Role of eye movements in chromatic induction

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There exist large interindividual differences in the amount of chromatic induction [Vis. Res. **49**, 2261 (2009)]. One possible reason for these differences between subjects could be differences in subjects' eye movements. In experiment 1, subjects either had to look exclusively at the background or at the adjustable disk while they set the disk to a neutral gray as their eye position was being recorded. We found a significant difference in the amount of induction between the two viewing conditions. In a second experiment, subjects were freely looking at the display. We found no correlation between subjects' eye movements and the amount of induction. We conclude that eye movements only play a role under artificial (forced looking) viewing conditions and that eye movements do not seem to play a large role for chromatic induction under natural viewing conditions.

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1. INTRODUCTION

Placing a gray surface within a green surround makes it look pink. This is known as chromatic induction. Its origin is best understood in relation to color constancy [1,2]. Chromatic induction arises when the color of the surrounding is incorrectly attributed to the illumination. For instance, if part of the green color of the surround is attributed to the illumination being greenish, then the fact that the light from the target is not greenish implies that the target surface must be pink (i.e., it must reflect less green light than red light).

Chromatic induction (also known as simultaneous color contrast) depends on many different variables [3,4], such as the spatial parameters of the stimulus [5,6], the current state of adaptation [7], perceptual organization [8–10], and observer instructions [11].

With respect to the spatial parameter, it is known that chromatic induction is primarily determined by the color of directly adjacent surfaces [12–15]. This is consistent with the idea that information at the borders is critical in determining the perceived color [16]. However, more distant surfaces can also influence the perceived color. Eye movements and cone adaptation could mediate such global interactions [17–19].

Most studies on chromatic induction have concentrated on studying the dependence on stimulus variables and largely neglected the possibility of substantial differences across observers. Most studies have been performed with just a couple of observers. There are, however, indications that there exist differences between subjects in their amount of chromatic induction [20–24].

Besides the often large differences between subjects in the amount of chromatic induction, there is a second factor that is largely ignored in color vision research—eye movements. Eye movements are almost never recorded or controlled when studying color vision, with notably very few exceptions [18]. This is remarkable, as subjects' eye movements can to a large extent influence the adaptation of the cones in the subjects' retina and therefore influence how colors are being perceived. Eye movements raise two questions for color vision research: whether where one is looking matters for the perceived color of a surface of interest (for an example in the lightness domain; see [25]) and whether where one was previously looking matters in this respect (for examples in the chromatic domain, see [26,27]).

If we stare at a scene for some time and then divert our gaze to a large blank surface, we are likely to temporarily see an afterimage of the original scene in complementary colors. This afterimage arises because photoreceptors in the retina have adapted to the light coming from different parts of the original scene and therefore respond differently to exposure to the light from the blank surface. Thus where one was previously looking matters for color vision. The notion that a combination of eye movements and retinal adaptation can contribute to color vision is often acknowledged, and there is clear evidence that restricting eye movements can make a significant difference in a color-matching task [17] when studying chromatic induction. However, eye movements may not only influence the perceived color by exposing the fovea successively in time to different parts of the scene. Eye movements also determine precisely which part of the scene the fovea will be exposed to at a time. Very little is known about whether the precise point at which one is directing one's gaze makes any difference for the perceived color. A study by Hansen and Gegenfurtner [26] suggests that it does. These authors found that subjects clearly relied most on the colors near the fixation point. Brenner *et al.* [27] showed that where people direct their gaze affects how they evaluate chromatic stimuli. This implies that the image on the fovea will generally dominate the percept. The fact that the perceived color depends on where one is looking implies that the way we direct our gaze influences how we see objects' colors. In daily life, such changes will mainly occur when we shift our gaze by making saccades.

Golz [28] investigated whether subjects' eye movements affect how they perceive chromatic stimuli. In this study, subjects were instructed to either look at the background or to look only at the adjustable disk when making achromatic settings. He found higher amounts of induction when directing subjects' gaze more to the background. These results are interesting as these data suggest that subjects' eye movements can have an effect on subjects' color percept in a chromatic induction experiment. However, Golz [28] did not measure eye movements directly but only instructed subjects where to look. Therefore, one cannot tell whether subjects were following the instructions or not. Moreover, Golz used a very small adjustable disk with a radius of 0.75°. It is very hard to fixate one's gaze at an adjustable disk of this size as we make microsaccades, which makes controlling for the foveal information problematic. For example [29] showed that the mean amplitude of microsaccades for subjects during a 40 s fixation task (about the amount of time that subjects had to fixate their gaze in Golz's experiment) was within a range of 0.223° and 1.079°. It could therefore be the case that the size of the effect of where one looks has an even larger effect than Golz's [28] data show. The most important caveat, however, in Golz's [28] study is that he did not study eye movements under normal (free-looking) conditions. Therefore, we are still left with the fundamental question of whether subjects' eye movements have an effect on the achromatic settings that they make. Because Golz [28] only studied four subjects, it is impossible to draw any firm conclusions regarding the effects of eye movements in explaining between-subject variability in the amount of induction obtained.

In this paper we want to investigate whether the variability between subjects in the amount of chromatic induction can be explained by differences in viewing strategies between subjects. We examined this by analyzing whether the amount of chromatic induction shown by different subjects is influenced by their eye movements. It could be that some subjects spend more time looking, or look more often than others, at the background and, consequently, expose their foveae to the colors of the surround to a larger extent. This could lead to a different state of adaptation at the moment subjects switch their gaze toward the center test patch. Consequently, subjects might perceive colors differently and make achromatic settings that are more influenced by the chromaticity of the background. In line with this form of reasoning are the results of studies showing that adaptation plays an important role in both color constancy and in chromatic induction [17,30,31]. To test the hypothesis, we measured subjects' eye movements both while they were forced to look either at the background or exclusively at the central patch that they had to set to gray (experiment 1) and when they were free in making eye movements while performing achromatic settings (experiment 2). By combining the information from these two experiments, we could estimate to what extent eye movements have altered the settings in the induction experiment. We compared this estimate with the actual difference between achromatic settings. We used variegated-colored backgrounds for experiment 1 and both variegated-colored backgrounds and uniform-colored backgrounds for experiment 2.

2. EXPERIMENT 1: "FORCED-VIEWING" CONDITION

The purpose of the first experiment was to replicate the results of Golz [28]. When subjects are forced to look more often at the background, the amount of adaptation toward the background is enhanced. If eye movements have an effect on the magnitude of chromatic induction, we hypothesize that the amount of induction will be larger when forcing subjects to look more often at the background compared to when forcing subjects to only look at the adjustable disk when making achromatic settings. Our hypothesis is that adaptation occurs locally, as there is direct support for this [17]. Thus, we only adapt to those parts of the scene that we have looked at. If however, one assumes global processing of color [32], one does not expect a large difference in the amount of chromatic induction between the "normal viewing" condition and the "forced-viewing" condition.

A. Method

For this experiment, we used four variegated-colored background conditions (see below) with a disk radius size of both 4° and 8° (see Fig. 1). Subjects sat 46 cm from the CRT screen with their chins supported by a chin rest. Subjects had to make achromatic settings. Subjects entered the room and dark-adapted for 10 min during which time instructions were given. A demo of the experiment was shown to the subjects to make sure that they understood the task. Before the start of the experiment, subjects could practice the task. Subjects made achromatic settings for 64 trials (four different backgrounds × *two* looking instructions × *eight* replications). Each session took about 1 h and 45 min. Halfway through the session, there was a break of 10 min. The order of looking condition (fixate background versus fixate disk; see below) was randomized within a session. Subjects were tested for the 8° and 4° radii disks in two separate sessions.

1. Monitor

The stimuli were presented on a calibrated Samsung Sync Master (1100 MB) monitor (40 cm × 30 cm, 1280 × 960 pixels, 85 Hz, 8 bits per gun). The nonlinear relationship between voltage output and luminance was linearized by a color look-up table for each primary. To generate the three red-green-blue (RGB) look-up tables, we measured the luminance of each phosphor at various voltage levels using a Graseby Optronics Model 307 radiometer with a Model 265 photometric filter, and a smooth function was used to interpolate between the measured data. The spectrum of each of the three primaries at their maximum intensity was measured with the Photo Research PR-650 spectroradiometer. The obtained spectra were then multiplied with the Judd-revised CIE 1931 color-matching functions [33,34] to derive CIE xyY coordinates of the monitor phosphors. The xyY coordinates were then used to convert between RGB and the DKL color space (see below).

