuned to the perceived relative depth plane of the adapting stimulus as well as to its spatial frequency and orientation (Werner et al 2000; Werner 2003). This suggests an important role for scene segmentation in chromatic adaptation and, consequently, in colour constancy: visual scenes are first segmented according to differences in texture or depth plane, and this results in the creation of 'adaptation frames' within which contextual processes of adaptation operate. As a result, inconsistent illumination changes across different depth planes are compensated for as successfully as consistent illumination changes.

The adjustment of colour appearance within such adaptation frames may be of particular relevance for target search. This is especially so in natural scenes, which require fast switching between, and adaptation to, regions of differing luminance and wavelength content. The spatial tuning of adaptation supports this process by defining spatial regions, which are likely to share the same illuminant and background reflectance.

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