2. Adjustable Disk

The stimulus consisted of either a 4° or an 8° radius adjustable disk (see Fig. 1). The luminance of the adjustable disk was 54 cd/m^2. Subjects could adjust the disk's color (within the range that could be rendered at this luminance) by moving the computer mouse in a two-dimensional opponent-color space ("DKL" [35]). The two isoluminant axes of this space refer to color directions that exclusively stimulate the $L - M$ and $S - (L + M)$ postreceptoral mechanisms. The end points of these color directions correspond to CIE coordinates (0.3273, 0.3111; 0.2764, 0.2722; 0.2621, 0.3412 and 0.3257, 0.4045). Data will be presented in this DKL color space.

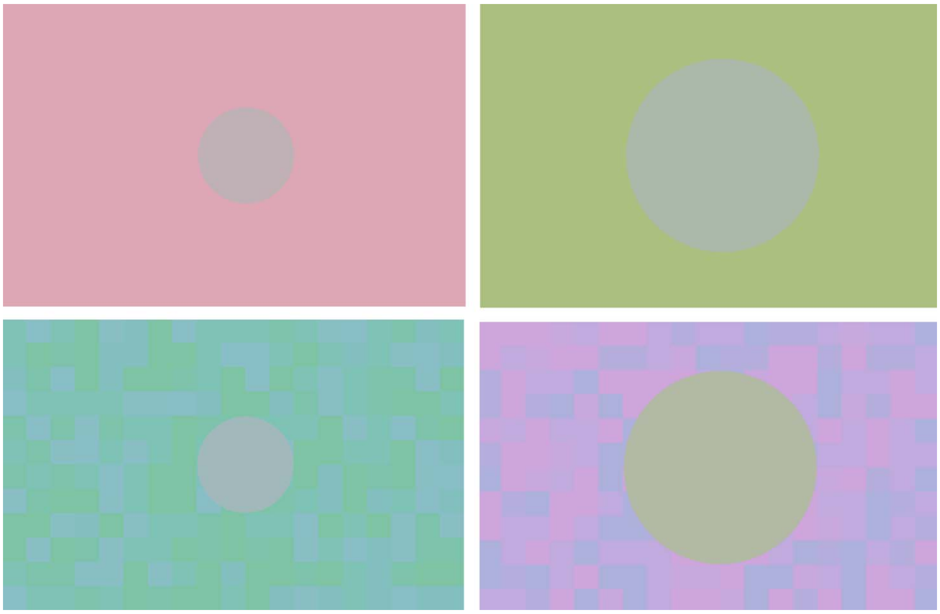

Fig. 1. (Color online) Examples of the stimuli used for experiment 1 and 2. The two photographs in the top row show the uniform-colored background condition, while the two photographs in the bottom row represent the variegated background condition. In the left column, the disks have a radius of 4°, while the two disks in the right column have a radius of 8°. All four types of stimuli were used for experiment 2, while only the variegated-colored background was used in experiment 1. The color of the adjustable disk as shown in the photographs is the average achromatic settings of subjects for that particular condition. For details of how the background colors were selected, see the main text.

All stimuli were described in the isoluminant plane of the DKL color space [35,36]. The DKL color space is a second-stage cone opponent color space, which reflects the preferences of retinal ganglion cells and LGN neurons. It is spanned by an achromatic luminance axis, the L+M axis, and two chromatic axes, the L – M axis and the S – (L + M) axis. The two chromatic axes define an isoluminant plane. These three so-called cardinal axes intersect at the white point. The L+M axis is determined by the sum of the signal generated by the long-wavelength cones (L cones) and the middle-wavelength cones (M cones). The L – M axis is determined by the differences in the signals as generated by the L cones and the M cones. Along the L – M axis, the L- and M-cone excitations covary at a constant sum, while the short-wavelength cone (S-cone) excitation does not change. Colors along the L – M axis vary between reddish and bluish–greenish. The S – (L + M) axis is determined by the difference in the signals generated by the S cones and the sum of the L and M cones. Along the S – (L + M) axis, only the excitation of the S cones changes and colors vary between yellow–greenish and purple. The axes of the DKL color space were scaled from –1 to 1, where ±1 corresponds to the maximum contrast achievable for the particular axis on the monitor used. Subjects were asked to set the disk to appear to be gray (achromatic). If subjects found it hard to achieve an achromatic setting, they were instructed to choose the closest match they could find to gray.

3. *Variegated Backgrounds*

In total we used four variegated-colored backgrounds (see Fig. 1). The variegated backgrounds consisted of a tiled pattern of 16 (width) by 12 (height) squares. Each square subtended 2° of arc. The eight kinds of differently colored squares had chromaticities that were equally spaced around a circle of radius 0.2 in DKL color space. There were four different centers used to make the four different variegated backgrounds: $C = (-0.5, 0)$; (0, 0.5); (0.5, 0); (0, −0.5), and in each case one of the eight colors generated fell between C and the origin of the DKL space.

The luminance of the background squares was equal to the luminance of the adjustable disk; 54 $\mathrm{cd/m^2}$.

4. *Two Looking Conditions*

The main procedure of this experiment was similar to that of Golz [28]. At the start of each trial, subjects had to fixate a fixation cross. Subsequently, they had to press the spacebar. This was to guarantee good calibration during the experiment. We had two looking conditions; one was the “fixate disk” condition, in which the subjects had to exclusively fixate the adjustable disk during the whole trial. A computer-controlled voice instructed subjects to look for 5 s at the adjustable disk. After the 5 s had elapsed, the voice instructed the participant to start the adjustment process. After 12 s, the procedure repeated itself twice; they had to look again at the disk for 5 s and then work on the achromatic setting for another 12 s. Thus, when subjects made their adjustments, they were looking exclusively at the adjustable disk. This means that per trial, subjects had in total 36 s (3 × 12 s) to find the achromatic setting.

The other looking condition, which we will refer to as the “fixate background” condition, entailed that subjects started the trial by looking at the background for 5 s in order to adapt to its color. After this time, a computer-controlled voice instructed them to work on the adjustment (for 12 s). When making achromatic settings, subjects were allowed to look back and forth between the disk and the background to find the gray to enhance a possible effect of the background’s color on the gray settings. As in the fixate disk condition, the procedure repeated itself twice. The procedure of the experiment was organized in this way so that subjects’ total amount of time to find the achromatic setting and the amount of time to adapt to either the disk or the background was identical. When subjects had found the achromatic setting, they did not have to press a computer button as the computer program stored the last chromatic values at the end of each trial. This meant that if subjects already found the achromatic setting in the first or second part of the 36 s trial, they had to wait until the trial had ended. Subjects were encouraged that once they had found the perfect achromatic setting that they should check during the remaining time of the trial whether the achromatic setting was still acceptable for them.

5. *Eye Movement Recordings*

Gaze position signals were recorded with a head-mounted, video-based eye tracker (EyeLink II, SR Research, Ltd., Osgoode, Ontario, Canada) and were sampled at 500 Hz. Observers viewed the display binocularly, but only the right eye was sampled. Stimulus display and data collection were controlled by a PC. The eye tracker was calibrated at the beginning of each session. During the calibration, the subject fixated nine calibration points on the face of the display for 1 s each. The location of the nine fixation points was at the four corners of the display, in the middle of the display, and to both the left and the right and below and above the middle of the screen. The order of presentation of the calibration points was randomized. In order to measure where subjects fixate their eyes, we measured subjects' pupil area. Calibrations before and during the experiment confirmed the high stability of the eye position recordings. A calibration was accepted only if the validation procedure revealed a mean error smaller than 0.4° of visual angle. Eye positions were transformed into positions on the screen on the basis of the calibrations immediately before and during the experiment. We determined the location and the time subjects spent looking at different positions within the stimulus. The data were analyzed over the full time of the recording. The duration of the experimental sessions was not limited. The achromatic settings, therefore, may therefore be considered as accurate as in a "normal" psychophysical experiment.

During the whole experiment, subjects' eye movements were recorded. However, for this experiment we did not use the eye movement data as such. We only used the eye movement data to check whether subjects followed the instructions. When subjects were forced to look at the background, but looked at the disk instead, the disk's color blended with the background's color and vice versa. In this way, we had control over subjects' state of adaptation. Between each trial, a white screen was presented for 5 s in order to diminish color aftereffects.

6. *Subjects*

Six subjects participated in the experiment, including authors J.G. and M.T. Three of the six subjects participated in both sessions (4° and 8° radii disks). All subjects had normal color vision as tested with Ishihara color plates [37]. All subjects were between 18 and 39 years of age. All had normal or corrected-to-normal visual acuity. The subjects (except of authors J.G. and M.T.) were naïve as to the purpose of the experiment.

7. *Subjective Gray*

In addition to performing in the main experiment, subjects were asked to set an 8° radius adjustable disk at the center of a white background to appear gray. The reason for performing this task is to measure what subjects regarded as being gray without having a chromatic bias in the background. The luminance of the adjustable disk was fixed at 54 $\mathrm{cd/m^2}$. The background was always white with the chromaticity of the neutral point in DKL space (0.280, 0.295, 100 $\mathrm{cd/m^2}$ in CIE space). The subjects changed the disk color (but not its luminance) by moving the computer mouse in an identical fashion to the main experiment. This was done 10 times, and the average setting was used as the subjective gray for that subject. The average within-subject standard deviation is 0.0788 for the $L-M$ axis and 0.0980 for the $S-(L+M)$ axis in the DKL color space. The subjective gray values for each subject were used to calculate the chromatic induction index of each subject (see below). We have chosen the method of subjective gray to measure the magnitude of chromatic induction as simply using the neutral point in DKL color space would not be a neutral color for each subject. In order to use a neutral point that is indeed neutral for each observer, we used subjective gray settings.

8. *Analysis*

We first determined the mean value in the DKL color space of each subjects' achromatic setting for each background condition. To obtain a measure of how the color of the background influenced what subjects perceived as gray, a chromatic-induction index was calculated for each subject, for each trial for each background. The chromatic induction index was calculated in the following way: we took subjects' achromatic settings (made during the main experiment with an inducer) in the DKL color space and projected those on a line that lies between the color of the background and the subjective gray setting (subjects' gray settings with no inducer present). We represented the amount of chromatic induction as the distance (in the DKL color space) between subjects' subjective gray and the projected settings on the direction of the background (p in Fig. 2). Thus the chromatic induction index is the difference between the projected setting of the adjustable disk and the subjective gray setting, as a percentage of the difference that we would expect if subjects attributed all differences in the background to differences in illumination. So 100% indicates that subjects set the color of the adjustable disk to the color of the background (full chromatic induction), and 0% indicates that subjects set the disk to the same gray value as when no inducer was present (subjective gray settings). Paired t-tests were used to see whether the difference in the amount of induction was significantly different from zero between the fixate background and the fixate disk condition.

B. Results

Figure 3 shows the chromatic induction index (plotted on the y axes) when tested with the 4° radius disk and an 8° radius disk (Figs. 3A and 3B, respectively). Each panel plots the chromatic induction index when subjects were instructed to look at the background or to look exclusively at the adjustable disk (depicted on the x axes of both panels). From these data, we can conclude that our hypothesis is confirmed: subjects' chromatic induction index is significantly larger when instructed to look at the background compared to when forced to look only at the adjustable disk. This effect is apparent for both the 4° [$t(5) = 2.8046$, $p = 0.0378$] and 8° radii

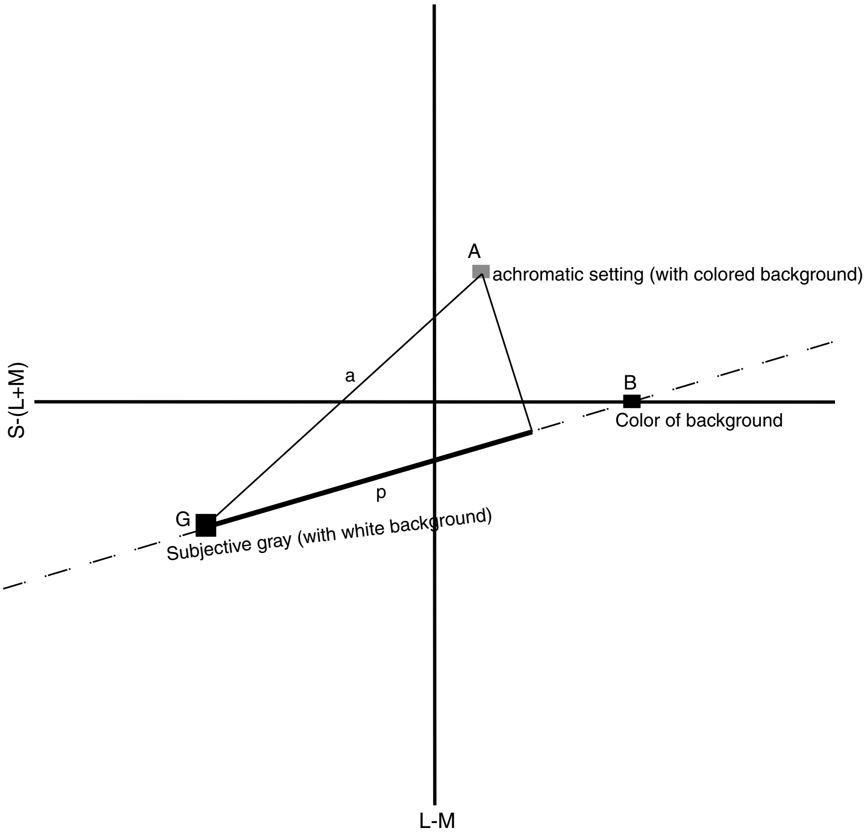

Fig. 2. Let *A*, *G* and *B* be the points in DKL space of the subject's achromatic setting, the subject's subjective gray setting and the background light. The projection *P* of *A*-*G* onto *B*-*G* is shown by the dark line. We take as our chromatic induction index, $100\% * |P|/|B\text{-}G|$, where $|P|$ is the length of *P* and $|B\text{-}G|$ is the length of *B*-*G*. Thus a chromatic induction index of 0% means that subject's setting has not shifted at all from *G* toward *B*. A chromatic induction index of 100% means that the subject's setting has shifted completely from *G* to *B*.

disks [$t(5) = 5.2113, p = 0.0034$]. However, this effect is larger for the 8° radius disk (Fig. 3B) compared to the 4° radius disk (Fig. 3A).

C. Discussion

We were able to replicate Golz's [28] results in that we also found significant differences in the amount of chromatic induction when forcing subjects to look at the background compared to forcing them to look at the adjustable disk. For the 4° radius disk, the induction effect in our setup increased from 36% to 46% when forcing subjects to look at the background compared to when forcing them to look at the disk. For the 8° radius disk, the effect increased from 16% to 44% when subjects were forced to look at the background.

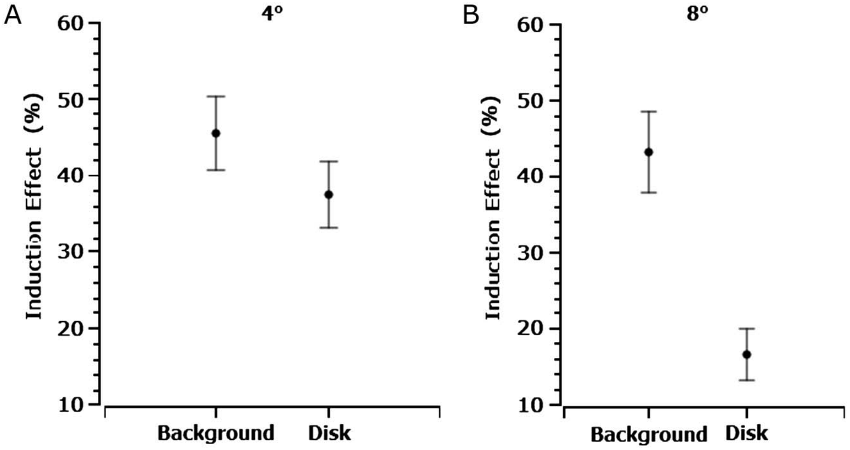

Fig. 3. Results of experiment 1. The graphs show the data for the variegated-colored background condition with A, a disk radius of 4° and B, the 8° radius adjustable disk. The average chromatic induction index is plotted (y axis) for when forcing subjects to look at the background (left symbol in each graph) and when to look exclusively at the adjustable disk (right symbol) when making achromatic settings. The results show that instructing subjects to look more often at the background has a large positive effect on the chromatic induction index. The difference between these two viewing instruction on the chromatic induction index is about 10% for the 4° radius disk and about 28% for the 8° radius disk.

These differences between forcing the subject to look either at the background or at the adjustable disk are even larger than reported by Golz [28]. One of the reasons why we were able to find even larger differences between these viewing conditions is that we used a larger disk radii than Golz [28] did. From our data, we were able to see that increasing the disk radius to 8° increased the difference in the chromatic induction index between forcing subjects to look at the background compared to forcing them to look at the disk. These results come as no big surprise as the background is relatively distant when fixating an 8° radius disk, which means that the fovea and parafovea are completely adapted to the color of the adjustable disk. Also, as we were able to detect where subjects were actually looking, we could change the stimulus accordingly when subjects were not following the instructions.

However, the results of experiment 1 do not tell us whether eye movements play a (large) role in the variability in chromatic induction between subjects under normal (free-viewing) conditions. To test this, we performed a second experiment.

3. EXPERIMENT 2: "NORMAL VIEWING" CONDITION

A. Experiment 2a

The purpose of the second experiment was to investigate the variability between subjects in their amount of chromatic induction and to investigate whether subjects' eye movements can explain this variability to some extent. For the main experiment, in which we tested subjects' variability in the amount of induction while recording their eye movements, only the variegated-colored background with an adjustable disk of 4° radius was tested. In order to study possible effects of scene statistics on eye movements and chromatic induction, we tested a smaller number of subjects for uniform-colored backgrounds with radii of both 4° and 8° and for a variegated background condition with a disk radius of 8° (see Fig. 1).

1. *Method*

Thirty subjects (including authors J.G. and M.T.) were measured in the main experiment. All subjects had normal color vision as tested with Ishihara color plates [37]. All subjects were between 18 and 39 years of age. All had normal or corrected-to-normal visual acuity. The subjects (except authors J.G. and M.T.) were naïve as to the purpose of the experiment. Twenty-two females and eight males participated in this study.

a. Procedure

Subjects sat 68 cm from the screen and viewed the stimulus with both eyes. Please note that although we changed the viewing distance between the observer and the CRT (compared to experiment 1), the visual angle of the stimulus was kept constant.

Participants could shift their gaze freely over the screen. This condition, in which subjects are free in where to look, will be referred to as the "normal viewing" condition. The chins of the subjects were supported to reduce the amount of head movements during the experiment. The room was dark except for the light from the screen. Subjects dark-adapted for about 10 min, during which time instructions were given. Each session took about 30 min. Each subject made 40 settings: each combination of the four backgrounds (see below), each presented 10 times. All the trials were presented in random order. A new background was generated for each trial.

b. Task

At the start of each trial, a black fixation cross appeared at the center of a white screen and subjects had to fixate on the cross while they pressed the space bar. This was to check whether subjects kept calibrated during the experiment. During each trial, subjects were asked to set an adjustable disk at the center of a (32 ° × 24 °) background so that it would appear gray. They could vary its color by moving the computer mouse. Subjects indicated that they were content with the set value by pressing a button. Once they did so, a white screen appeared. The white screen was presented for 5 s in order to attenuate possible color aftereffects. The initial color of the adjustable disk was determined randomly from within the range that they could set. Immediately before the session, the subjects were allowed to practice until they were confident that they understood the task and procedure. When they indicated that this was the case, the session started. The stimuli were identical to those of experiment 1 (see above).

c. Analyses

For the eye movement data, the following factors were considered: the proportion of time that subjects looked at the background, the average number of times that a subject looked across the border between the adjustable disk and the background, and the proportion of time subjects' looked directly at the border between the adjustable disk and its immediate background.

Pearson correlations were computed to see whether there was a linear relationship between subjects' eye movements and the chromatic induction index obtained. We computed the correlation between the amount of induction and the eye movement parameters for each trial for each background for each observer. Second, we averaged these correlations across trials and across backgrounds to compute the correlation across participants.

Finally, the variables mentioned above were used in a linear regression model to try to predict the index of chromatic induction.

2. *Results*

Figure 4 shows the variability in the chromatic induction index for each of the 30 subjects (each represented by a separate symbol) for experiment 2a. The big triangle shows the average induction index averaged across subjects with the standard deviation. From Fig. 4 we can conclude that the variability between subjects in the chromatic induction index is large, as explained in the introduction of this paper. In fact, looking at the difference in induction between the subject with the least amount compared to the subject with the largest amount of induction in this experiment, we can say that the chromatic induction index varies between roughly between 14% and 60%.

To explore whether there is also variability between subjects in what they perceive as gray when there is no inducer present (e.g., a white background) and to compare this to the variability in subjects' settings when an inducer is present, we

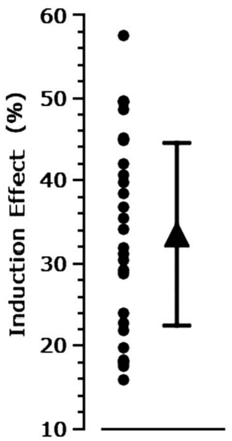

Fig. 4. Results of experiment 2a. Shown are the average chromatic induction-indices obtained for each of the thirty subjects (sometimes overlapping each other) when tested with the variegated-colored background condition with the 4° radius disk. Each disk represents a subject. The big triangle represents the average amount of induction across subjects (with the standard deviation). These data show that there is a large variability between subjects in the amount of chromatic induction.

plotted the average achromatic settings in DKL color space for each of the thirty subjects, for each background. Figure 5 shows these data. Symbols of a certain color show the average achromatic settings for that particular inducer. Thus, green symbols show average settings for each individual for a green background. Also shown are the average subjective gray values for each subject; these data are plotted in black. The small crosses on the cardinal axes represent the four colors of the inducers. Maximum variability axes were determined by computing the eigenvectors of the covariance matrix of the mean matches of the observers. From this figure we can conclude that there is also a large variability in what subjects perceive as gray when there is no inducer present. This is not unexpected as subjects have to set the disk toward an internal standard as what they perceive as gray. Obviously, subjects vary in this respect. Figure 6 shows the area of the ellipses defined by the two maximum variability axes, shown for each of the four inducers (represented by a different color) and for the variability in subjects' subjective gray settings (gray symbol) separately. This figure shows that the maximum variability is less for subjects' subjective gray settings compared to their achromatic settings when an inducer is present. Thus, we can conclude that at least part of the variability between subjects in the chromatic induction index is due to a real perceptual difference between subjects.

Where do subjects look the largest amount of time when they perform the task? Figure 7 explores this. This figure shows the proportion of time during each trial that a subject looks either at the adjustable disk, at the background, or at the border between the disk and the background. Subjects looked for more than 85% of the trial duration at the disk, for about 5% of the trial duration they looked at the background, and about 5% of the time they looked at the borders. As we have a mean error in our eye movement data that is around 0.4° of visual angle, we cannot be completely sure whether a subject is actually looking at the border or not. Therefore, we accepted values within a range of ±0.4° with respect to the border as an indication that subjects were looking at the border.

A straightforward explanation for these data is that we used a 4° radius disk for this experiment. Subjects did not have to look directly at the background or at the border because in

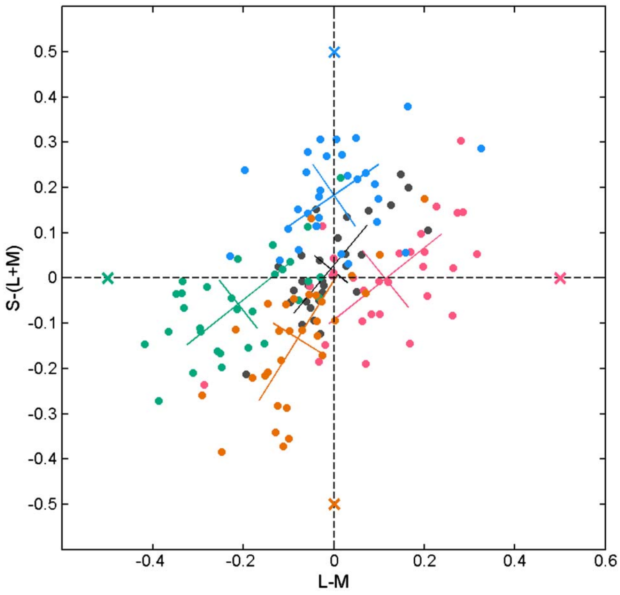

Fig. 5. (Color online) Results of experiment 2a. Shown are the average achromatic settings for each of the thirty subjects, separately plotted for each of the four inducers (shown in a different color). Also shown are the subjective gray settings for each subject (shown in black). The small crosses on the cardinal axes show the chromaticity of the inducers. The maximum variability axes were determined by computing the eigenvectors of the covariance matrix of the mean matches of the observers. From this figure we can conclude that the variability in subjects' subjective gray settings was smaller compared to the variability in their achromatic settings during the main experiment.

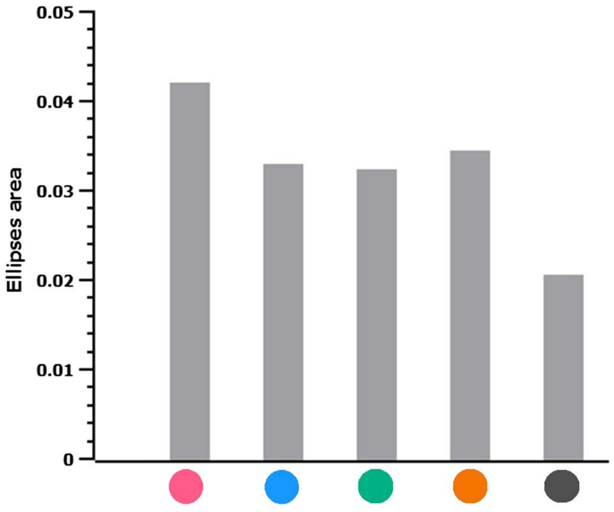

Fig. 6. (Color online) Results of experiment 2a. This figure shows the area of the ellipses defined by the two maximum variability axes as shown in Fig. 5, plotted for each of the four inducers (represented by a different color) and for the variability in subjects' subjective gray settings (gray symbol) separately. From this figure we can conclude that the least variability in subjects' settings occurred for their subjective gray settings and that subjects showed the largest variability in their achromatic settings when a purple inducer was present. Thus, at least part of the variability between subjects in the chromatic induction index is most likely due to a real perceptual difference between subjects.

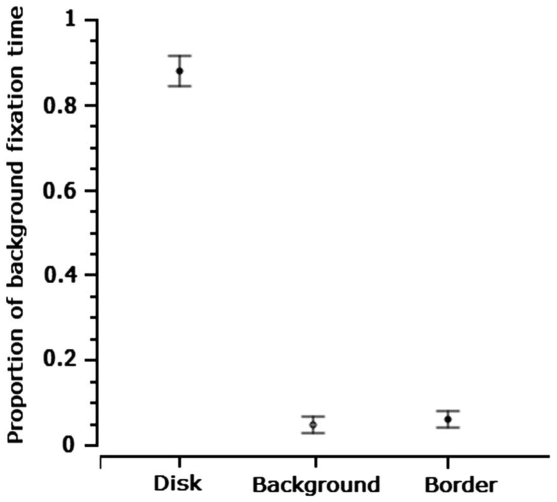

Fig. 7. Results of experiment 2a. Shown is the average proportion of time (with their standard errors) that subjects look either at the adjustable disk, the background, or at the border when they made achromatic settings. From this figure, we can conclude that subjects spent about 88% of the time looking at the adjustable disk when making achromatic settings, about 6.5% of their time they looked at the border between the adjustable disk and the immediate background, and they only spent about 5.5% of the trial looking at the background. From this we can conclude that subjects hardly looked at the background at all.

their peripheral vision they could still see the border and the background. This could also explain the fact that the background's color has an influence on subjects' achromatic settings, although subjects do not directly look at the background nor at the border.

The main question, however, is whether the variability in subjects' eye movements can explain the variability in the subjects' induction. Our main hypothesis is that if people look for a longer time at the background, that they adapt more to the background's color and therefore show a high score on the chromatic induction index. Figures 8A–C investigate this option. Shown in Fig. 8A is the proportion of time subjects spent looking at the background (plotted on the x axis) and their chromatic induction index (as plotted on the y axis). Two things stand out from this figure. First, subjects do not spent a lot of time looking at the background (only a few data points have large x coordinates). Second, there does not seem to be a (linear) relationship between the proportion of time that subjects spent looking at the background and the chromatic induction index obtained. In other words, even if subjects do not look directly at the background at all (zero point on the x axis), their achromatic settings are still biased by the background's color (values greater than zero at the y axis). Regression analysis reveals that the proportion of time that subjects look at the background cannot explain to a significant degree the variability in induction ($R^2 = 0.079$, $p = 0.131$).

A second factor to explore is the hypothesis that subjects' eye movements can explain their variability in the chromatic induction index. We investigated this by looking at the number of times subjects look between the adjustable disk and the background, in order to compare the achromatic settings with the background's color. The hypothesis is that if subjects compare the color of the adjustable more often with the color of the background, the background's color will have a larger influence on the achromatic setting. Figure 8B explores this

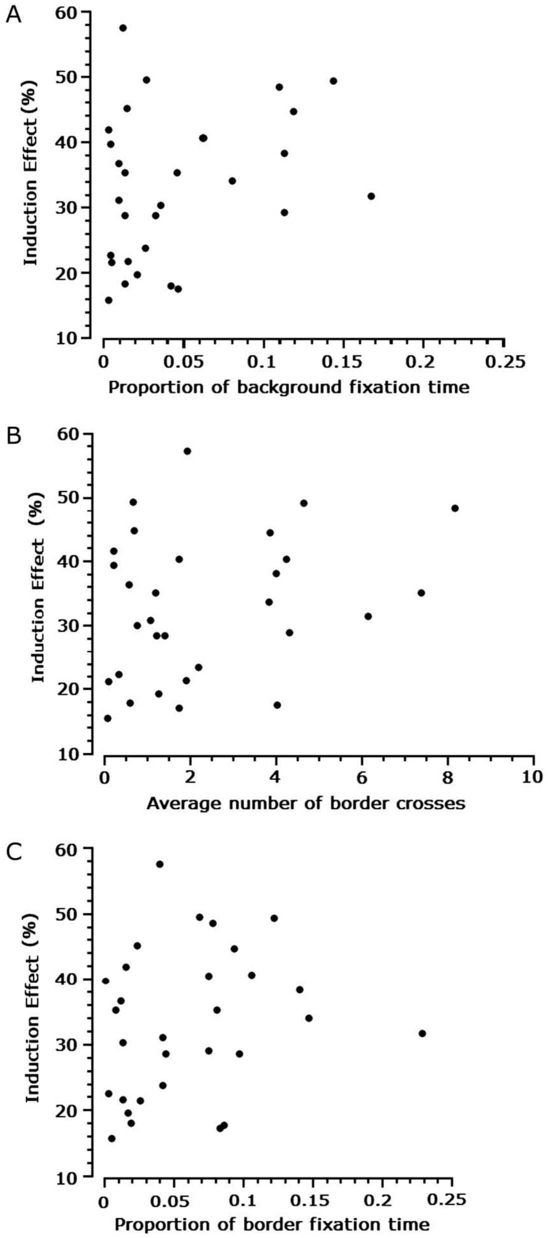

Fig. 8. Results of experiment 2a. A. Proportion of time that subjects looked at the background during each trial (x axis) plotted against the chromatic induction index obtained (y axis). These data reveal that there is no linear relationship between the proportion of time looking at the background and subjects' amount of induction. Regression analysis showed that the proportion of time looking at the background could not explain the variability between subjects in the chromatic induction index to a significant degree ($R^2 = 0.079$, $p = 0.131$). B. Average number that each subject looks across the border between the adjustable disk and the background (x axis) plotted against the amount of induction obtained for that subject (y axis). These results show that there is no linear relationship between the number of border crosses and the chromatic induction index obtained. Regression analysis revealed that the average number of border crosses could not significantly explain the variability between subjects' chromatic induction ($R^2 = 0.075$, $p = 0.142$). C. Proportion of time subjects' looked at the border between the adjustable disk and its immediate background (shown on the x axis) and the amount of induction obtained (y axis). These results show that looking for a longer time at the border between the adjustable disk and the colored background does not increase the chromatic induction index for subjects. Regression analysis indicated that the proportion of time fixating on the border could not significantly explain the variability in subjects' chromatic induction ($R^2 = 0.045$, $p = 0.258$).

idea; shown are the average number of border crosses when making the achromatic setting (plotted on the x axis) and the average chromatic induction index obtained (plotted on the y axis). From this figure we can conclude that there once again is no significant linear relationship between the score on the chromatic induction index and the number of times a subject looks back and forth between the disk and the background. Regression analysis revealed no significant contribution of the number of times looking back and forth between the disk and the background in explaining the variability in induction between subjects ($R^2 = 0.075$, $p = 0.142$).

Finally, in the introduction, it was explained that the information at the borders is critical in determining the perceived color (e.g., local color contrast). To study whether looking at the borders had an effect on the chromatic induction index, we analyzed the proportion of time that subjects fixated on the border between the disk and the background when making achromatic settings. Figure 8C shows the results of this analysis. Shown in this figure is the time looking at the border (displayed on the x axis) and the chromatic induction index. No significant correlation could be detected between the time spent looking at the border and the chromatic induction index. Once again, regression analysis revealed that the proportion of time fixating the border did not significantly contribute in explaining the variability in induction between subjects ($R^2 = 0.045$, $p = 0.258$).

3. Discussion

The results from the main experiment do not confirm our hypothesis that there is a correlation between subjects' eye movements and the score on the chromatic induction index. It could be the case that we were unable to find any statistical correlation between the two factors because of the particular stimuli that we used. In order to test whether this lack of correlation can be generalized to other scene statistics, we performed additional experiments.

4. Additional Results

In order to investigate whether scene statistics would have any effect on the correlation between eye movements and the chromatic induction index, we tested subjects in four uniform-colored backgrounds with disk radii of both 8° and 4° and in the same variegated backgrounds as used in the main experiment, but now with a disk radius of 8° (see Fig. 1). The two different disk sizes (8° and 4° radii sizes) and the uniform and the variegated-colored background conditions were each tested in separate sessions. The order of the sessions was randomized between subjects. The procedure and analyses was identical to the main experiment.

a. Subjects

For the uniformed-colored background with a disk radius of 4°, eight subjects participated, including the first author. Six subjects also participated in the main experiment. For the uniform-colored background with a disk radius of 8°, seven subjects participated (including the same six participants who also participated in the main experiment). Finally, for the variegated-colored background condition with a disk radius of 8°, fifteen subjects participated, including the first author. Seven subjects also participated in the main experiment. All subjects (except the author) were naïve as to the purpose of the experiment and all had normal color vision as tested with the Ishihara color plates.

5. Results

Does subjects' viewing behavior also change when tested with different disk radii and using uniform-colored backgrounds? Figure 9 shows the average proportion of time (with the standard error) that subjects look at the background (plotted on the y axis) separately plotted for a disk radius of 4° and 8° (x axis). Dark gray bars show the data for the uniform-colored background, while the light gray bars represents the variegated-colored background. The results show that for a 4° radius disk, there does not seem to be a significant difference between the uniform-colored and the variegated-colored background in the amount of time that subjects looked at the background. However, for the 8° radius disk, subjects looked longer at the background when tested with the uniform-colored background compared to the variegated-colored background condition. Overall, subjects spent a larger amount of time looking at the background when tested with the 4° radius disk compared to when tested with the 8° radius disk.

All these results suggest the following: when tested with the 4° radius disk, subjects are more willing to make saccades to the background. It is as if it takes much less effort to make saccades to the background when tested with a smaller adjustable disk compared to when a larger adjustable disk is used. It is unclear, however, why subjects look more often at the background when tested with an 8° radius disk in the

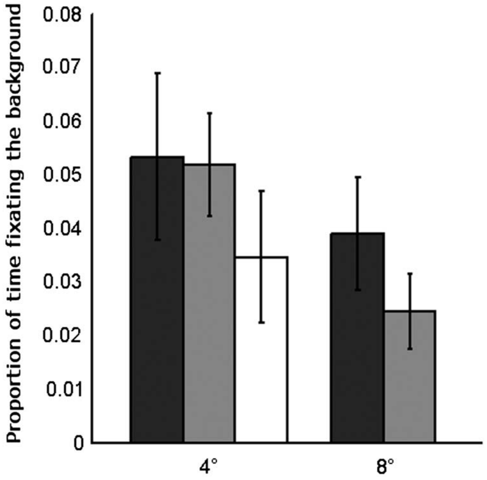

Fig. 9. Results from experiments 2a and 2b. Shown are the proportion of time during each trial that subjects looked at the background (y axis) separately plotted for the uniform-colored background (dark gray bar), the variegated-colored background (light gray bar), and the random-colored background of experiment 2b (white data bar). The results are shown separately for both the 4° and the 8° radius adjustable disks (plotted on the x axis). Note that for the random-color background condition, only the 4° radius disk was measured. The results show that for the 4° radius disk, there is no significant difference in the amount of time looking at the background between the uniform-colored and the variegated-colored background. However, subjects looked for less time at the background when tested with the random-colored background. For the 8° radius disk, subjects looked overall for less time at the background compared to when tested with the 4° radius disk. Moreover, subjects looked significantly longer at the background when tested with the uniform-colored background compared to the variegated-colored background condition. These data show that changing the scene statistics of the stimuli has an effect on subjects' viewing behavior.

uniform-colored background condition compared to when tested with the variegated background condition. Subjects reported that looking at the variegated background confused them when making gray settings; they had the impression that the background's color had an influence on what they perceived as gray. This dependency on the background's color when considering what they perceived as gray was less apparent when tested with the uniform-colored background condition. However, this hypothesis cannot explain the fact why subjects were equally willing to look at the background between when tested with the uniform-colored background compared to when tested with the variegated-colored background with a 4° radius disk.

We also wanted to look at whether using uniform-colored backgrounds and changing the radius of the adjustable disk would have any effect on the chromatic induction index. Figure 10 shows the chromatic induction index (plotted on the y axis) separately plotted for the uniform-colored background (dashed gray line) and the variegated-colored background (solid black line), shown for a 4° radius disk and an 8° radius disk (plotted on the x axis). We can conclude from these data that induction is significantly larger when tested with the uniform-colored background condition compared to the variegated-colored background condition. This effect is especially apparent when tested with a 4° radius disk.

More importantly, we wanted to know whether there is a correlation between subjects' eye movements and the chromatic induction index obtained when tested with these new stimulus parameters. This was not the case; no significant correlation was found between the chromatic induction index and the time looking at the background, the time looking at the border, or the number of times subjects looked between the adjustable disk and the background.

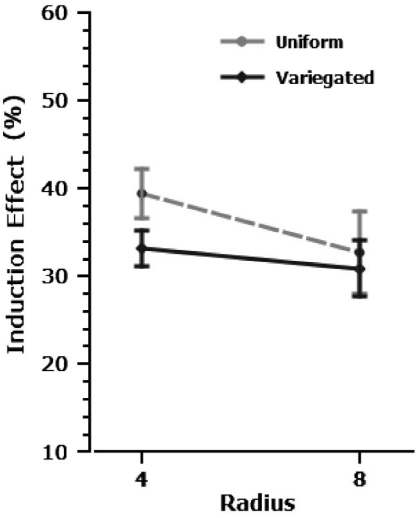

Fig. 10. Results of experiment 2a. Shown is the chromatic induction index (y axis) plotted separately for the uniform-colored background (gray dashed line) and the variegated-colored background (black solid line). The data are split for the 4° radius disk and the 8° radius disk (x axis). From this figure we can conclude that overall, the chromatic induction index is larger for the uniform-colored background compared to the variegated-colored background. Moreover, the chromatic induction index is significantly larger when making achromatic settings for the 4° radius disk compared to setting an 8° radius disk to gray. This last effect is especially apparent for the uniform-colored background condition.

6. Discussion

The most important finding from experiment 2a was that we were unable to find a correlation between subjects' eye movements and the chromatic induction index. The data indicate that subjects hardly looked at the background while they made achromatic settings. Thus, these results are not in line with the results of Golz [28], which indicate that eye movements can play a large role in chromatic induction experiments. Changing the layout of the scene (uniform- versus variegated-colored background) or changing the spatial parameter of the adjustable disk did not have an effect on the correlation between the chromatic induction index and the eye movement parameters that we studied. That there was a large variability between subjects in that their chromatic induction index shows that the lack of correlation between eye movements and induction cannot be explained by a lack of variability in the amount of induction. That the amount of induction is less with more chromatic variability has been demonstrated before [38,39]. Apparently, subjects had the largest amount of induction for when tested with the 4° radius disk. This is not so strange, because subjects could still see the chromaticity of the background in their peripheral vision. This could also explain the fact that the chromaticity of the background had an effect on subjects' gray settings, although subjects did hardly look at the background when making gray settings.

One important difference between the stimuli used by Golz [28] and our stimuli is that Golz used stimuli that had a greater variety of colors displayed in the background. It could be the case that the scenes used in our experiments lacked this chromatic complexity and that this was the main reason why our subject did not look more at the backgrounds, because looking more frequently at the background did not give them much more information than they already had when making achromatic settings. In order to study whether increasing the chromatic variability in the background had any effect on subjects' eye movements, we performed another experiment.

B. Experiment 2b

The procedure of this experiment was identical to the previous one with notably few exceptions: first, we decreased the distance between the observer and the screen to increase to the visual field in which the display was shown. Now subjects sat at a distance of 46 cm from the screen. Also we decreased the size of the background tiles to increase the number of tiles that could be displayed on the screen. The size of the tiles was now 0.5°. We only used a radius of 4° for the adjustable disk. As in the previous experiment, subjects made 10 matches for each background, leading to 40 trials for this experiment. We also used a larger variety of colored tiles in the background to test whether displaying more chromatic variability in the background has any effect. We will refer to this background condition as the "random-colors" background condition (see Fig. 11).

1. Background

For the random-colors background condition, we used the same average four color coordinates (−0.5, 0); (0, 0.5); (0.5, 0); (0, −0.5) as used in the previous experiments. Once again, we chose colors that lie on the same circle of radius 0.2 with respect to the above-mentioned DKL coordinates. However,

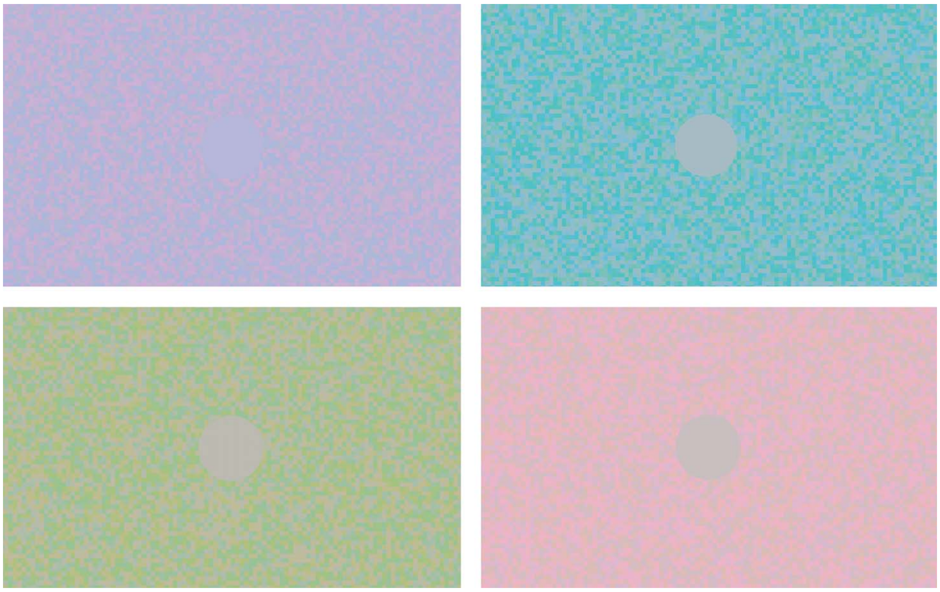

Fig. 11. (Color online) Stimuli used for experiment 2b: the random-colors experiment.

for this condition, we randomly chose colors that lie on this circle (see Fig. 11). By randomly assigning colors to the background that lie on this circle, we made sure that the average chromaticity displayed on the background for this condition was equal to the average chromaticity of both the uniform-colored and variegated-colored background condition used in the previous experiment. This was verified by measuring the average chromaticity of the background using a Photo Research PR-650 spectroradiometer.

2. *Subjects*

Ten subjects (including authors J.G. and M.T.) performed in this experiment. With the exception of the authors, they were naïve as to the purpose of the experiment. Seven subjects also participated in the main experiment. All subjects had normal color vision as tested with Ishihara color plates [37] and had normal or corrected-to-normal visual acuity.

4. RESULTS

Figure 9 shows that subjects spent less time looking at the background when tested with the random-colors background condition (white bar) compared to the uniform-colored and the variegated-colored background. The crucial question is whether there is a correlation between the time that subjects' looked at the background and the chromatic induction index that they obtained. Figure 12 explores this question. This figure plots the chromatic induction index (plotted on the y axis) as a function of the proportion of time that subjects fixate the background. This figure shows that there is no linear relationship between these two factors. Also no significant relationship could be observed between the time spent looking at the border or the number of times looking back and forth between the adjustable disk and the background and subjects' chromatic induction index.

5. DISCUSSION

The important result from experiment 2b is that increasing the chromatic variability in the background does not have a significant effect on the correlation between eye movements and chromatic induction. These data in combination with the data of the previous experiment make us confident that the lack of correlation between eye movements and the amount of chromatic induction obtained by our subjects is not due to some particular condition that we used but can be generalized toward displays, which are very different with respect to their scene statistics. In a pilot study, we also measured eye movements in a small number of subjects when making achromatic adjustments for a smaller adjustable disk (2° radius disk) and similar results as reported in experiment 2 were found.

The results of experiment 2 also show that increasing the amount of chromatic variability in the background (the

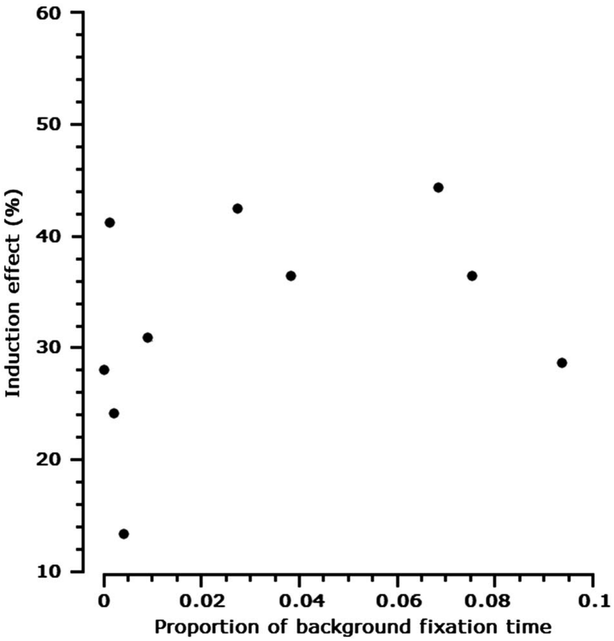

Fig. 12. Results of experiment 2b. Shown is the proportion of time subjects looked at the background (x axis) and the chromatic induction index obtained (y axis). Each dot represents the average value per subject. The results show that there is no linear relationship between time spent looking at the background and the amount of chromatic induction.

random-colors background condition) diminishes the amount that subjects look at the background even more (compared to when using both the uniform and the variegated background condition). The results do suggest that changing the parameters of the stimulus has an effect on subjects' eye movements. However, it is unclear at this point why this occurs.

6. GENERAL CONCLUSIONS

The most important result of the second experiment, in which subjects could freely fixate their eyes, was that there was no correlation between subjects' eye movements and the chromatic induction index obtained. For the second experiment, we used a number of different backgrounds and spatial parameters for the adjustable disk all leading to the same conclusion. Moreover, that we were able to replicate Golz's [28] results showed that the lack of effect in experiment 2 was not due to using very particular scenes. We can therefore conclude that the results of Golz's [28] finding an effect of eye movements on chromatic induction cannot be generalized to normal (free-looking) conditions. It seems therefore that eye movements have a smaller effect when making achromatic settings than the results of Golz [28] suggest. Our results show that when subjects make achromatic settings, they hardly look at the background at all. However, the fact that subjects did show chromatic induction effects in our setup demonstrates that the color of the background had an effect on subjects' achromatic settings. It must then be the case that although subjects did not directly look at the background when making achromatic settings, the color of the background seen in the near periphery of their vision was taken into account when making achromatic settings.

Our results confirm the idea that chromatic induction is a local process (i.e., that only the part where subjects are looking or their near peripheral vision is important), as the amount of induction is significantly less when subjects have to keep looking within the colored field of the adjustable disk. We used various chromatic induction stimuli ranging in visual complexity and also varying the size of the adjustable disk. That we were unable to find a correlation between subjects' chromatic induction effects and their eye movements makes us confident in claiming that in conventional chromatic induction experiments using achromatic settings, eye movements cannot explain subjects' variability in chromatic induction. Therefore the between-subject variability in the chromatic induction index must be caused by some other factor(s).

A disadvantage of using the method of achromatic settings is that there is no explicit reference color present during the experiment as subjects have to set the adjustable disk to gray according to an internal representation of what they consider as being a "perfect gray." This introduces variability within the settings that subjects make, as can be observed by looking at the variability of the achromatic settings that we found when making subjective gray settings.

Finally, changing the parameters of our stimulus (e.g., changing the disk radii and chromatic variability in the background) did change our subjects' eye movement behavior. It is unclear at this point why this happened. Apparently, subjects adapt their viewing strategies under changes in stimulus presentations. Discovering what these adaptable viewing strategies are when changing the stimulus would probably be a big step in understanding individual differences in color perception and in understanding how changing the stimulus changes the way subjects search for different sources of information within the stimulus to perform the task.

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REFERENCES

1. A. Hurlbert, "Color vision: putting it in context," Curr. Biol. **6**, 1381–1384 (1996).
2. J. Walraven, T. L. Benzschawel, and B. E. Rogowitz, "Color constancy interpretation of chromatic induction," Die Farbe **34**, 269–273 (1987).
3. F. A. A. Kingdom, "Perceiving light versus material," Vis. Res. **48**, 2090–2105 (2008).
4. S. K. Shevell and F. A. A. Kingdom, "Color in complex scenes," Annu. Rev. Psychol. **59**, 143–166 (2008).
5. E. Brenner and F. W. Cornelissen, "Spatial interactions in color vision depend on distances between boundaries," Naturwissenschaften **78**, 70–73 (1991).
6. T. Hansen, S. Walter, and K. R. Gegenfurtner, "Effects of spatial and temporal context on color categories and color constancy," J. Vis. **7**(4), 2 (2007).
7. O. Rinner and K. R. Gegenfurtner, "Time course of chromatic adaptation for color appearance and discrimination," Vis. Res. **40**, 1813–1826 (2000).
8. E. H. Adelson, "Perceptual organization and the judgment of brightness," Science **262**, 2042–2044 (1993).
9. E. H. Adelson, "Lightness perception and lightness illusions," in *The New Cognitive Neurosciences*, 2nd ed., M. Gazzaniga, ed. (MIT, 2000), pp. 339–351.
10. B. L. Anderson, "A theory of illusory lightness and transparency in monocular and binocular images: the role of contour junctions," Perception **26**, 419–453 (1997).
11. L. Arend and R. Goldstein, "Simultaneous constancy, lightness and brightness," J. Opt. Soc. Am. A **4**, 2281–2285 (1987).
12. J. J. M. Granzier, E. Brenner, F. W. Cornelissen, and J. B. J. Smeets, "Luminance-color correlation is not used to estimate the color of the illumination," J. Vis. **5**(1), 2 (2005).
13. D. Jameson and L. M. Hurvich, "Opponent chromatic induction: experimental evaluation and theoretical account," J. Opt. Soc. Am. **51**, 46–53 (1961).
14. J. Walraven, "Spatial characteristics of chromatic induction; the segregation of lateral effects from straylight artifacts," Vis. Res. **13**, 1739–1753 (1973).
15. E. W. Yund and J. C. Armington, "Color and brightness contrast effects as a function of spatial variables," Vis. Res. **15**, 917–929 (1975).
16. J. Krauskopf, "Effect of retinal image stabilization on the appearance of heterochromatic targets," J. Opt. Soc. Am. **53**, 741–744 (1963).
17. F. W. Cornelissen and E. Brenner, "On the role and nature of adaptation in chromatic induction," in *Channels in the Visual Nervous System: Neurophysiology, Psychophysics and Models*, B. Blum ed. (Freund, 1991), pp. 109–123.
18. F. W. Cornelissen and E. Brenner, "Simultaneous color constancy revisited: an analysis of viewing strategies," Vis. Res. **35**, 2431–2448 (1995).
19. P. Lennie and M. D'Zmura, "Mechanisms of color vision," Crit. Rev. Neurobiol. **3**, 333–400 (1988).
20. J. M. Bosten and J. Mollon, "Kirschmann's fourth law," Perception **36**, 190, ECVP Abstract Suppl. (2007).
21. J. M. Bosten and J. Mollon, "Individual differences in simultaneous contrast," Perception **37**, 105, ECVP Abstract Suppl. (2008).
22. J. Cataliotti and R. Becklen, "Single dissociation between lightness contrast effects," Perception, Vol. 36, ECVP Abstract Suppl. (ECVP, 2007), p. 79.
23. M. D. Fairchild, "A victory for equivalent background—on average," in *IS&T/SID Seventh Color Imaging Conference* (Society for Imaging Science and Technology, 1999), pp. 87–92.

24. V. Ekroll and F. Faul, “A simple model describes large individual differences in simultaneous color contrast,” Vis. Res. **49**, 2261–2272 (2009).
25. M. Toscani, M. Valsecchi, and K. R. Gegenfurtner, “Where we look determines what we see,” J. Vis. **11** (11), 346 (2011).
26. T. Hansen and K. R. Gegenfurtner, “Classification images for chromatic signal detection,” J. Opt. Soc. Am. A **22**, 2081–2089 (2005).
27. E. Brenner, J. J. M. Granzier, and J. B. J. Smeets, “Perceiving color at a glimpse: the relevance of where one fixates,” Vis. Res. **47**, 2557–2568 (2007).
28. J. Golz, “Color constancy: influence of viewing behaviour on gray settings,” Perception **39**, 606–619 (2010).
29. F. Moller, M. L. Laursen, J. Tygesen, and A. K. Sjolie, “Binocular quantification and characterization of microsaccades,” Graefe’s Archive Clin. Exper. Ophthalmol. **240**, 765–770 (2002).
30. M. P. Lucassen and J. Walraven, “Quantifying color constancy: evidence for nonlinear processing of cone-specific contrast,” Vis. Res. **33**, 739–757 (1993).
31. D. H. Brainard and B. A. Wandell, “Asymmetric color matching: how color appearance depends on the illuminant,” J. Opt. Soc. Am. A **9**, 1433–1448 (1992).
32. E. H. Land, “Recent advances in retinex theory,” Vis. Res. **26**, 7–21 (1986).
33. D. B. Judd, “Report on U.S. Secretariat Committee on colorimetry and artificial daylight,” in *Proceedings of the Twelfth Session of the CIE* (Bureau Central de la CIE, 1951).
34. G. Wyszecki and W. S. Stiles, *Color Science Concepts and Methods*, *Quantitative Data and Formulae* (Wiley, 1982).
35. A. M. Derrington, J. Krauskopf, and P. Lennie, “Chromatic mechanisms in lateral geniculate nucleus of macaque,” J. Physiol. **357**, 241–265 (1984).
36. J. Krauskopf, D. R. Williams, and D. W. Heeley, “Cardinal directions of color space,” Vis. Res. **22**, 1123–1131 (1982).
37. S. Ishihara, *Ishihara’s Tests for Color Deficiency* (Kanehara Trading, 2004).
38. E. Brenner and F. W. Cornelissen, “The influence of chromatic and achromatic variability on chromatic induction and perceived color,” Perception **31**, 225–232 (2002).
39. J. J. M. Granzier, T. C. W. Nijboer, J. B. J. Smeets, and E. Brenner, “Does realistic rendering of a gradient in illumination increase chromatic induction?” in *AIC Colour 05—10th Congress of the International Colour Association* (2005), pp. 227–230.